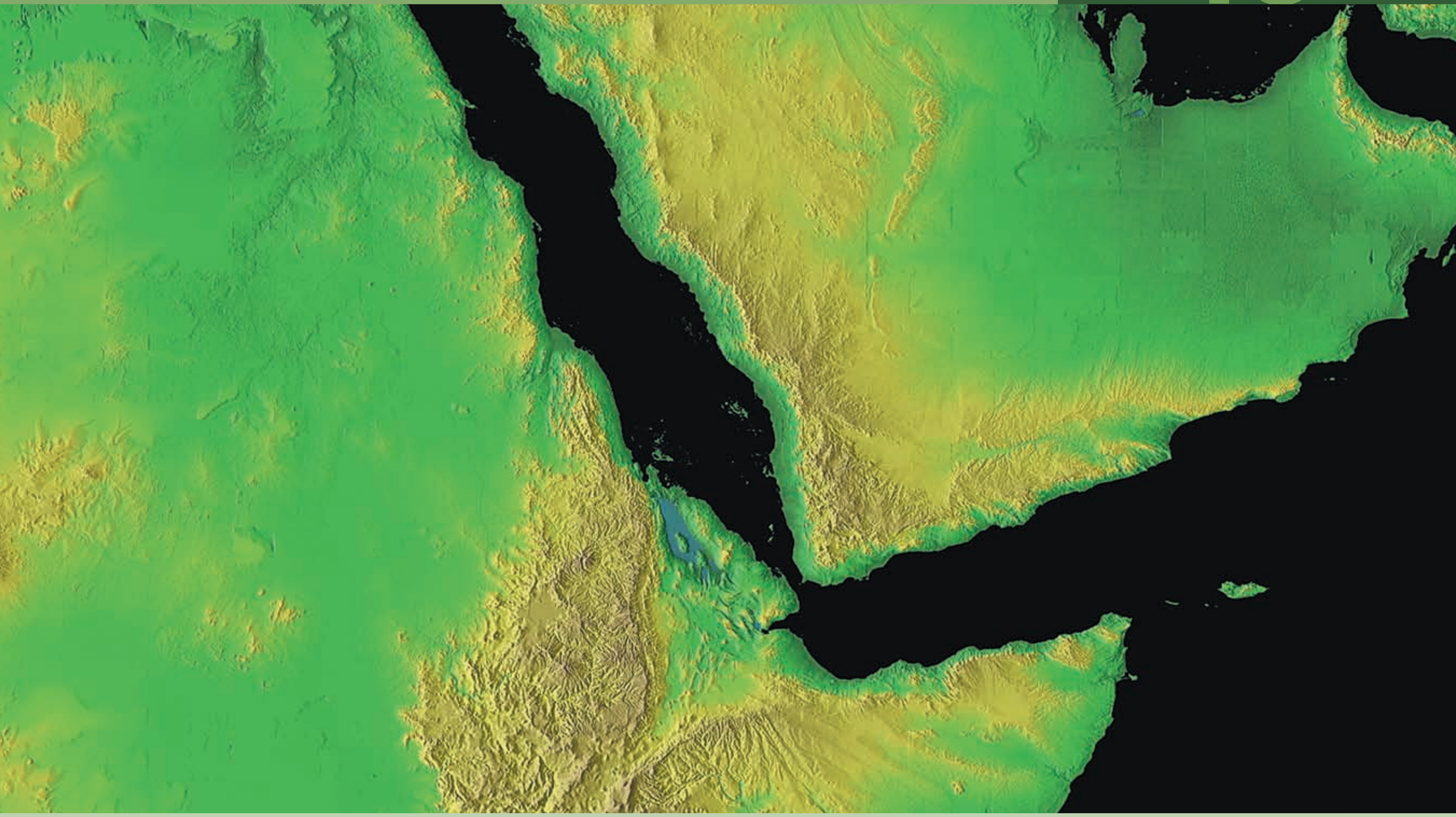
CHAPTER

19

# Plate Tectonics—The Unifying Theory



Satellite image of the Red Sea and Arabia. Plate motion has torn the Arabian Peninsula (right center) away from Africa (left) to form the Red Sea (center). *NOAA*

## LEARNING OBJECTIVES

- Summarize Wegener's evidence for continental drift. Why did the scientific community not initially accept the idea of continental drift?
- Outline the evidence that revived interest in continental drift.
- Explain the concept of seafloor spreading. Discuss how seafloor spreading explains features on the sea floor.
- Describe the evidence that plates move.
- Sketch and describe the various types of plate boundaries and the different geologic features associated with each.
- Discuss the possible driving mechanisms for plate tectonics.

As you studied volcanoes; igneous, metamorphic, and sedimentary rocks; and earthquakes, you learned how these topics are related to plate tectonics. In this chapter, we take a closer look at plates and plate motion. We will pay particular attention to plate boundaries and the possible driving mechanisms for plate motion.

The history of the concept of plate tectonics is a good example of how scientists think and work and how a hypothesis can be proposed, discarded, modified, and then reborn. In the first part of this chapter, we trace the evolution of an idea—how the earlier hypotheses of moving continents (continental drift) and a moving sea floor (seafloor spreading) were combined to form the theory of plate tectonics.

*Tectonics* is the study of the origin and arrangement of the broad structural features of Earth's surface, including not only folds and faults but also mountain belts, continents, and earthquake belts. Tectonic models such as an expanding Earth or a contracting Earth have been used in the past to explain *some* of the surface features of Earth. Plate tectonics has come to dominate geologic thought today because it can explain so *many* features. The basic idea of **plate tectonics** is that Earth's surface is divided into a few large, thick plates that move slowly and change in size. Intense geologic activity occurs at *plate boundaries* where plates move away from one another, past one another, or toward one another. The eight large lithospheric plates shown in figure 19.1, plus a few dozen smaller plates, make up the outer shell of Earth (the crust and upper part of the mantle).

The concept of plate tectonics was born in the late 1960s by combining two preexisting ideas—continental drift and seafloor spreading. **Continental drift** is the idea that continents move freely over Earth's surface, changing their positions relative to one another. **Seafloor spreading** is a hypothesis that the sea floor forms at the crest of the mid-oceanic ridge, then moves horizontally away from the ridge crest toward an oceanic trench. The two sides of the ridge are moving in opposite directions like slow conveyor belts.

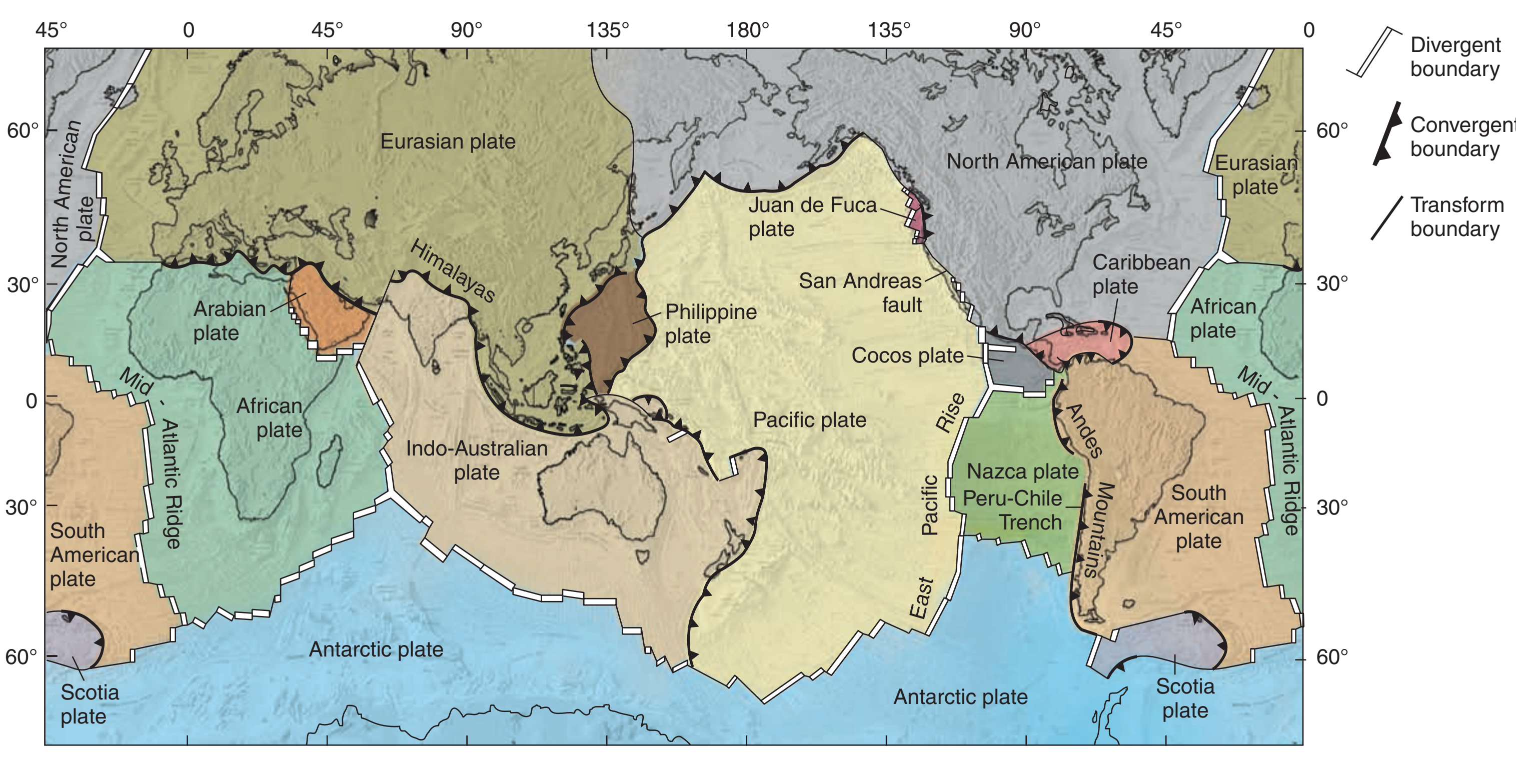



**FIGURE 19.1**

The major plates of the world. The western edge of the map repeats the eastern edge so that all plates can be shown unbroken. Double lines indicate spreading axes on divergent plate boundaries. Single lines show transform boundaries. Heavy lines with triangles show convergent boundaries, with triangles pointing down subduction zones. *Modified from W. Hamilton, U.S. Geological Survey*

Before we take a close look at plates, we will examine the earlier ideas of moving continents and a moving sea floor because these two ideas embody the theory of plate tectonics.

## THE EARLY CASE FOR CONTINENTAL DRIFT

Continents can be made to fit together like pieces of a picture puzzle. The similarity of the Atlantic coastlines of Africa and South America has long been recognized. The idea that continents were once joined together and have split and moved apart from one another has been around for more than a century (figure 19.2).

In the early 1900s, Alfred Wegener, a German meteorologist, made a strong case for continental drift. He noted that South America, Africa, India, Antarctica, and Australia had almost identical late Paleozoic rocks and fossils.

The plant *Glossopteris* is found in Pennsylvanian and Permian-age rock on all five continents, and fossil remains of *Mesosaurus,* a freshwater reptile, are found in Permian-age rocks only in Brazil and South Africa (figure 19.3). In addition, fossil remains of land-dwelling reptiles *Lystrosaurus* and *Cynognathus* are found in Triassic-age rocks on all five continents.

Wegener reassembled the continents to form a giant supercontinent, *Pangaea* (also spelled *Pangea* today). Wegener thought that the similar rocks and fossils were easier to explain if the continents were joined together, rather than in their present, widely scattered positions.

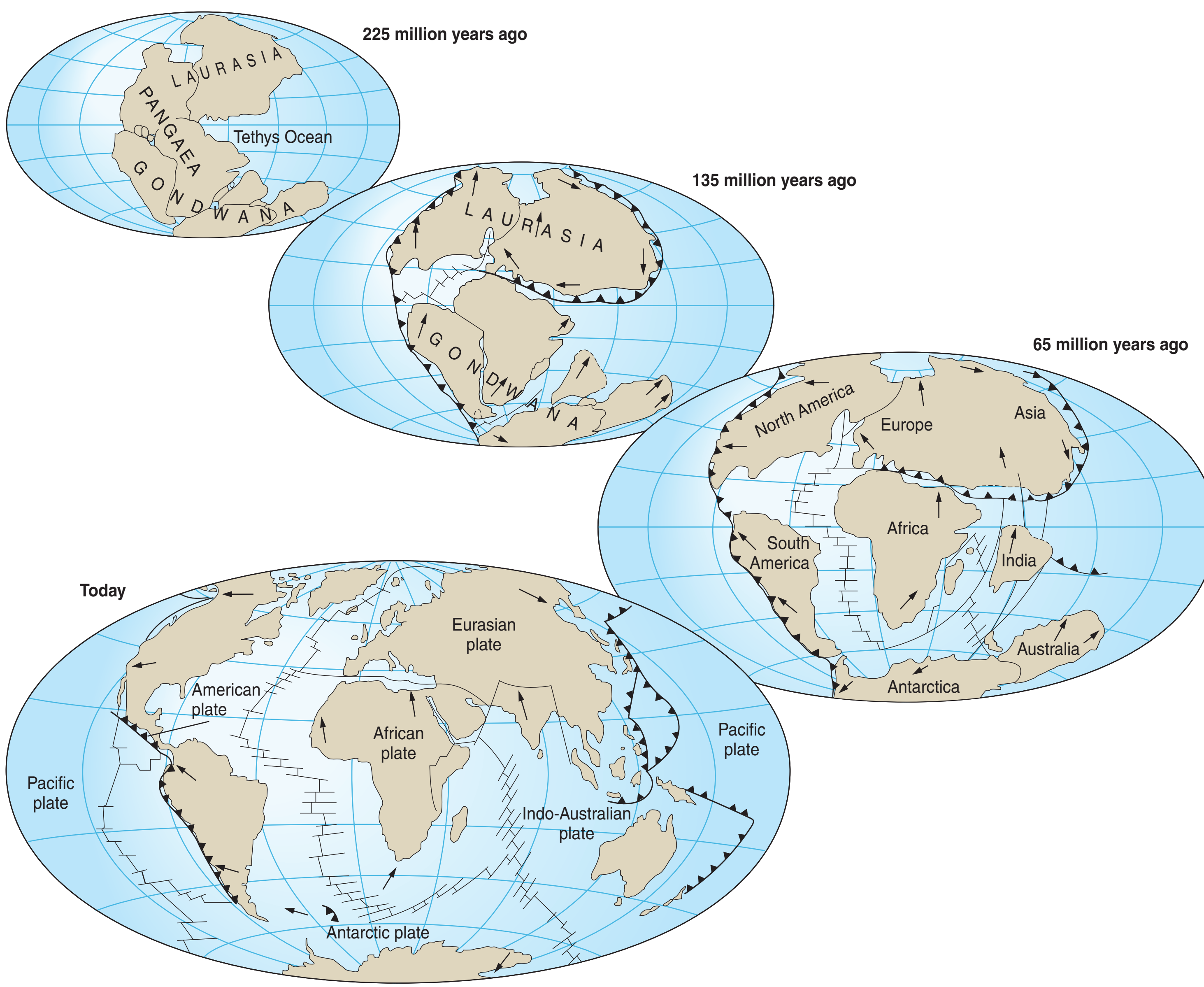



**FIGURE 19.2**

Pangaea breakup and continental drift. *After C. R. Scotese (www.scotese.com)*

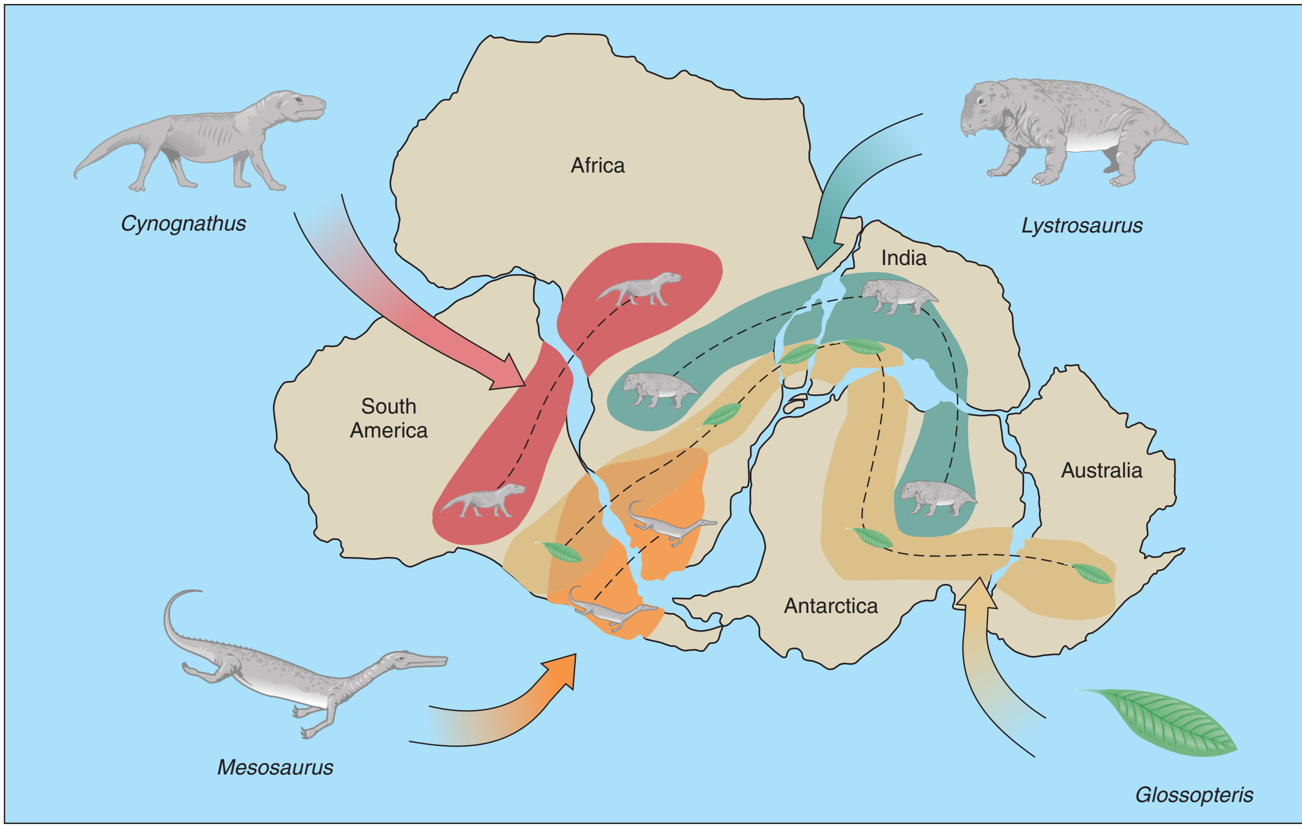



**FIGURE 19.3**

Distribution of plant and animal fossils that are found on the continents of South America, Africa, Antarctica, India, and Australia give evidence for the southern supercontinent of Gondwana. *Glossopteris* and other fernlike plants are found in Permian- and Pennsylvanian-age rocks on all five continents. *Cynognathus* and *Lystrosaurus* were sheep-sized land reptiles that lived during the Early Triassic Period. Fossils of the freshwater reptile *Mesosaurus* are found in Permian-age rocks on the southern tip of Africa and South America.

Pangaea initially separated into two parts. *Laurasia* was the northern supercontinent, containing what is now North America and Eurasia (excluding India). *Gondwanaland* was the southern supercontinent, composed of all the present-day Southern Hemisphere continents and India (which has drifted north).

The distribution of Late Paleozoic glaciation strongly supports the idea of Pangaea (figure 19.4). The Gondwanaland continents (the Southern Hemisphere continents and India) all have glacial deposits of Late Paleozoic age. If these continents were spread over Earth in Paleozoic time as they are today, a climate cold enough to produce extensive glaciation would have had to prevail over almost the whole world. Yet, no evidence has been found of widespread Paleozoic glaciation in the Northern Hemisphere. In fact, the late Paleozoic coal beds of North America and Europe were being laid down at that time in swampy, probably warm environments. If the continents are arranged according to Wegener's Pangaea reconstruction, then glaciation in the Southern Hemisphere is confined to a much smaller area (figure 19.4), and the absence of widespread glaciation in the Northern Hemisphere becomes easier to explain. Also, the present arrangement of the continents would require that late Paleozoic ice sheets flowed from the oceans toward the continents, which is impossible.

Wegener also reconstructed old climate zones (the study of ancient climates is called *paleoclimatology*) from evidence preserved in sedimentary rocks. For example, glacial till and striations indicate a cold climate near the North or South Pole. Coral reefs indicate warm water near the equator. Cross-bedded sandstones can indicate where ancient deserts formed near 30 degrees North and 30 degrees South latitude. If ancient climates had the same distribution on Earth that modern climates have, then sedimentary rocks can show where the ancient poles and equator were located.

Wegener determined the positions of the North and South Poles for each geologic period. He found that ancient poles were in different positions than the present poles (figure 19.5*A*). He called this apparent movement of the poles **polar wandering.** Polar wandering, however, is a deceptive term. The evidence can actually be explained in the following ways:

1. The continents remained motionless and the poles actually *did* move—polar wandering (figure 19.5*A*).
2. The poles stood still and the continents moved—continental drift (figure 19.5*B*).
3. Both occurred.

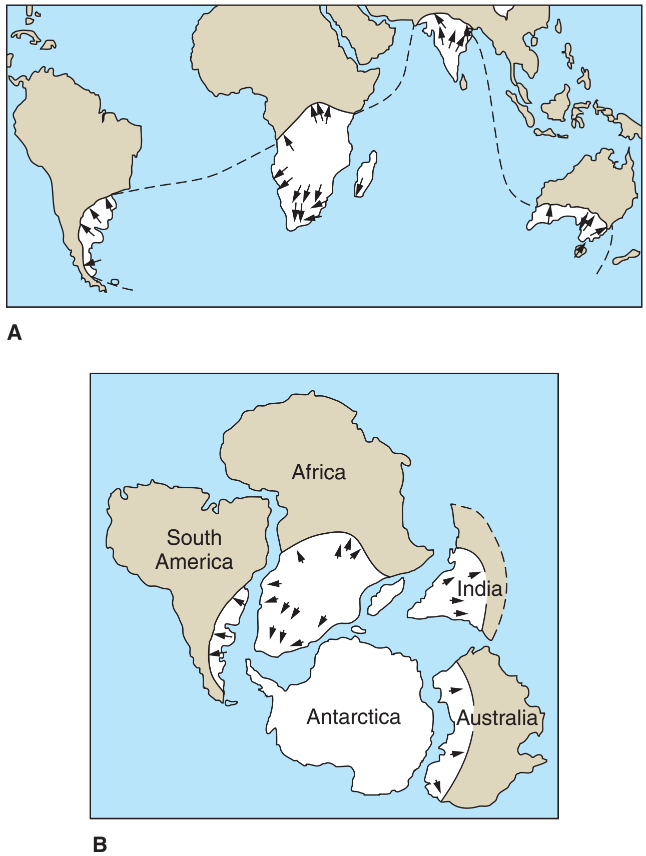



**FIGURE 19.4**

Distribution of late Paleozoic glaciation; arrows show direction of ice flow. (*A*) Continents in present positions show wide distribution of glaciation (white land areas with flow arrows). (*B*) Continents reassembled into Pangaea. Glaciated region becomes much smaller. *From Arthur Holmes, 1965,* Principles of Physical Geology, *2d ed., Ronald Press*

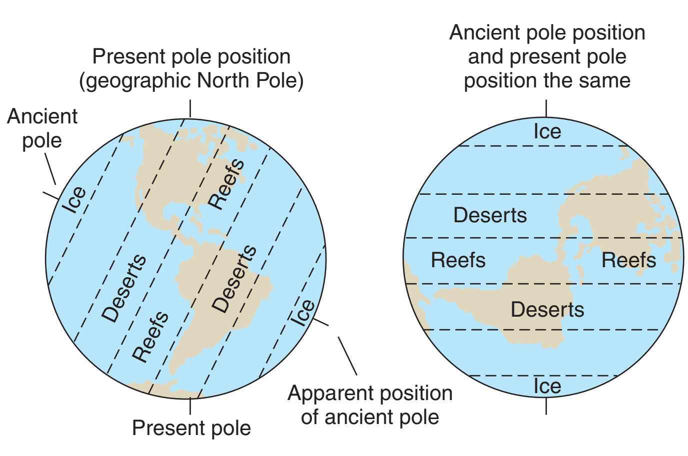



**FIGURE 19.5**

Two ways of interpreting the distribution of ancient climate belts. (*A*) Continents are fixed, poles wander. (*B*) Poles are fixed, continents drift. For simplicity, the continents in (*B*) are shown as having moved as a unit, without changing positions relative to one another. If continents move, they should change relative positions, complicating the pattern shown.


**FIGURE 19.6**

Apparent wandering of the South Pole since the Cretaceous Period as determined by Wegener from paleoclimate evidence. Wegener, of course, believed that *continents,* rather than the poles, moved. *From A. Wegener, 1928,* The Origins of Continents and Oceans, *reprinted and copyrighted. 1968, Dover Publications*

Wegener plotted curves of apparent polar wandering (figure 19.6). Since one interpretation of polar wandering data was that the continents moved, Wegener believed that this supported his concept of continental drift. (Notice that in only one interpretation of polar wandering do the poles actually move. You should keep in mind that when geologists use the term *polar wandering,* they are referring to an *apparent* motion of the poles, which may or may not have actually occurred.)

## Skepticism about Continental Drift

Although Wegener presented the best case possible in the early 1900s for continental drift, much of his evidence was not clear-cut. The presence of land-dwelling reptiles throughout the scattered continents was explained by land bridges, which were postulated to somehow rise up from the sea floor and then subside again. The existence or nonexistence of land bridges was difficult to prove without data on the topography of the sea floor. Also, fossil plants could have been spread from one continent to another by winds or ocean currents. Their distribution over more than one continent does not *require* that the continents were all joined in the supercontinent, Pangaea. In addition, polar wandering might have been caused by moving poles rather than by moving continents. Because his evidence was not conclusive, Wegener's ideas were not widely accepted. This was particularly true in the United States, largely because of the mechanism Wegener proposed for continental drift.

Wegener proposed that continents plowed through the oceanic crust (figure 19.7), perhaps crumpling up mountain

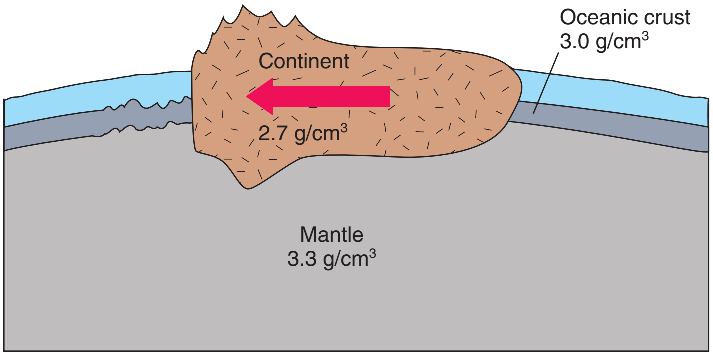



**FIGURE 19.7**

Wegener's concept of continental drift implied that the less-dense continents drifted *through* oceanic crust, crumpling up mountain ranges on their leading edges as they pushed against oceanic crust.

ranges on the leading edges of the continents where they pushed against the sea floor. Most geologists in the United States thought that this idea violated what was known about the strength of rocks at the time. The driving mechanism proposed by Wegener for continental drift was a combination of centrifugal force from Earth's rotation and the gravitational forces that cause tides. Careful calculations of these forces showed them to be too small to move continents. Because of these objections, Wegener's ideas received little support in the United States or much of the Northern Hemisphere (where the great majority of geologists live) in the first half of the twentieth century. The few geologists in the Southern Hemisphere, however, where Wegener's matches of fossils and rocks between continents were more evident, were more impressed with the concept of continental drift.

## THE REVIVAL OF CONTINENTAL DRIFT

Much work in the 1940s and 1950s set the stage for the revival of the idea of continental drift and its later incorporation, along with seafloor spreading, into the new concept of plate tectonics. The new investigations were in two areas: (1) study of the sea floor and (2) geophysical research, especially in relation to rock magnetism.

### Evidence from Paleomagnetism

Convincing new evidence about polar wandering came from the study of rock magnetism. Wegener's work dealt with the wandering of Earth's *geographic* poles of rotation. The *magnetic* poles are located close to the geographic poles, as you saw in chapter 17 on Earth's interior. Historical measurements show that the position of the magnetic poles moves from year to year but that the magnetic poles stay close to the geographic poles as they move. As we discuss magnetic evidence for polar wandering, we are referring to an apparent motion of the magnetic poles. Because the magnetic and geographic poles are close together, our discussion will refer to apparent motion of the geographic poles as well.

As we discussed in chapter 17, many rocks record the strength and direction of Earth's magnetic field at the time the rocks formed. Magnetite in a cooling basaltic lava flow acts like a tiny compass needle, preserving a record of Earth's magnetic field when the lava cools below the *Curie point.* Iron-stained sedimentary rocks such as red shale can also record Earth's magnetism. The magnetism of old rocks can be measured to determine the direction and strength of the magnetic field in the past. The study of ancient magnetic fields is called *paleomagnetism.*

Because magnetic lines of force dip more steeply as the north magnetic pole is approached, the inclination (dip) of the magnetic alignment preserved in the magnetite minerals in the lava flows can be used to determine the distance from a flow to the pole at the time that the flow formed (figure 19.8).

Old pole positions can be determined from the magnetism of old rocks. The magnetic alignment preserved in magnetite minerals points to the pole, and the dip of the alignment tells how far away the pole was. Figure 19.9 shows how Permian lava flows in North America indicate a Permian pole position in eastern Asia.

For each geologic period, North American rocks reveal a different magnetic pole position; this path of the *apparent* motion of the north magnetic pole through time is shown in figure 19.10. Paleomagnetic evidence thus verifies Wegener's idea of polar wandering (which he based on paleoclimatic evidence).

Like Wegener's paleoclimatic evidence, the paleomagnetic evidence from a *single* continent can be interpreted in two ways: either the continent stood still and the magnetic pole moved, or the pole stood still and the continent moved. At first glance, paleomagnetic evidence does not seem to be a significant advancement over paleoclimatic evidence. But when paleomagnetic evidence from *different* continents was compared, an important discovery was made.

Although Permian rocks in North America point to a pole position in eastern Asia, Permian rocks in *Europe* point to a different position (closer to Japan), as shown in figure 19.10. Does this mean there were *two* north magnetic poles in the Permian Period? In fact, every continent shows a different position for the Permian pole. A different magnetic pole for each continent seems highly unlikely. A better explanation is that a single pole stood still while continents split apart and rotated as they diverged.

Note the polar wandering paths for North America and Europe in figure 19.10. The paths are of similar shape, but the path for European poles is to the east of the North American path. If we mentally push North America back toward Europe, closing the Atlantic Ocean, the paths of polar wandering are almost identical between North America and Europe. This strongly suggests that there was one north magnetic pole and that the continents were joined together. There appear to be two north magnetic poles because the rocks of North America moved west; their magnetic minerals now point to a different polar position than they did when the minerals first formed.

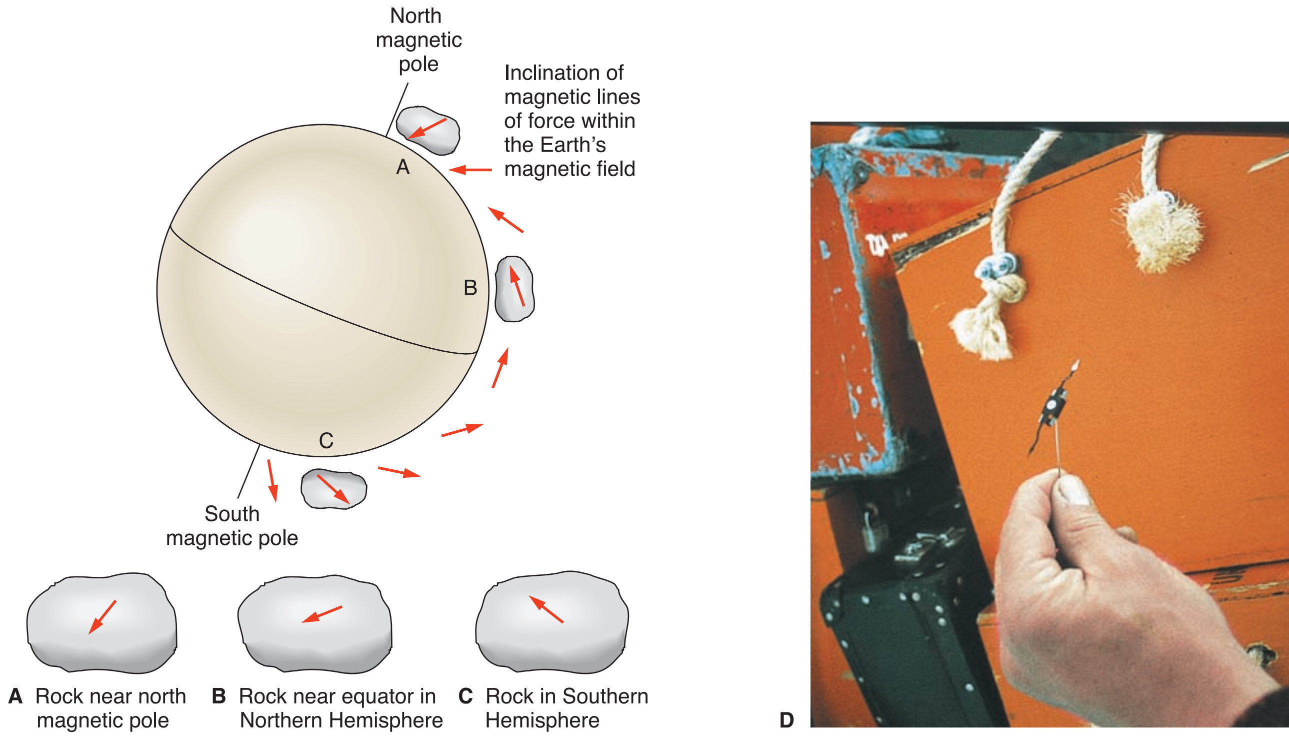



**FIGURE 19.8**

Magnetic dip (inclination) increases toward the north magnetic pole. Rocks in bottom part of figure are small samples viewed horizontally at locations A, B, and C on the globe. The magnetic dip can therefore be used to determine the distance from a rock to the north magnetic pole. (*D*) Compass needle showing steep inclination near south magnetic pole in Antarctica. *Photo by C. C. Plummer*

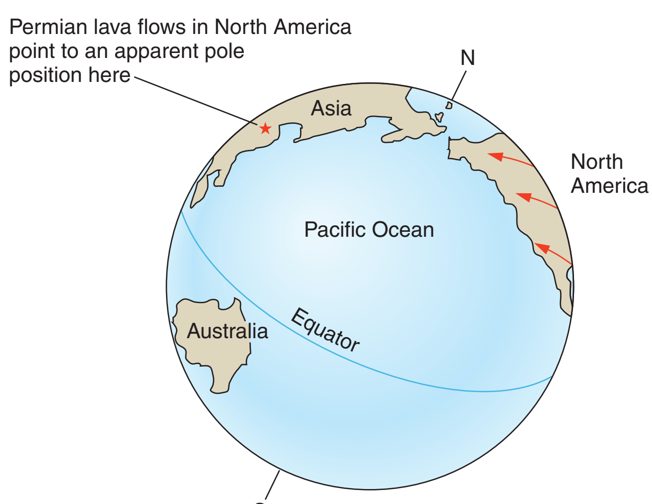



**FIGURE 19.9**

Paleomagnetic studies of Permian lava flows in North America indicate an apparent position for the north magnetic pole in eastern Asia.

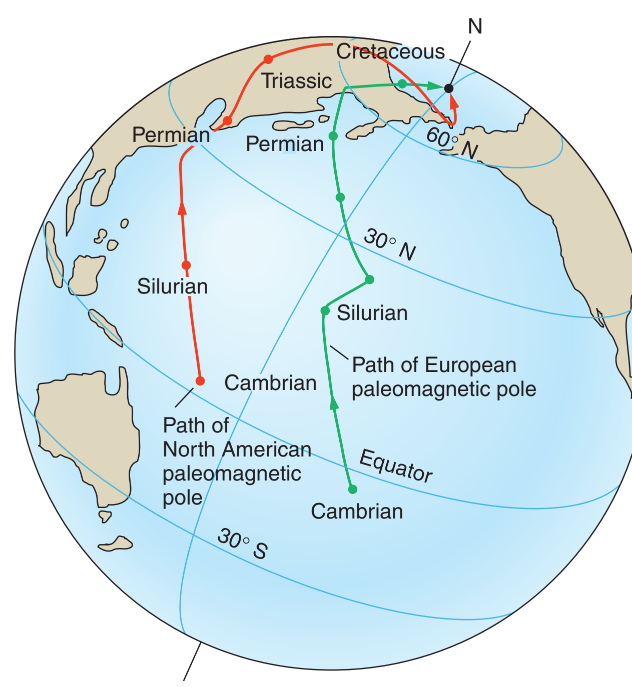



**FIGURE 19.10**

Apparent polar wandering of the north magnetic pole for the past 520 million years as determined from measurements of rocks from North America (red) and Europe (green).

## Geologic Evidence for Continental Drift

As paleomagnetic evidence revived interest in continental drift, new work was done on fitting continents together. By defining the edge of a continent as the middle of the continental slope, rather than the present (constantly changing) shoreline, a much more precise fit has been found between continents (figure 19.11).

The most convincing evidence for continental drift came from greatly refined rock matches between now-separated continents. If continents are fitted together like pieces of a jigsaw puzzle, the "picture" should match from piece to piece.

The matches between South America and Africa are particularly striking. Some distinctive rock contacts extend out to sea along the shore of Africa. If the two continents are fitted together, the identical contacts are found in precisely the right position on the shore of South America (figure 19.11). Isotopic ages of rocks also match between these continents.

Glacial striations show that during the late Paleozoic Era, continental glaciers moved from Africa toward the present Atlantic Ocean, while similar glaciers seemingly moved *from* the Atlantic Ocean *onto* South America (figure 19.11). Continental glaciers, however, cannot move from sea onto land. If the two continents had been joined together, the ice that moved off Africa could have been the ice that moved onto South America. This hypothesis has now been confirmed; from their lithology, many of the boulders in South American tills have been traced to a source that is now in Africa.

Some of the most detailed matches have been made between rocks in Brazil and rocks in the African country of Gabon. These rocks are similar in type, structure, sequence, fossils, ages, and degree of metamorphism. Such detailed matches are convincing evidence that continental drift did, in fact, take place.


**FIGURE 19.11**

Jigsaw puzzle fit and matching rock types between South America and Africa. Light-blue areas around continents are continental shelves (part of continents). Colored areas within continents are broad belts of rock that correlate in type and age from one continent to another. Arrows show direction of glacier movement as determined from striations.

There is also an abundance of satellite geodetic data from the Global Positioning Satellite (GPS) system, so we can now watch the continents move—about as eventful as watching your fingernails grow!

## History of Continental Positions

Rock matches show when continents were together; once the continents split, the new rocks formed are dissimilar. Paleomagnetic evidence indicates the direction and rate of drift, allowing maps of old continental positions, such as figure 19.2, to be drawn.

Although Pangaea split up 200 million years ago to form our present continents, the continents were moving much earlier. Pangaea was formed by the collision of many small continents long before it split up. Recent work shows that continents have been in motion for at least the past 2 billion years (some geologists say 4 billion years), well back into Precambrian time. For more than half of Earth's history, the continents appear to have collided, welded together, then split and drifted apart, only to collide again, over and over, in an endless, slow dance.

# SEAFLOOR SPREADING

At the same time that many geologists were becoming interested again in the idea of moving *continents,* Harry Hess, a geologist at Princeton University, proposed that the *sea floor* might be moving, too. This proposal contrasted sharply with the earlier ideas of Wegener, who thought that the ocean floor remained stationary as the continents plowed through it (figure 19.7). Hess's 1962 proposal was quickly named seafloor spreading, for it suggests that the sea floor moves away from the mid-oceanic ridge as a result of mantle convection (figure 19.12).

According to the initial concept of **seafloor spreading,** the sea floor is moving like a conveyor belt away from the crest of the mid-oceanic ridge, down the flanks of the ridge, and across the deep-ocean basin, to disappear finally by plunging beneath a continent or island arc (figure 19.12). The ridge crest, with sea floor moving away from it on either side, has been called a *spreading axis* (or *spreading center*). The sliding of the sea floor beneath a continent or island arc is termed **subduction.** The sea floor moves at a rate of 1 to 24 centimeters per year (your fingernail grows at about 1 centimeter per year). Although this may seem to be quite slow, it is rapid compared to most geologic processes.

## Hess's Driving Force

Why does the sea floor move? Hess's original hypothesis was that seafloor spreading is driven by deep mantle convection. **Convection** is a circulation pattern driven by the rising of hot material and/or the sinking of cold material. Hot material has

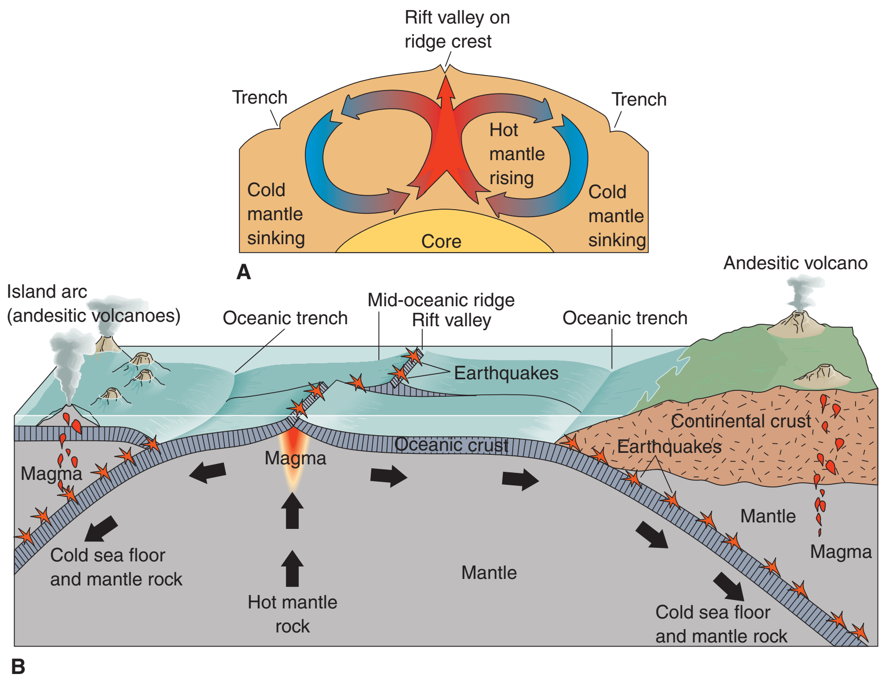



**FIGURE 19.12**

Seafloor spreading hypothesis of Harry Hess. (*A*) Hess proposed that convection extended throughout the mantle. (Scale of ridge and trenches is exaggerated.) (*B*) Hot mantle rock rising beneath the mid-oceanic ridge (a spreading axis) causes basaltic volcanism and high heat flow. Divergence of sea floor splits open the rift valley and causes shallow-focus earthquakes (stars on ridge). Sinking of cold rock causes subduction of older sea floor at trenches, producing Benioff zones of earthquakes and andesitic magma.

a lower density, so it rises; cold material has a higher density and sinks. The circulation of water heating in a pan on a stove is an example of convection. Convection in the mantle was a controversial idea in 1962; for although convection can be easily demonstrated in a pan of water, it was hard to visualize the solid rock of the mantle behaving as a liquid. Over very long periods of time, however, it is possible for the hot mantle rock to flow in a ductile manner. A slow, convective circulation is set up by temperature differences in the rock, and convection can explain many seafloor features as well as the young age of the seafloor rocks. (The heat that flows outward through Earth to drive convection is both original heat from the planet's formation and heat from the decay of radioactive isotopes, as discussed in chapter 17.)

## Explanations

### The Mid-Oceanic Ridge

If convection drives seafloor spreading, then hot mantle rock must be rising under the mid-oceanic ridge. Hess showed how the *existence of the ridge* and its *high heat flow* are caused by the rise of this hot mantle rock. The *basalt eruptions* on the ridge crest are also related to this rising rock, for here the mantle rock is hotter than normal and begins to undergo decompression melting.

As hot rock continues to rise beneath the ridge crest, the circulation pattern splits and diverges near the surface. Mantle rock moves horizontally away from the ridge crest on each side of the ridge. This movement accompanies tension at the ridge crest, cracking open the oceanic crust to form the **rift valley** and its associated *shallow-focus earthquakes.*

### Oceanic Trenches

As the mantle rock moves horizontally away from the ridge crest, it carries the sea floor (the basaltic oceanic crust) piggyback along with it. As the hot rock moves sideways, it cools and becomes denser, sinking deeper beneath the ocean surface. Hess thought it would become cold and dense enough to sink back into the mantle. This downward plunge of cold rock accounts for the *existence of the oceanic trenches* as well as their *low heat flow* values. It also explains the large *negative gravity anomalies* associated with trenches, for the sinking of the cold rock provides a force that holds trenches out of isostatic equilibrium (see chapter 17).

As the sea floor moves downward into the mantle along a subduction zone, it interacts with the rock above it. This interaction between the moving seafloor rock and the overlying crustal and mantle rock can cause the *Benioff zones of earthquakes* associated with trenches. It can also produce *andesitic volcanism,* which forms volcanoes either on the edge of a continent or in an island arc (figure 19.12).

Hess's ideas have stood up remarkably well over more than thirty years. We now think of lithospheric plates moving instead of sea floor riding piggyback on convecting mantle, and we think that several mechanisms cause plate motion, but Hess's explanation of seafloor topography, earthquakes, and age remains valid today.

### Age of the Sea Floor

The *young age of seafloor rocks* (see chapter 18) is neatly explained by Hess's seafloor spreading. New, young sea floor is continually being formed by basalt eruptions at the ridge crest. This basalt is then carried sideways by convection and is subducted into the mantle at an oceanic trench. Thus, old sea floor is continually being destroyed at trenches, while new sea floor is being formed at the ridge crest. (This is also the reason for the puzzling lack of pelagic sediment at the ridge crest. Young sea floor at the ridge crest has little sediment because the basalt is newly formed. Older sea floor farther from the ridge crest has been moving under a constant rain of pelagic sediment, building up a progressively thicker layer as it goes.)

Note that seafloor spreading implies that the youngest sea floor should be at the ridge crest, with the age of the sea floor becoming progressively older toward a trench. This increase in age away from the ridge crest was not known to exist at the time of Hess's proposal but was an important prediction of his hypothesis. This prediction has been successfully tested, as you shall see in the section on "Marine Magnetic Anomalies" in this chapter.

# PLATES AND PLATE MOTION

By the mid-1960s, the twin ideas of moving continents and a moving sea floor were causing great excitement and emotional debate among geologists. By the late 1960s, these ideas had been combined into a single theory that revolutionized geology by providing a unifying framework for Earth science—the theory of plate tectonics.

As described earlier, a **plate** is a large, mobile slab of rock that is part of Earth's surface (figure 19.1). The surface of a plate may be made up entirely of sea floor (as is the Nazca plate), or it may be made up of both continental and oceanic rock (as is the North American plate). Some of the smaller plates are entirely continental, but all the large plates contain some sea floor.

Plate tectonics has added some new terms, based on rock behavior, to the zones of Earth's interior, as we have discussed in some previous chapters. The plates are composed of the relatively rigid outer shell of Earth called the **lithosphere.** The lithosphere includes the rocks of the crust and uppermost mantle (figure 19.13).

The lithosphere beneath oceans increases in both age and thickness with distance from the crest of the mid-oceanic ridge. Young lithosphere near the ridge crest may be only 10 kilometers thick, while very old lithosphere far from the ridge crest may be as much as 100 kilometers thick. An average thickness for oceanic lithosphere might be 70 kilometers, as shown in figure 19.13.

Continental lithosphere is thicker, varying from perhaps 125 kilometers thick to as much as 200 to 250 kilometers thick beneath the oldest, coldest, and most inactive parts of the continents.

Below the rigid lithosphere is the **asthenosphere,** a zone that behaves in a ductile manner because of increased temperature and pressure. Some geologists think that the upper part of the asthenosphere is partially molten because P and S waves slow down here. This low-velocity zone probably reflects partial melting of just a few percent of the upper asthenosphere's volume, which would account for its properties and behavior. The partially melted upper asthenosphere acts as a lubricating layer under the lithosphere, allowing the plates to move. The low-velocity zone may extend from a depth of 70 to 200 kilometers beneath oceans; its thickness, depth, and even existence under continents are vigorously debated. Below the asthenosphere is more rigid mantle rock.

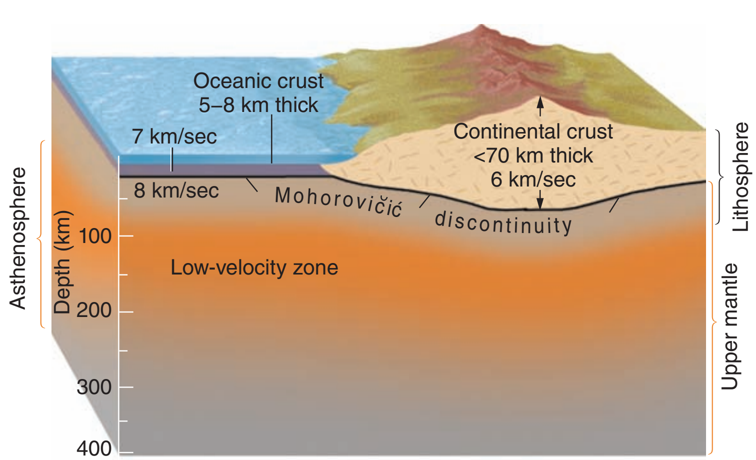



**FIGURE 19.13**

The rigid lithosphere includes the crust and uppermost mantle; it forms the plates. The ductile asthenosphere acts as a lubricating layer beneath the lithosphere. Oceanic lithosphere averages 70 kilometers thick; continental lithosphere varies from 125 to 250 kilometers thick. Asthenosphere may not be present under continents.

The idea that plates move is widely accepted by geologists, although the reasons for this movement are debated. Plates move away from the mid-oceanic ridge crest or other spreading axes. Some plates move toward oceanic trenches. If the plate is made up mostly of sea floor (as are the Nazca and Pacific plates), the plate can be subducted down into the mantle, forming an oceanic trench and its associated features. If the leading edge of the plate is made up of continental rock (as is the South American plate), that plate will not subduct. Continental rock, being less dense (specific gravity 2.7) than oceanic rock (specific gravity 3.0), is too light to be subducted.

To a first approximation, a plate may be viewed as a rigid slab of rock that moves as a unit. As a result, the interior of a plate is relatively inactive tectonically (but see box 19.1). Plate interiors generally lack earthquakes, volcanoes, young mountain belts, and other signs of geologic activity. According to plate-tectonic theory, these features are caused by plate interactions at plate boundaries.

Plate boundaries are of three general types, based on whether the plates move away from each other, move toward each other, or move past each other. A **divergent plate boundary** is a boundary between plates that are moving apart. A **convergent plate boundary** lies between plates that are moving toward each other. A **transform plate boundary** is one at which two plates move horizontally past each other.

# HOW DO WE KNOW THAT PLATES MOVE?

The proposal that Earth's surface is divided into moving plates was an exciting, revolutionary hypothesis, but it required testing to win acceptance among geologists. You have seen how the study of paleomagnetism supports the idea of moving continents. In the 1960s, two critical tests were made of the idea of a moving sea floor. These tests involved marine magnetic anomalies and the seismicity of fracture zones. These two successful tests convinced most geologists that plates do indeed move.

## Marine Magnetic Anomalies

In the mid-1960s, magnetometer surveys at sea disclosed some intriguing characteristics of marine magnetic anomalies. Most magnetic anomalies at sea are arranged in bands that lie parallel to the rift valley of the mid-oceanic ridge. Alternating positive and negative anomalies (chapter 17) form a stripelike pattern parallel to the ridge crest (figure 19.14).

### *The Vine-Matthews Hypothesis*

Two British geologists, Fred Vine and Drummond Matthews, made several important observations about these anomalies. They recognized that the pattern of magnetic anomalies was symmetrical about the ridge crest. That is, the pattern of magnetic anomalies on one side of the mid-oceanic ridge was a mirror image of the pattern on the other side (figure 19.14). Vine and Matthews also noticed that the same pattern of magnetic anomalies exists over different parts of the mid-oceanic ridge. The pattern of anomalies over the ridge in the northern Atlantic Ocean is the same as the pattern over the ridge in the southern Pacific Ocean.

The most important observation that Vine and Matthews made was that the pattern of magnetic *anomalies* at sea matches the pattern of magnetic *reversals* already known from studies of lava flows on the continents (figure 19.15 and chapter 17). This correlation can be seen by comparing the pattern of colored bands in figure 19.15 (reversals) with the pattern in figure 19.14 (anomalies).

Putting these observations together with Hess's concept of seafloor spreading, which had just been published, Vine and Matthews proposed an explanation for magnetic anomalies. They suggested that there is continual opening of tensional cracks within the rift valley on the mid-oceanic ridge crest. These cracks on the ridge crest are filled by basaltic magma from below, which cools to form dikes. Cooling magma in the dikes records Earth's magnetism at the time the magnetic minerals crystallize. The process is shown in figure 19.16.

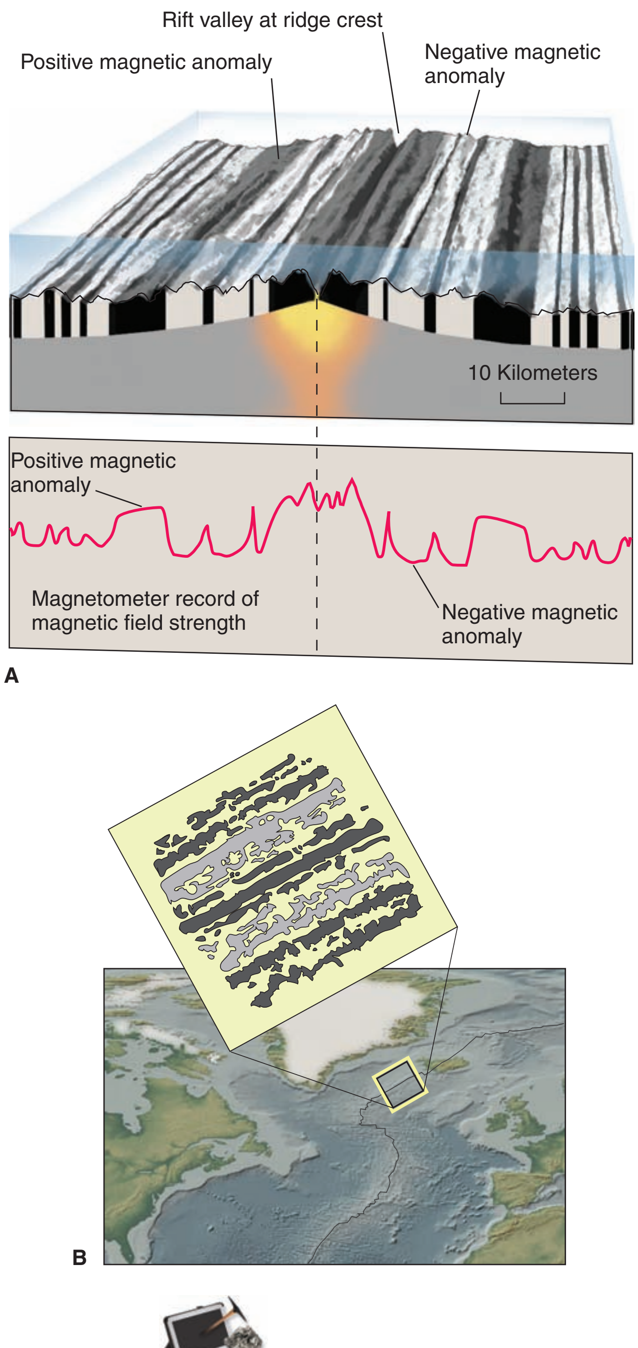



**FIGURE 19.14**

Marine magnetic anomalies. (*A*) The red line shows positive and negative magnetic anomalies as recorded by a magnetometer towed behind a ship. Positive anomalies are shown in black and negative anomalies are shown in tan. Notice how magnetic anomalies are parallel to the rift valley and symmetric about the ridge crest. (*B*) Symmetric magnetic anomalies ("stripes") from the mid-Atlantic ridge south of Iceland.

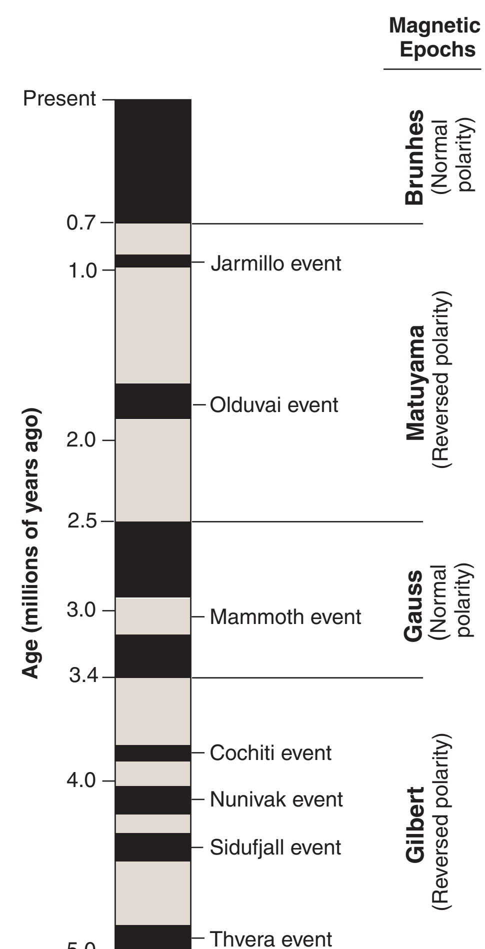



**FIGURE 19.15**

Magnetic reversals during the past 5 million years determined from lava flows that have been radiometrically dated. Black represents normal magnetism; tan represents reverse magnetism. *After Mankinen, E. A. and Dalrymple, G. B., 1979. Revised geomagnetic polarity time scale for the interval 0–5 m.y. B.P.* Journal of Geophysical Research, *v. 84, pp. 615–626.*

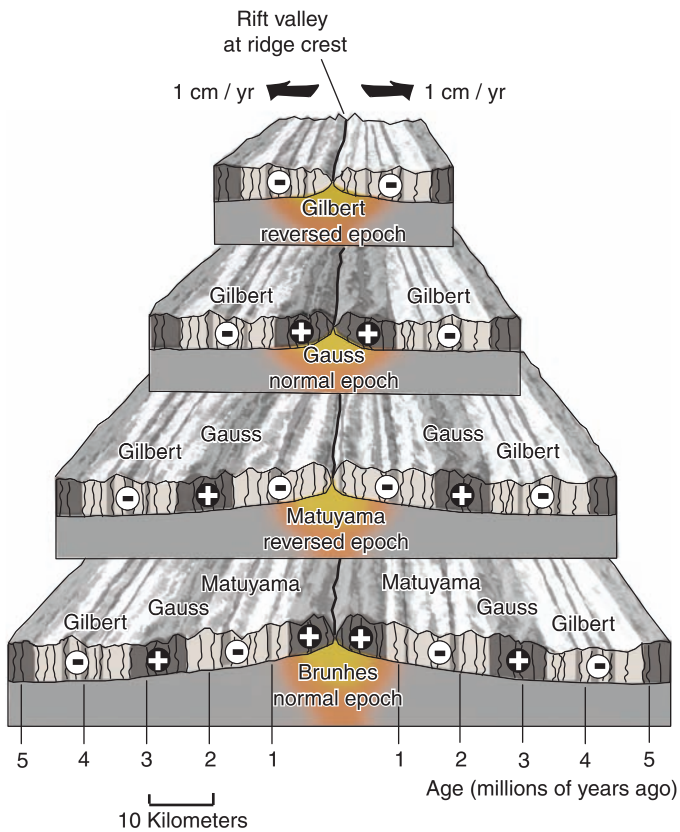



**FIGURE 19.16**

The origin of magnetic anomalies. During a time of reversed magnetism (Gilbert reversed epoch), a series of basaltic dikes intrudes the ridge crest, becoming reversely magnetized. The dike zone is torn in half and moved sideways, as a new group of normally magnetized dikes forms at the ridge crest. A new series of reversely magnetized dikes forms at the ridge crest. The dike pattern becomes symmetric about the ridge crest. Correlating the magnetic anomalies with magnetic reversals allows anomalies to be dated. Magnetic anomalies can therefore be used to predict the age of the sea floor and to measure the rate of seafloor spreading (plate motion).

When Earth's magnetic field has a *normal polarity* (the present orientation), cooling dikes are normally magnetized. Dikes that cool when the field is reversed (figure 19.16) are reversely magnetized. So each dike preserves a record of the polarity that prevailed during the time the magma cooled. Extension produced by the moving sea floor then cracks a dike in two, and the two halves are carried away in opposite directions down the flanks of the ridge. New magma eventually intrudes the newly opened fracture. It cools, is magnetized, and forms a new dike, which in turn is split by continued extension. In this way, a system of reversely magnetized and normally magnetized dikes forms parallel to the rift valley. These dikes, in the Vine-Matthews hypothesis, are the cause of the anomalies.

The magnetism of normally magnetized dikes adds to Earth's magnetism, and so a magnetometer carried over such dikes registers a stronger magnetism than average—a *positive* magnetic anomaly. Dikes that are reversely magnetized subtract from the present magnetic field, and so a magnetometer towed over such dikes measures a weaker magnetic field—a *negative* magnetic anomaly. Since seafloor motion separates these dikes into halves, the patterns on either side of the ridge are mirror images.

### Measuring the Rate of Plate Motion

There are two important points about the Vine-Matthews hypothesis of magnetic anomaly origin. The first is that it allows us to measure the *rate of seafloor motion* (which is the same as plate motion, since continents and the sea floor move together as plates).

Because magnetic reversals have already been dated from lava flows on land (figure 19.15), the anomalies caused by these reversals are also dated and can be used to discover how fast the sea floor has moved (figure 19.16). For instance, a piece of the sea floor representing the reversal that occurred 4.5 million years ago may be found 45 kilometers away from the rift valley of the ridge crest. The piece of sea floor, then, has traveled 45 kilometers since it formed 4.5 million years ago. Dividing the distance the sea floor has moved by its age gives 10 kilometers per million years, or 1 centimeter per year, for the rate of seafloor motion here. In other words, on each side of the ridge, the sea floor is moving away from the ridge crest at a rate of 1 centimeter per year. Such measured rates generally range from 1 to 24 centimeters per year.

### Predicting Seafloor Age

The other important point of the Vine-Matthews hypothesis is that it *predicts the age of the sea floor* (figure 19.16). Magnetic reversals are now known to have occurred back into Precambrian time. Sea floor of *all* ages is therefore characterized by parallel bands of magnetic anomalies. Figure 17.20 shows the pattern of marine magnetic anomalies (and the reversals that caused them) during the past 160 million years. The distinctive pattern of these anomalies through time allows them to be identified by age, a process similar to dating by tree rings.

Now, even before they sample the sea floor, marine geologists can predict the age of the igneous rock of the sea floor by measuring the magnetic anomalies at the sea surface. Most sections of the sea floor have magnetic anomalies. By matching the measured anomaly pattern with the known pattern that is shown in figure 17.20, the age of the sea floor in the region can be predicted, as shown in figure 19.17.

This is a very powerful test of the hypothesis that the sea floor moves. Suppose, for example, that the sea floor in a particular spot is predicted to be 70 million years old from a study of its magnetic anomalies. If the hypothesis of seafloor motion and the Vine-Matthews hypothesis of magnetic anomaly origin are correct, a sample of igneous rock from that spot *must* be 70 million years old. If the rock proves to be 10 million years old or 200 million years old or 1.2 billion years old, or any other age except 70 million years, then both of these hypotheses are wrong. But if the rock proves to be 70 million years old, as predicted, then both hypotheses have been successfully tested.

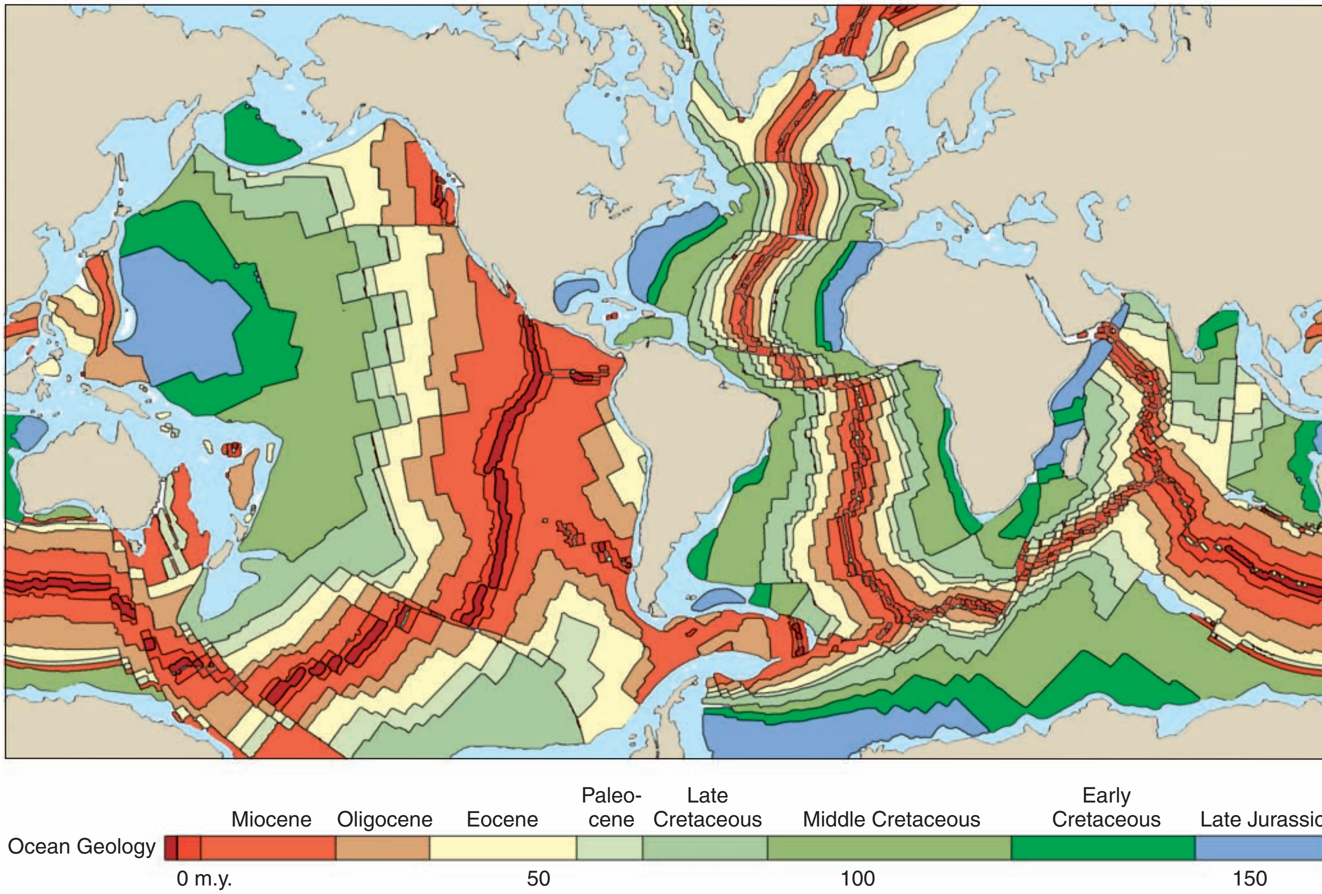



**FIGURE 19.17**

The age of the sea floor as determined from magnetic anomalies. *After* The Bedrock Geology of the World *by R. L. Larson, W. C. Pitman, III, et al., W. H. Freeman*

Hundreds of rock and sediment cores recovered from holes drilled in the sea floor were used to test these hypotheses. Close correspondence has generally been found between the predicted age and the measured age of the sea floor. (The seafloor age is usually measured by fossil dating of sediment in the cores rather than by isotopic dating of igneous rock.) This evidence from deep-sea drilling has been widely accepted by geologists as verification of the hypotheses of plate motion and magnetic anomaly origin. Most geologists now think that these concepts are no longer hypotheses but can now be called theories. (A *theory,* as discussed in box 1.4 in connection with the scientific method, is a hypothesis that has been tested and found to explain observations.)

## Another Test: Fracture Zones and Transform Faults

Cores from deep-sea drilling tested plate motion by allowing us to compare the actual age of the sea floor with the age predicted from magnetic anomalies. Another rigorous test of plate motion has been made by studying the seismicity of fracture zones.

The mid-oceanic ridge is offset along fracture zones (see figure 19.1). Conceivably, the mid-oceanic ridge was once continuous across a fracture zone but has been offset by strike-slip motion along the fracture zone (figure 19.18*A*). If such motion is occurring along a fracture zone, we would expect to find two things: (1) earthquakes should be distributed along the entire length of the fracture zone, and (2) the motion of the rocks on either side of the fracture zone should be in the direction shown by the arrows in figure 19.18*A*.

In fact, these things are not true about fracture zones. Earthquakes do occur along fracture zones, but only in those segments between offset sections of ridge crest. In addition, first-motion studies of earthquakes (see chapter 16) along fracture zones show that the motion of the rocks on either side of the fracture zone during an earthquake is exactly opposite to the motion shown in figure 19.18*A*. The actual motion of the rocks as determined from first-motion studies is shown in figure 19.18*B*. The portion of a fracture zone between two offset portions of ridge crest is called a **transform fault.**

The motion of rocks on either side of a transform fault was predicted by the hypothesis of a moving sea floor. Note that

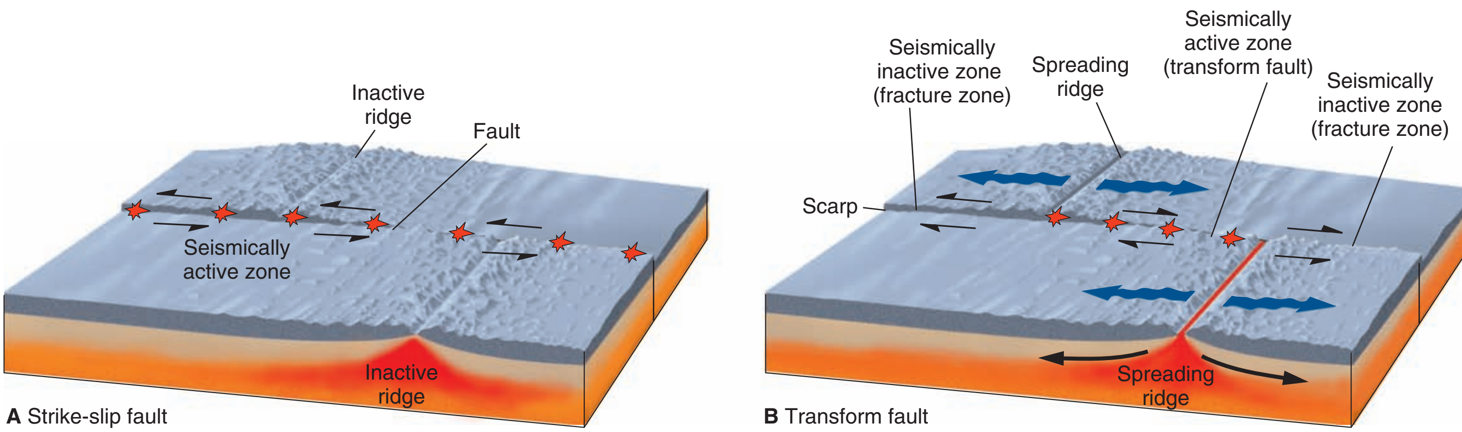



**FIGURE 19.18**

Two possible explanations for the relationship between fracture zones and the mid-oceanic ridge. (*A*) The expected rock motions and earthquake distribution, assuming that the ridge was once continuous across the fracture zone. (*B*) The expected rock motions and earthquake distribution, assuming that the two ridge segments were never joined together and that the sea floor moves away from the rift valley segments. Only explanation (*B*) fits the data. The portion of the fracture zone between the ridge segments is a transform fault.

sea floor moves away from the two segments of ridge crest (figure 19.18*B*). Looking along the length of the fracture zone, you can see that blocks of rock move in opposite directions only on that section of the fracture zone between the two segments of ridge crest. Earthquakes, therefore, occur only on this section of the fracture zone, the transform fault. The direction of motion of rock on either side of the transform fault is exactly predicted by the assumption that rock is moving away from the ridge crests. Verification by first-motion studies of this predicted motion along fracture zones was another successful test of plate motion.

## Measuring Plate Motion Directly

In recent years, the motion of plates has been directly measured using satellites, radar, lasers, and the Global Positioning System (GPS). These techniques can measure the distance between two widely separated points to within 1 centimeter. GPS is now routinely used to measure the relative motion between plates because of its accuracy and because the receivers are relatively inexpensive and fairly portable (figure 19.19*A*). Plate motions are now recorded on a yearly basis throughout the world (figure 19.19*B*).

If two plates move toward each other at individual rates of 2 centimeters per year and 6 centimeters per year, the combined rate of convergence is 8 centimeters per year. The measurement techniques are sensitive enough to easily measure such a rate if measurements are repeated each year. Such measured rates match closely the predicted rates from magnetic anomalies.

# DIVERGENT PLATE BOUNDARIES

Divergent plate boundaries, where plates move away from each other, can occur in the middle of the ocean or in the middle of a continent. The result of divergent plate boundaries is to create, or open, new ocean basins. This dynamic process has occurred throughout the geologic past.

When a supercontinent such as Pangaea breaks up, a divergent boundary can be found in the middle of a continent. The divergent boundary is marked by rifting, basaltic volcanism, and uplift. During rifting, the continental crust is stretched and thinned. This extension produces shallow-focus earthquakes on normal faults, and a *rift valley* forms as a central *graben* (a downdropped fault block). The faults act as pathways for basaltic magma, which rises from the mantle to erupt on the surface as cinder cones and basalt flows. Uplift at a divergent boundary is usually caused by the upwelling of hot mantle beneath the crust; the surface is elevated by the thermal expansion of the hot, rising rock and of the surface rock as it is warmed from below.

Figure 19.20 shows how a continent might rift to form an ocean. The figure shows rifting before uplift, because recent work indicates that this was the sequence for the opening of the Red Sea. The crust is initially stretched and thinned. Numerous normal faults break the crust, and the surface subsides into a central graben (figure 19.20*A*). Shallow earthquakes and basalt eruptions occur in this rift valley, which also has high heat flow. An example of a boundary at this stage is the African Rift Valleys in eastern Africa (figure 19.21). The valleys are grabens that may mark the site of the future breakup of Africa. A dramatic example of rifting occurred in September 2005 when a 60-kilometer-long fissure or crack opened in just three weeks after a series of earthquakes shook the Afar region. The opening cracks swallowed goats and camels, and nomads in the area reported black smoke that smelled of sulfur venting out of the fissures and also saw what looked like "large black birds" flying out of the linear vents. What they were witnessing was the largest single rip in the crust since the advent of satellite monitoring, and the associated injection of mafic magma (enough

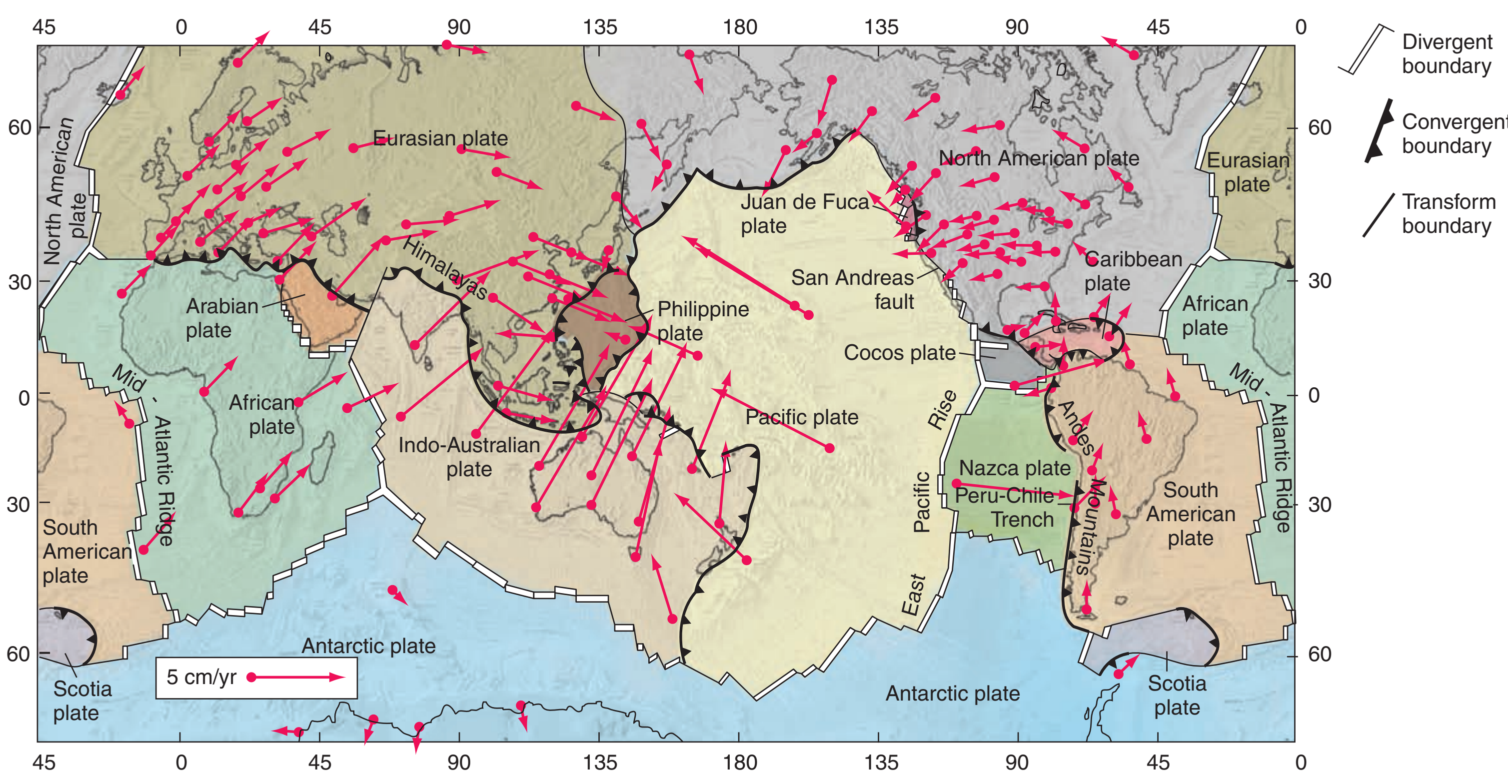
A

to fill a football stadium 2,000 times) along a vertical crack as new crust was being formed (figure 19.21*C*). The stretching apart of this area may eventually tear northeastern Africa away from the rest of the continent.

As divergence continues, the continental crust on the upper part of the plate clearly separates, and seawater floods into the linear basin between the two divergent continents (figure 19.20*B*). A series of fault blocks have rotated along curved fault planes at the edges of the continents, thinning the continental crust. The rise of hot mantle rock beneath the thinned crust causes continued basalt eruptions that create true oceanic crust between the two continents. The center of the narrow ocean is marked by a rift valley with its typical high heat flow and shallow earthquakes. The Red Sea is an example of a divergent margin at this stage (figure 19.21).

After modest widening of the new ocean, uplift of the continental edges may occur. As continental crust thins by stretching and faulting, the surface initially subsides. At the same time, hot mantle rock wells up beneath the stretched crust (figure 19.20*B*). The rising diapir of hot mantle rock would cause uplift by thermal expansion.

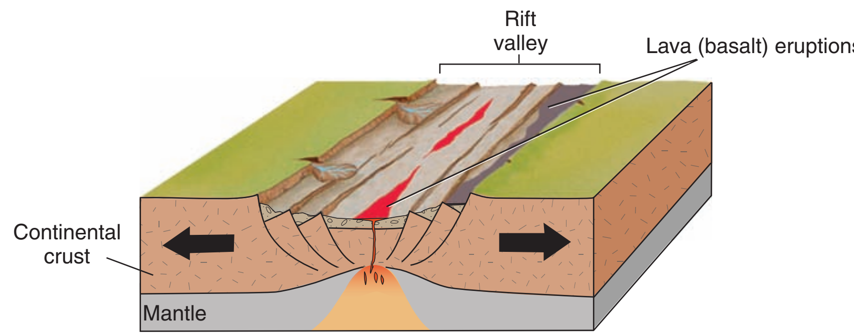
The new ocean is narrow, and the tilt of the adjacent land is away from the new sea, so rivers flow away from the sea (figure 19.20*B*). At this stage, the seawater that has flooded into the rift may evaporate, leaving behind a thick layer of rock salt overlying the continental sediments. The likelihood of salt precipitation increases if the continent is in one of the desert



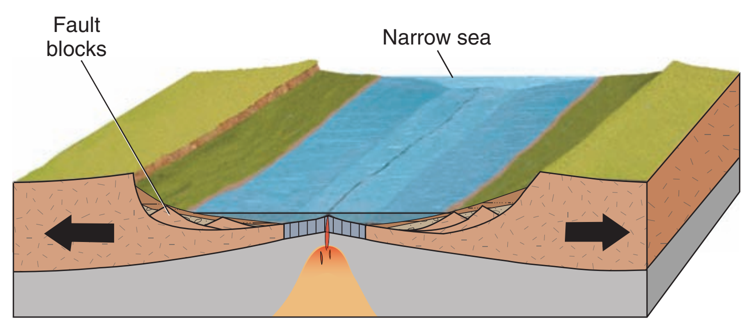

B

**FIGURE 19.19**

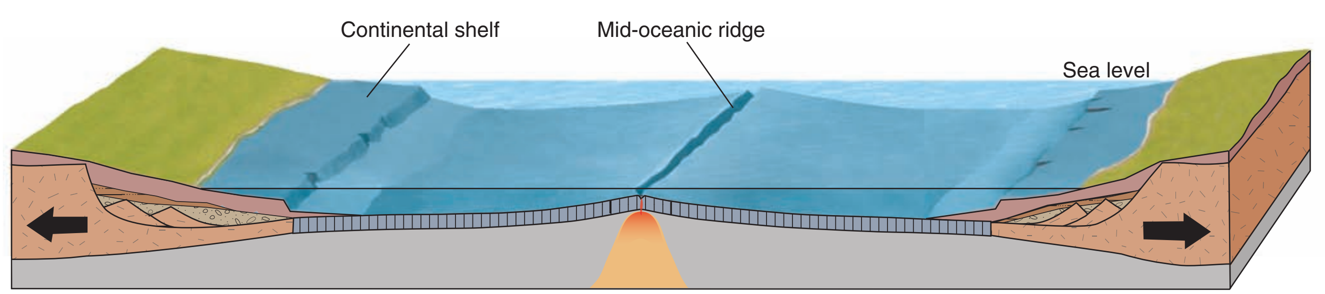
(*A*) Global Positioning System (GPS) station being installed in Iceland that will collect signals from orbiting GPS satellites to determine plate motions. (*B*) Yearly plate motions from stations around the world as measured by GPS. *Photo (A) © Icelandic Met Office; (B) from NASA* http://sideshow.jpl.nasa.gov/post/series.html




**A** Continent undergoes extension. The crust is thinned and a rift valley forms.




**B** Continent tears in two. Continent edges are faulted and uplifted. Basalt eruptions form oceanic crust.




**C** Continental sediments blanket the subsiding margins to form continental shelves. The ocean widens and a mid-oceanic ridge develops, as in the Atlantic Ocean.

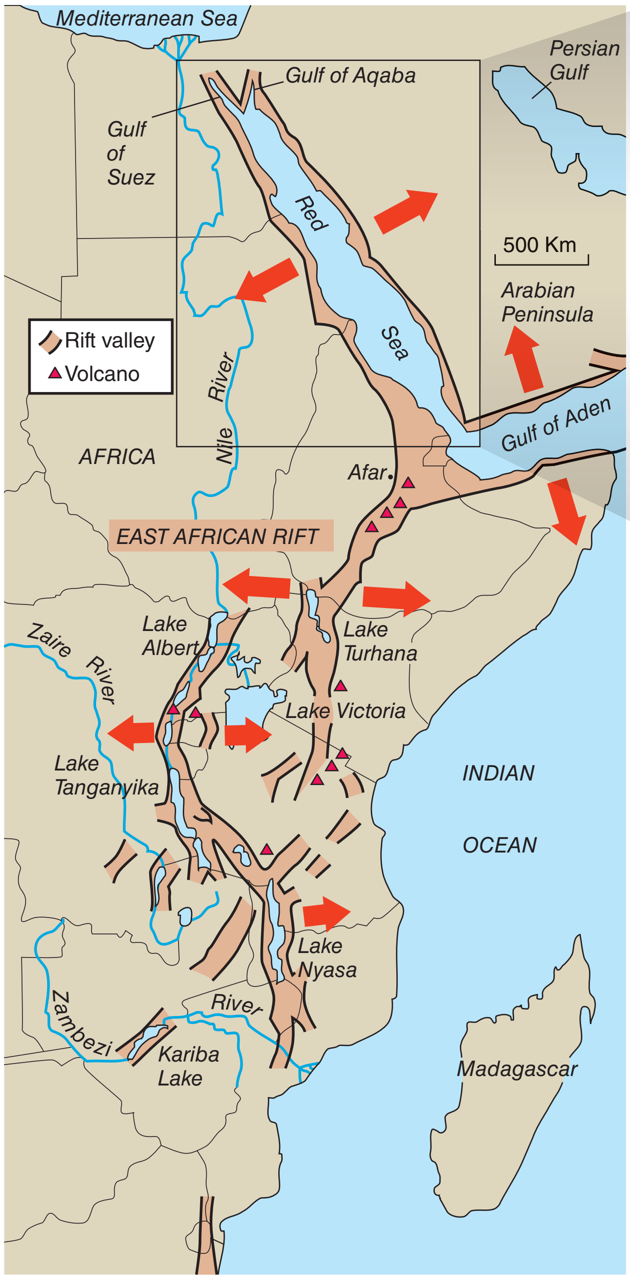
**FIGURE 19.20**
A divergent plate boundary forming in the middle of a continent will eventually create a new ocean.

belts or if one or both ends of the new ocean should become temporarily blocked, perhaps by volcanism. Not all divergent boundaries contain rock salt, however.

The plates continue to diverge, widening the sea. Thermal uplift creates a mid-oceanic ridge in the center of the sea (figure 19.20*C*). The flanks of the ridge subside as the seafloor rock cools as it moves.

The trailing edges of the continents also subside as they are lowered by erosion and as the hot rock beneath them cools. Subsidence continues until the edges of the continents are under water. A thick sequence of marine sediment blankets the thinned continental rock, forming a *passive continental margin* (figures 19.20*C* and 19.22; see also chapter 18). The sediment forms a shallow continental shelf, which may contain a deeply buried salt layer. The deep continental rise is formed as sediment is carried down the continental slope by turbidity currents and other mechanisms. The Atlantic Ocean is currently at this stage of divergence.

A divergent boundary on the sea floor is located on the crest of the mid-oceanic ridge. If the spreading rate is slow, as it is in the Atlantic Ocean (1 centimeter per year), the crest has a rift valley. Fast spreading, as along the East Pacific Rise (18 centimeters per year) and along other ridges in the Pacific Ocean, prevents a rift from forming. A divergent boundary at



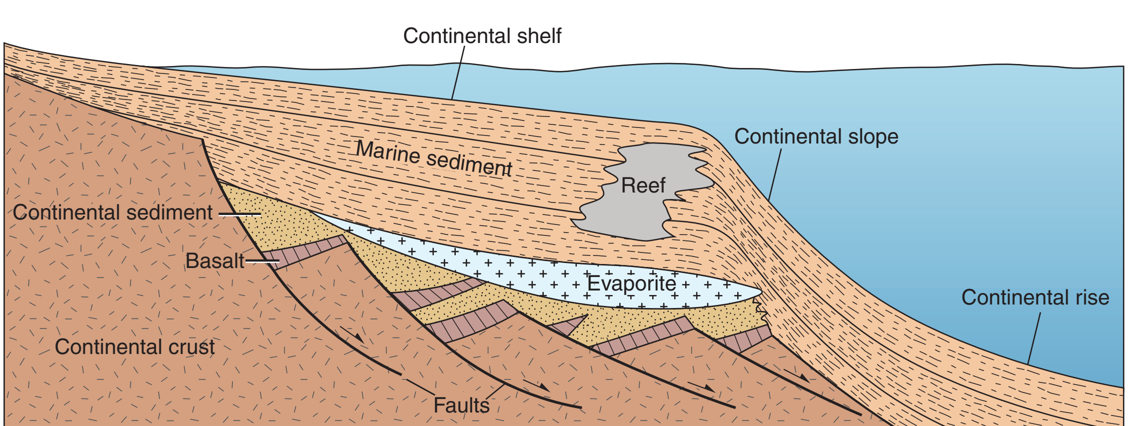

A

B

C

## FIGURE 19.21

(*A*) The East African Rift Valleys and the Red Sea. (*B*) Satellite photo of Red Sea. Gulf of Suez is on the upper left and Gulf of Aqaba on upper right. Note the similarities in the shorelines of the Arabian Peninsula (right) and Africa (left) suggesting that the Red Sea was formed by splitting of the continent. (*C*) Da'Ure volcanic vent and fracture that opened during the September 2005 rifting event in Afar, Ethiopia. This rifting event was the largest ever observed on land, and will eventually lead to eastern Ethiopia being torn away from the rest of Africa and the birth of a new sea. Note people for scale. *Photo B by Jeff Schmaltz, MODIS Rapid Response Team, NASA/GSFC; photo C by Anthony R. Philpotts*




## FIGURE 19.22

A passive continental margin formed by continental breakup and divergence. Downfaulted continental crust forms basins, which fill with basalt and sediment. A layer of rock salt may form if a narrow ocean evaporates. A thick sequence of marine sediments covers these rocks and forms the continental shelf, slope, and rise. A reef may form at the shelf edge if the water is warm; buried reefs occur on many parts of the Atlantic shelf of North America.

sea is marked by the same features as a divergent boundary on land—tensional cracks, normal faults, shallow earthquakes, high heat flow, and basaltic eruptions. The basalt forms dikes within the cracks and pillow lavas on the sea floor, creating new oceanic crust on the trailing edges of plates.

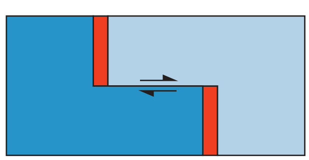
## TRANSFORM BOUNDARIES

At transform boundaries, where one plate slides horizontally past another plate, the plate motion can occur on a single fault or on a group of parallel faults. Transform boundaries are marked by shallow-focus earthquakes in a narrow zone for a single fault or in a broad zone for a group of parallel faults (see figure 16.26). First-motion studies of the quakes indicate strike-slip movement parallel to the faults.

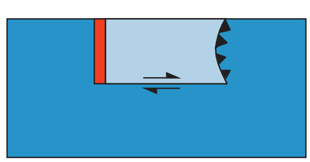
The name *transform fault* comes from the fact that the displacement along the fault abruptly ends or transforms into another kind of displacement. The most common type of transform fault occurs along fracture zones and connects two divergent plate boundaries at the crest of the mid-oceanic ridge (figures 19.23 and 19.18*B*). The spreading motion at one ridge segment is transformed into the spreading motion at the other ridge segment by strike-slip movement along the transform fault.

Not all transform faults connect two ridge segments. As you can see in figure 19.23, a transform fault can connect a ridge to a trench (a divergent boundary to a convergent boundary), or it can connect two trenches (two convergent boundaries). The most famous example of a transform fault is the San Andreas fault in California (figure 19.23*D* and box 19.2). The San Andreas fault forms a ridge-ridge transform plate boundary between the North American and Pacific plates. To explore the surface features of the fault as it cuts across California, visit box 15.2. Continued transform plate motion on the San Andreas fault creates an earthquake risk for those living near the fault (see box 16.3).

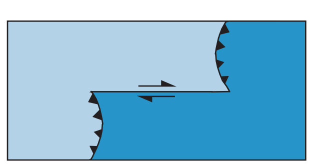
What is the origin of the offset in a ridge-ridge transform fault? The offsets appear to be the result of irregularly shaped divergent boundaries (figure 19.24). When two oceanic plates begin to diverge, the boundary may be curved on a sphere. Mechanical constraints prevent divergence along a curved boundary, so the original curves readjust into a series of right-angle bends. The ridge crests align perpendicular to the spreading direction, and the transform faults align parallel to the spreading direction. An old line of weakness in a continent may cause the initial divergent boundary to be oblique to the spreading direction when the continent splits. The boundary will then readjust into a series of transform faults parallel to the spreading direction.



**A** Ridge-Ridge Transform



**B** Ridge-Trench Transform



**C** Trench-Trench Transform


**D**

**FIGURE 19.23**

Transform boundaries (*A*) between two ridges; (*B*) between a ridge and a trench; and (*C*) between two trenches. Triangles on trenches point down subduction zones. Trench-trench transform boundaries are common in the southeast Pacific. Color tones show two plates in each case. (*D*) The San Andreas fault is a ridge-ridge transform plate boundary between the North American plate and the Pacific plate. The south end of the San Andreas fault is a ridge segment (shown in red) near the U.S.-Mexico border. The north end of the fault is a "triple junction" where three plates meet at a point. The relative motion along the San Andreas fault is shown by the large black arrows, as the Pacific plate slides horizontally past the North American plate. *(D) Modified from U.S. Geological Survey*

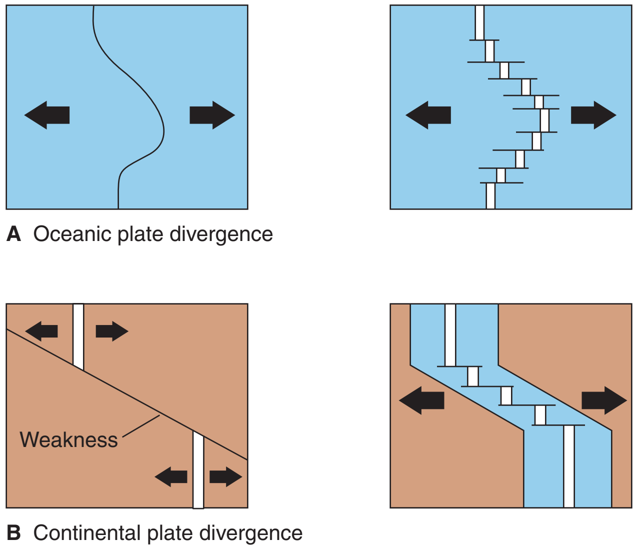



**FIGURE 19.24**

Divergent boundaries form ridge crests perpendicular to the spreading direction and transform faults parallel to the spreading direction. (*A*) Oceanic plates. (*B*) Continental plates.

# CONVERGENT PLATE BOUNDARIES

At convergent plate boundaries, two plates move toward each other (often obliquely). The character of the boundary depends partly on the types of plates that converge. A plate capped by oceanic crust can move toward another plate capped by oceanic crust, in which case one plate dives (subducts) under the other. If an oceanic plate converges with a plate capped by a continent, the dense oceanic plate subducts under the continental plate. If the two approaching plates are both carrying continents, the continents collide and crumple, but neither is subducted.

## Ocean-Ocean Convergence

Where two plates capped by sea floor converge, one plate subducts under the other (the Pacific plate sliding under the western Aleutian Islands is an example). The subducting plate bends downward, forming the outer wall of an oceanic trench, which usually forms a broad curve convex to the subducting plate (figures 19.25 and 19.26).

As one plate subducts under another, a Benioff zone of shallow-, intermediate-, and deep-focus earthquakes is created within the upper portion of the down-going lithosphere (see figure 16.23). The reasons for these quakes are discussed in chapter 16. The existence of deep-focus earthquakes to a depth of 670 kilometers tells us that brittle plates continue to (at least) that depth. The pattern of quakes shows that the angle of subduction changes with depth, usually becoming steeper (figure 19.25). Some plates crumple or break into segments as they descend.

As the descending plate reaches depths of at least 100 kilometers, magma is generated in the overlying asthenosphere (figure 19.25). The magma probably forms by partial melting of the asthenosphere, perhaps triggered by dewatering of the down-going oceanic crust as it is subducted, as described in chapter 3. Differentiation and assimilation may also play an important role in the generation of the magma, which is typically andesitic to basaltic in composition.

The magma works its way upward to erupt as an **island arc,** a curved line of volcanoes that form a string of islands parallel to the oceanic trench (figure 19.25). Beneath the volcanoes are large plutons in the thickened arc crust.

The distance between the island arc and the trench can vary, depending upon where the subducting plate reaches the 100-kilometer depth. If the subduction angle is steep, the plate reaches this magma-generating depth at a location close to the trench, so the horizontal distance between the arc and trench is short. If the subduction angle is gentle, the arc-trench distance is greater. A thick, buoyant plate (such as a subducting aseismic ridge) may subduct at such a gentle angle that it merely slides horizontally along under another plate. Because the top of the subducting plate never reaches the 100-kilometer depth, such very shallow subduction zones lack volcanism.

When a plate subducts far from a mid-oceanic ridge, the plate is cold, with a low heat flow. Oceanic plates form at ridge crests, then cool and sink as they spread toward trenches. Eventually, they become cold and dense enough to sink back into the mantle. Oceanic trenches are marked by strong negative gravity anomalies. These show that trenches are not currently in isostatic equilibrium but are being actively pulled down. Hess

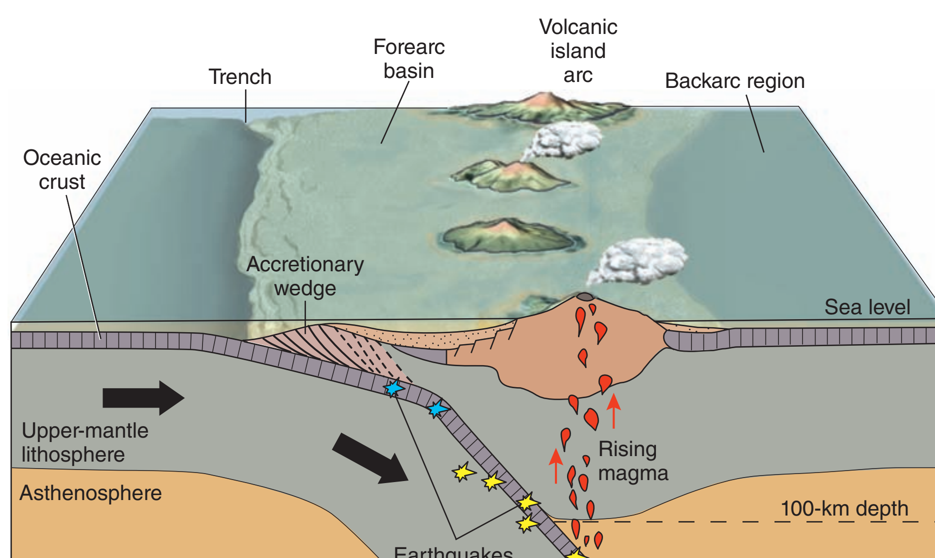



**FIGURE 19.25**

Ocean-ocean convergence forms a trench, a volcanic island arc, and a Benioff zone of earthquakes.

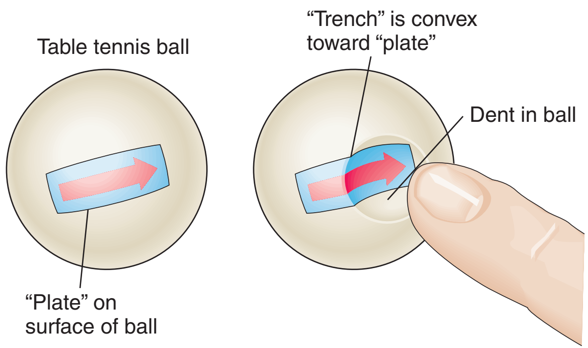



**FIGURE 19.26**

A dented table tennis ball can show why trenches are curved on a sphere.

thought that this pulling was caused by a down-turning convection current in the mantle. Today, most geologists think that the pulling is caused by the sinking of cold, dense lithosphere.

The inner wall of a trench (toward the arc) consists of an *accretionary wedge* (or *subduction complex*) of thrust-faulted and folded marine sediment and pieces of oceanic crust (figure 19.25). The sediment is "snowplowed" off the subducting plate by the overlying plate. New slices of sediment are continually added to the bottom of the accretionary wedge, pushing it upward to form a ridge on the sea floor. A relatively undeformed *forearc basin* lies between the accretionary wedge and the volcanic arc. (The trench side of an arc is the forearc; the other side of the arc is the backarc.)

Trench positions change with time. As one plate subducts, the overlying plate may be moving toward it. The motion of the leading edge of the overlying plate will force the trench to migrate horizontally over the subducting plate. The Peru-Chile Trench is moving over the Nazca plate in this manner as South America moves westward (figure 19.1). There is another reason that trenches move. A subducting plate may not sink in a direction parallel to the length of the plate but may fall through the mantle at an angle that is *steeper* than the dip of the downgoing plate. This steep sinking pulls the subducting plate progressively away from the overlying plate and causes the hinge line of bending and the oceanic trench to migrate seaward onto the subducting plate. The migration may cause stretching or extension in the backarc region of the overlying plate, a process called *backarc spreading*. The location at which the subducting plate contacts the 100-kilometer depth where magmas are generated in the asthenosphere also migrates seaward toward the subducting plate and may cause the position of the island arc to migrate toward the subducting plate as well.

## Ocean-Continent Convergence

When a plate capped by oceanic crust is subducted under the *continental* lithosphere, an accretionary wedge and forearc basin form an *active continental margin* between the trench and the continent (figure 19.27). A Benioff zone of earthquakes dips under the edge of the continent, which is marked by andesitic volcanism and a young mountain belt. Examples of this type of

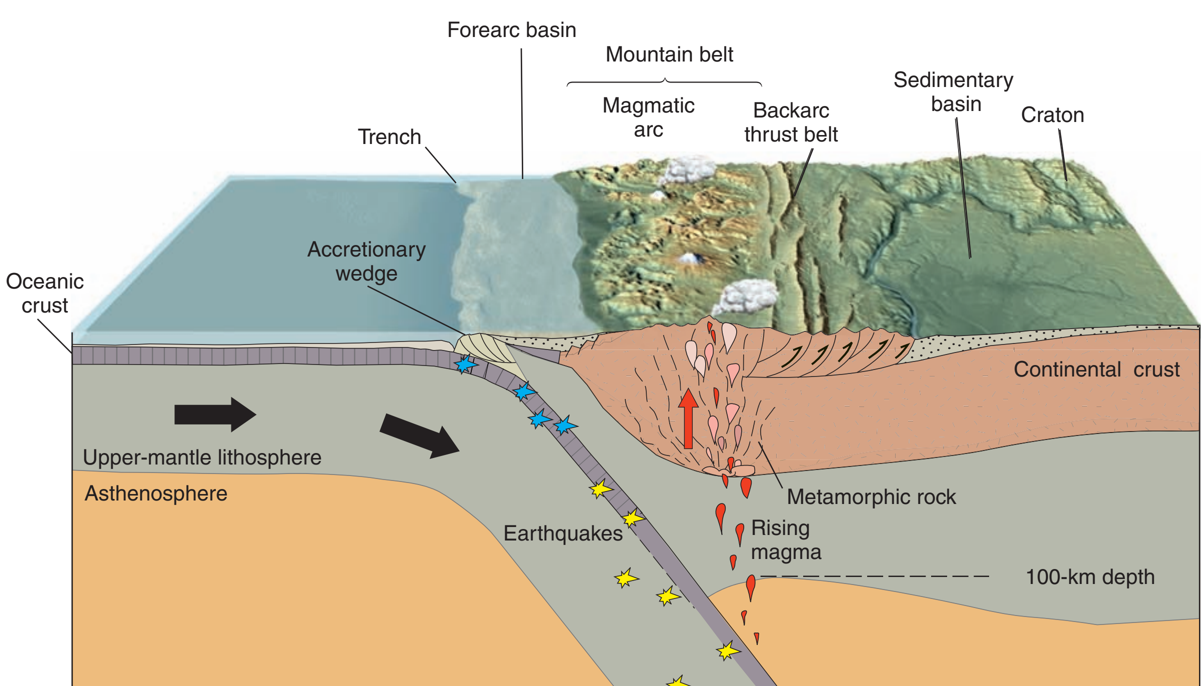



**FIGURE 19.27**

Ocean-continent convergence forms an active continental margin with a trench, a Benioff zone, a magmatic arc, and a young mountain belt on the edge of the continent.

boundary are the subduction of the Nazca plate under western South America and the Juan de Fuca plate under North America.

The magma that is created by ocean-continent convergence forms a **magmatic arc,** a broad term used both for island arcs at sea and for belts of igneous activity on the edges of continents. The surface expression of a magmatic arc is either a line of andesitic islands (such as the Aleutian Islands) or a line of andesitic continental volcanoes (such as the Cascade volcanoes of the Pacific Northwest). Beneath the volcanoes are large plutons in thickened crust. We see these plutons as batholiths on land when they are exposed by deep erosion. The igneous processes that form the granitic and intermediate magmas of batholiths are described in chapter 3.

The hot magma rising from the subduction zone thickens the continental crust and makes it weaker and more mobile than cold crust. Regional metamorphism takes place within this hot, mobile zone. Crustal thickening causes uplift, so a young mountain belt forms here as the thickened crust rises isostatically.

Another reason for the growth of the mountain belt is the stacking up of thrust sheets on the continental (backarc) side of the magmatic arc (figure 19.27). The thrust faults, associated with folds, move slivers of mountain-belt rocks landward over the continental interior (the *craton*). Underthrusting of the rigid craton beneath the hot, mobile core of the mountain belt may help form the fold-thrust belt.

Inland of the backarc fold-thrust belt, the craton subsides to form a sedimentary basin (sometimes called a *foreland basin*). The weight of the stacked thrust sheets depresses the craton isostatically. The basin receives sediment, some of which may be marine if the craton is forced below sea level. This basin extends the effect of subduction far inland. Subduction of the sea floor off California during the Mesozoic Era produced basin sedimentation as far east as the central Great Plains.

## Continent-Continent Convergence

Two continents may approach each other and collide. They must be separated by an ocean floor that is being subducted under one continent and that lacks a spreading axis to create new oceanic crust (figure 19.28). The edge of one continent

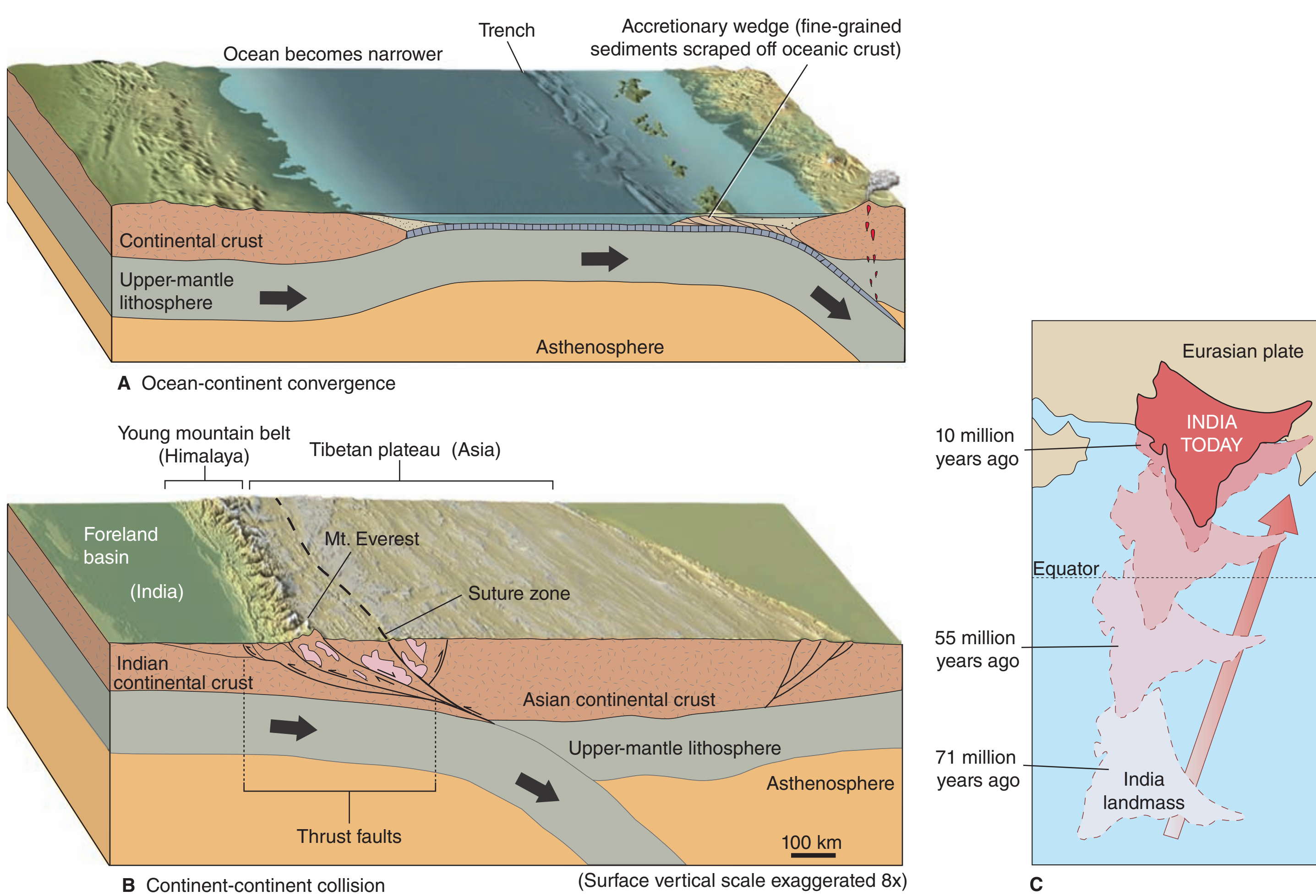



**FIGURE 19.28**

The collision of two continents forms a young mountain belt in the interior of a new, larger continent. The most famous example of continent-continent collision is the collision of India with Asia. (*A*) India is moving toward Asia due to ocean-continent convergence. (*B*) India collides with Asia to form the Himalayas, the highest mountain range on Earth. (*C*) Map view of the northward movement of India through time.

will initially have a magmatic arc and all the other features of ocean-continent convergence.

As the sea floor is subducted, the ocean becomes narrower and narrower until the continents eventually collide and destroy or close the ocean basin. Oceanic lithosphere is heavy and can sink into the mantle, but continental lithosphere is less dense and cannot sink. One continent may slide a short distance under another, but it will not go down a subduction zone. After collision, the heavy oceanic lithosphere breaks off the continental lithosphere and continues to sink, leaving the continent behind.

The two continents are welded together along a dipping *suture zone* that marks the old site of subduction (figure 19.28*B*). Thrust belts and subsiding basins occur on both sides of the original magmatic arc, which is now inactive. The presence of the original arc thickens the crust in the region of impact. The crust is thickened further by the shallow underthrusting of one continent beneath the other and by the stacking of thrust sheets in the two thrust belts. The result is a mountain belt in the interior of a continent (a new, large continent formed by the collision of the two, smaller continents). The entire region of impact is marked by a broad belt of shallow-focus earthquakes along the numerous faults, as shown in figure 16.26. A few deeper quakes may occur within the sinking oceanic lithosphere beneath the mountain range.

The Himalayas in central Asia are thought to have formed in this way, as India collided with and underthrust Asia to produce exceptionally thick crust and high elevations. Paleomagnetic studies show that India was once in the Southern Hemisphere and moved north to its present position (figure 19.28*C*). The collision with Asia occurred after an intervening ocean was destroyed by subduction (figure 19.2).

## DO PLATE BOUNDARIES MOVE?

Almost nothing is fixed in plate tectonics. Not only do plates move, but plate boundaries move as well. Plates may move away from each other at a divergent boundary on a ridge crest for tens of millions of years, but the ridge crest can be migrating across Earth's surface as this occurs. Ridge crests can also jump to new positions. The original ridge crest may suddenly become inactive; the divergence will jump quickly to a new position and create a new ridge crest (the evidence lies in the seafloor magnetic anomaly pattern).

Convergent boundaries migrate, also. As they do, trenches and magmatic arcs migrate along with the boundaries. Convergent boundaries can also jump; subduction can stop in one place and begin suddenly in a new place.

Transform boundaries change position, also. California's San Andreas fault has been in its present position about 5 million years. Prior to that, the plate motion was taken up on seafloor faults parallel to the San Andreas. In the future, the San Andreas may shift eastward again. The 1992 Landers earthquake, on a new fault in the Mojave Desert, and its pattern of aftershocks extending an astonishing 500 miles northward, suggest that the San Andreas may be trying to jump inland again. Geodetic studies have shown that more than 25% of the plate motion between the Pacific and North American plates is accommodated along faults in eastern California and western Nevada (see box 19.1, figure 2). If more motion is taken up along this zone, most of California will be newly attached to the Pacific plate instead of the North American plate, and California will slide northwestward relative to the rest of North America.

## CAN PLATES CHANGE IN SIZE?

Plates can change in size. For example, new sea floor is being added onto the trailing edge of the North American plate at the spreading axis in the central Atlantic Ocean. Most of the North American plate is not being subducted along its leading edge because this edge is made up of lightweight continental rock. Thus, the North American plate is growing in size as it moves slowly westward.

The Nazca plate is getting smaller. The spreading axis is adding new rock along the trailing edge of the Nazca plate, but the leading edge is being subducted down the Peru-Chile Trench. If South America were stationary, the Nazca plate might remain the same size, because the rate of subduction and the rate of spreading are equal. But South America is slowly moving westward because of spreading on the Atlantic Ridge, pushing the Peru-Chile Trench in front of it. This means that the site of subduction of the Nazca plate is gradually coming closer to its spreading axis to the west, and so the Nazca plate is getting smaller. The same thing is probably happening to the Pacific plate as the Eurasian plate moves eastward into the Pacific Ocean.

## THE ATTRACTIVENESS OF PLATE TECTONICS

The theory of plate tectonics is attractive to geologists because it can explain in a general way the distribution and origin of many Earth features. These features are discussed throughout this book, and we summarize them here.

The distribution and composition of the world's *volcanoes* can be explained by plate tectonics. *Basaltic* volcanoes and lava flows form at divergent plate boundaries when hot mantle rock rises at a spreading axis. *Andesitic* volcanoes, particularly those in the circum-Pacific belt, result from subduction of an oceanic plate beneath either a continental plate or another oceanic plate. Although most of the world's volcanoes occur at plate margins, some do not (Hawaii being an example). We will discuss some of these isolated volcanoes in the "Mantle Plumes and Hot Spots" section of this chapter.

*Earthquake* distribution and first motion can largely be explained by plate tectonics. Shallow-focus earthquakes along normal faults are caused by extension at divergent plate boundaries. Shallow-focus earthquakes also occur on transform faults when plates slide past one another. Broad zones of shallow-focus earthquakes are located where two continents collide.

Dipping Benioff zones of shallow-, intermediate-, and deep-focus quakes are found along the giant thrust faults formed when an oceanic plate is subducted beneath another plate. Most of the world's earthquakes (like most volcanoes) occur along plate boundaries, although a few take place within plates and are difficult to explain in terms of plate tectonics.

*Young mountain belts*—with their associated igneous intrusions, metamorphism, and fold-thrust belts—form at convergent boundaries. "Subduction mountains" form at the edges of continents where sea floor is sliding under continents. Examples include the Andes and Cascade Mountains. "Continental-collision" mountains such as the Himalayas form in continental interiors when two continents collide to form a larger continent. Old mountain belts such as the Urals in Russia mark the position of old, now inactive, plate boundaries.

The major features of the sea floor can also be explained by plate tectonics. The *mid-oceanic ridge* with its rift valley forms at divergent boundaries. *Oceanic trenches* are found where oceanic plates are subducted at convergent boundaries. *Fracture zones* are created at transform boundaries.

## WHAT CAUSES PLATE MOTIONS?

A great deal of speculation currently exists about why plates move. There may be several reasons for plate motion. Any mechanism for plate motion has to explain why:

1. mid-oceanic ridge crests are hot and elevated, while trenches are cold and deep;
2. ridge crests have tensional cracks; and
3. the leading edges of some plates are subducting sea floor, while the leading edges of other plates are continents (which cannot subduct).

Possible driving mechanisms for plate tectonics include: mantle convection, ridge push, slab pull, trench suction, and mantle plumes.

### Mantle Convection

There is no doubt that convection in the mantle is linked in some crucial way to plate motions (see figure 19.12). Mantle convection—the slow overturning of Earth's hot, ductile interior as heated rock wells up from below, cools near the surface, and sinks back down again—could take place as a series of giant cells, individually extending all the way from the heat source at the core-mantle boundary to the base of the lithosphere itself. Recent studies using seismic tomography and computer modeling indicate that this idea of "whole mantle convection" is too simplistic, however (figure 19.29). Change in density with depth in the Earth, the property of large continents to trap mantle heat, and the "stirring" of the mantle from the sinking of subducted oceanic lithosphere all contribute to a more complex pattern of convective heat loss. Cold lithospheric plates may subduct down to the core-mantle boundary, whereas other, less-dense (younger) plates may only reach the 670-kilometer boundary. One of the most recent models suggests that the lowermost part of the mantle does not mix with the upper and middle mantle but acts like a "lava lamp" turned on low, fueled by internal heating and heat flow across the core-mantle boundary. Variation in the thickness of this dense layer may control where mantle plumes rise and subducted plates ultimately rest.

Some geologists think that mantle convection is a *result* of plate motion rather than a cause of it. The sinking of a cold, subducting plate can create mantle convection (convection can be driven by either hot, rising material or by cold, sinking

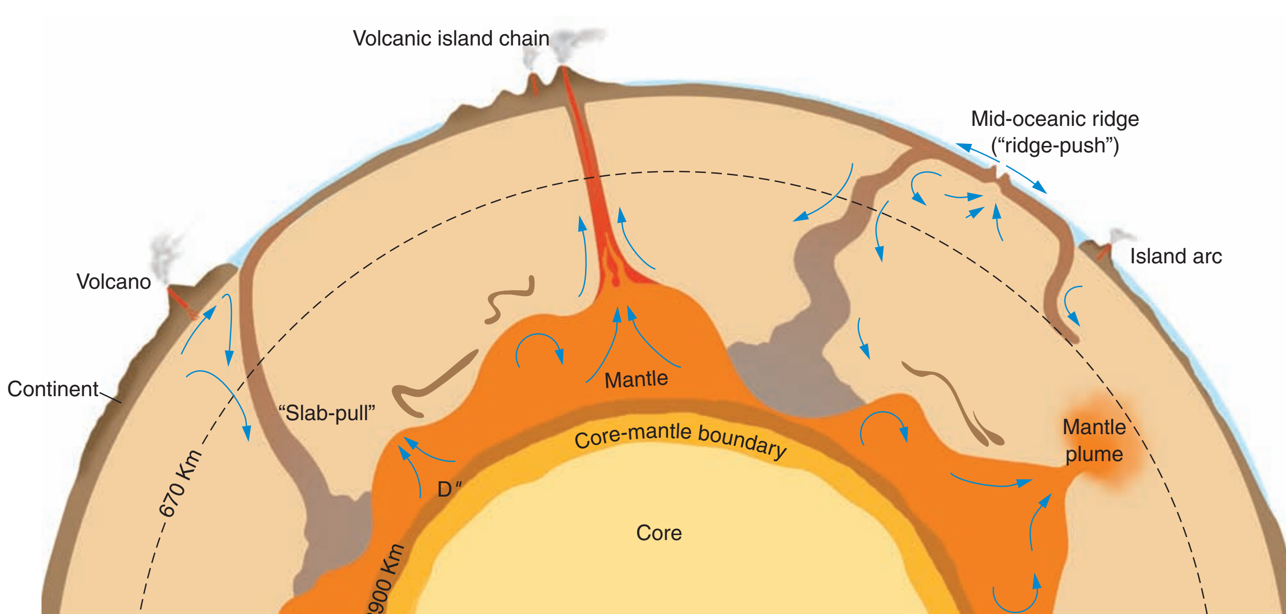



**FIGURE 19.29**

A possible model of mantle convection. *Modified from L. H. Kellogg, B. H. Hager, and R. D. van der Hilst, 1999,* Science, *283:1881–84* material). Hot mantle rock rises at divergent boundaries to take the place of the diverging plates; however, such plate-caused convection would be shallow rather than mantle-deep.

The basic question in plate motion is, why do plates diverge and sink? Two or three different mechanisms may be at work here.

## Ridge Push

One proposal is called "*ridge push.*" As a plate moves away from a divergent boundary, it cools and thickens. Cooling sea floor subsides as it moves, and this subsidence forms the broad side slopes of the mid-oceanic ridge. An even more important slope forms on the base of the lithosphere mantle. The mantle thickens as cooling converts asthenospheric mantle to lithospheric mantle. Therefore, the boundary between them is a slope down which the lithosphere slides (figure 19.30). The oceanic plate is thought to slide down this slope at the base of the lithosphere, which may have a relief of 80 to 100 kilometers.

## Slab Pull

Another mechanism is called "*slab pull*" (figure 19.30). Cold lithosphere sinking at a steep angle through hot mantle should pull the surface part of the plate away from the ridge crest and then down into mantle as it cools. A subducting plate sinks because it is denser than the surrounding mantle. This density contrast is partly due to the fact that the sinking lithosphere is cold. The subducting plate may also increase its density while it sinks, as low-density materials such as water are lost and as plate minerals collapse into denser forms during subduction. Slab pull is thought to be at least twice as important as ridge push in moving an oceanic plate away from a ridge crest. Slab pull causes rapid plate motion. Recent studies show that the bigger the plate and the longer the subduction zone, the faster the plates move. This can be observed in figure 19.19, where the largest plates, the Pacific, Nazca, and Indo-Australian plates, have the fastest motion and subduct into very long zones of convergence.

## Trench Suction

If subducting plates fall into the mantle at angles steeper than their dip (figure 19.30), then trenches and the overlying plates are pulled horizontally seaward toward the subducting plates. This mechanism has been termed "*trench suction.*" It is probably a minor force, but it may be important in moving continents apart. Divergent continents at the leading edges of plates cannot be moved by slab pull, because they are not on subducting plates. They might be moved by ridge push from the rear, or trench suction from the front, or both (figure 19.30). They move much more slowly than subducting plates.

All three of these mechanisms (ridge push, slab pull, and trench suction), particularly in combination, are compatible with high, hot ridges; cold, deep trenches; and tensional cracks at the ridge crest. They can account for the motion of both oceanic and continental plates. In this scheme, plate motions are controlled by variations in lithosphere density and thickness, which, in turn, are controlled largely by cooling. In other words, the reasons for plate motions are the properties of the plates themselves and the pull of gravity. This idea is in sharp contrast to most convection models, which assume that plates are dragged along by the movement of mantle rock beneath the plates.

## Mantle Plumes and Hot Spots

A modification of the convection process was suggested by W. Jason Morgan of Princeton University. Morgan proposed that convection occurs in the form of **mantle plumes,** narrow columns of hot mantle rock that rise through the mantle, much like smoke rising from a chimney (figure 19.31). Mantle plumes are now thought to have large spherical or mushroom-shaped heads above a narrow, rising tail. They are essentially stationary with respect to moving plates and to each other.

Plumes may form **hot spots** of active volcanism at Earth's surface. Note in figure 19.32 that many hot spots are located in volcanic regions such as Iceland, Yellowstone, and Hawaii. Recent seismic tomography images of the mantle suggest that not all hot spots are fed by mantle plumes. Of the forty-five hot spots identified on Earth, only twelve show evidence of a deep, continuous plume in the underlying mantle.

According to one hypothesis, when the head of a large plume ("super plume") nears the surface, it may cause uplift and the eruption of vast fields of flood basalts. As the head widens beneath the crust, the flood-basalt area widens and the

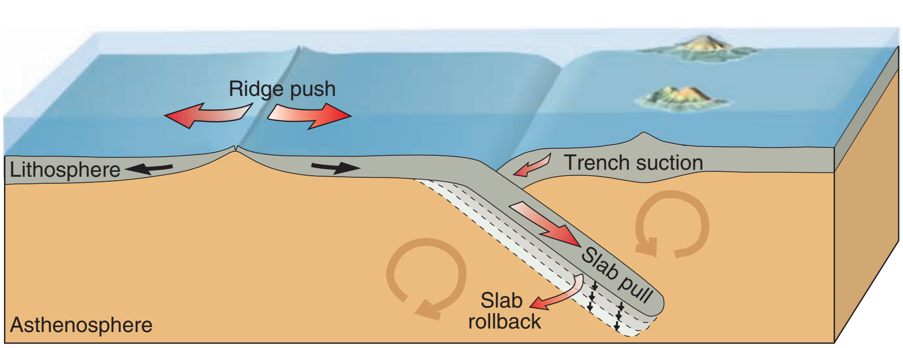



**FIGURE 19.30**

Other possible mechanisms for plate motion. Plates are pushed apart at the ridge (*ridge push*) by sliding downhill on the sloping boundary between the lithosphere and asthenosphere. Plates may also be pulled (*slab pull*) as the dense leading edge of a subducting plate sinks down into the asthenosphere. If the subducting plate falls into the asthenosphere at angles steeper than its dip (*slab rollback*) then the trench and overlying plate are pulled horizontally seaward toward the subducting plate by *trench suction.*

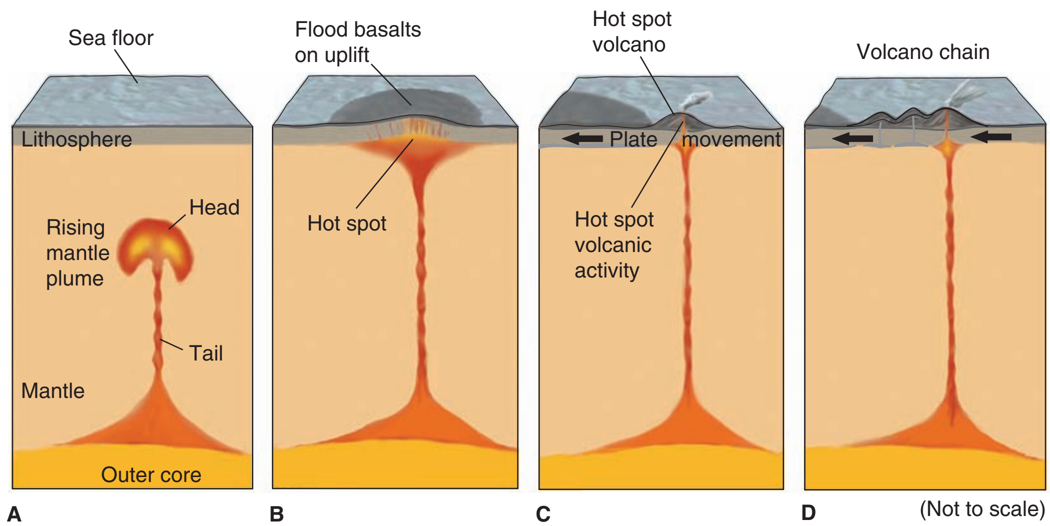



**FIGURE 19.31**

Model of mantle plume rising upward through the mantle to form a hot spot and associated flood basalts and volcanic chain. (*A*) Rising mantle plume contains a hot, mushroom-shaped plume head and a narrow tail. (*B*) Plume head forms a broad hot spot when it reaches the top of the mantle and causes uplift and stretching of the crust and eruption of flood basalts. (*C*) When the tail rises to the surface, a narrower hot spot forms a volcano. (*D*) Continued plate motion over the hot spot creates a trail or chain of volcanoes. Visit mantleplumes.org for more information on mantle plumes.

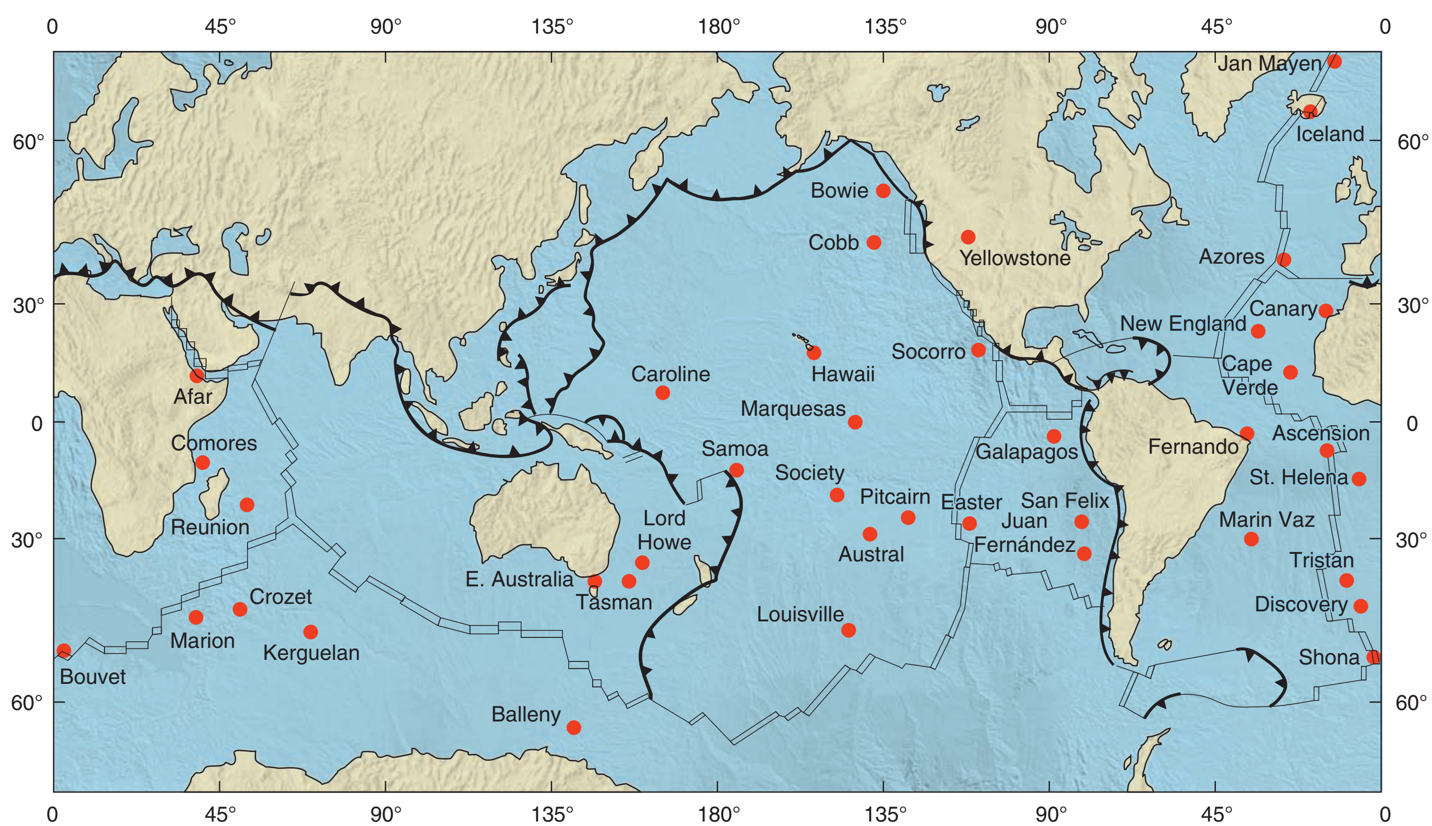



**FIGURE 19.32**

Distribution of hot spots, identified by volcanic activity and structural uplift within the past few million years. The hot spots near the poles are not shown.

crust is stretched. The tail that follows the head produces a narrow spot of volcanic activity, much smaller than the head.

The outward, radial flow of the expanding head may be strong enough to break the lithosphere and start plates moving. In Morgan's view, a few plumes, such as those underlying some of the hot spots on the mid-oceanic ridge in the Atlantic Ocean in figure 19.32, are enough to drive plates apart (in this case, to push the American plates westward). Lithospheric tension set up by trench suction or slab pull could combine with mantle plume action to break a large plate (such as the former Pangaea) into smaller, diverging fragments. New studies suggest that plumes can also push a plate and speed up its movement. The Indian plate may have gotten an initial push northward from the plume under the Reunion hot spot (see figures 19.28 and 19.32).

IN GREATER DEPTH 19.1

# Indentation Tectonics and "Mushy" Plate Boundaries

While it is easiest to conceive of Earth's skin as being made up of rigid tectonic plates that interact narrowly along their edges, the reality is more complicated—and interesting. The forces that cause plates to be geologically active along their boundaries may extend far into their interiors as well. Consider the following two examples:

## The Collision of India with Asia

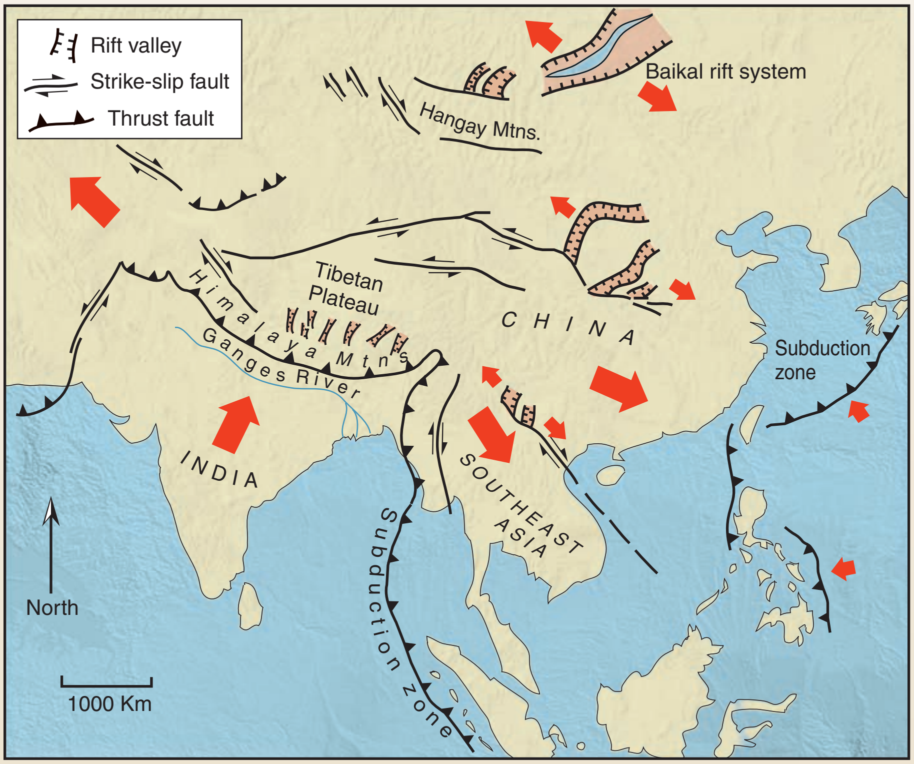
Approximately 40 million years ago, India began colliding with Asia to form the Himalaya Mountains, the biggest mountain system in the world. The sea that once separated India from Asia drained away as the former ocean floor rose into ridges and peaks as much as 5 miles high. The stresses of the continent-continent convergence extend far to the north of the Himalaya plate boundary, however—perhaps as far as 5,000 kilometers into Central Asia. Huge strike-slip fault systems with roughly east-west orientation break China apart (box figure 1). These have formed as Central Asia shifts out of the way of India, with the lithosphere moving primarily eastward to override the Pacific and Philippine plates in a series of very active subduction zones. India, in other words, has greatly "indented" Asia by colliding with it. The world's most destructive earthquakes have occurred in China, far from any plate boundaries. The Shaanxi earthquake in 1556 alone killed over 800,000 people, and the more recent 2008 Sichuan earthquake killed more than 70,000 and was one of the costliest natural disasters in Chinese history.

Near the northern edge of the zone of collisional stress, huge grabens have opened up, including the Baikal Rift, which contains the deepest lake in the world. A hot spot lies near the southern end of the Baikal Rift system, creating the Hangay Mountain Range in western Mongolia, which has been volcanically active within the past few thousand years—smack in the middle of Eurasia.

In Tibet, the northern prow of the Indian landmass has slipped beneath Central Asia along a series of Himalayan thrust faults, causing a doubling up of the lithosphere and uplift of the largest high-elevation plateau in the world. Lhasa, the capital of Tibet, lies in a fertile valley at an elevation of 3,700 meters (12,000 feet) above sea level.

## The San Andreas Transform Boundary

The San Andreas fault is a 1,100-kilometer-long rupture marking the border between the Pacific and North American plates in California. But only about *one-third* of the approximately 2,000 kilometers

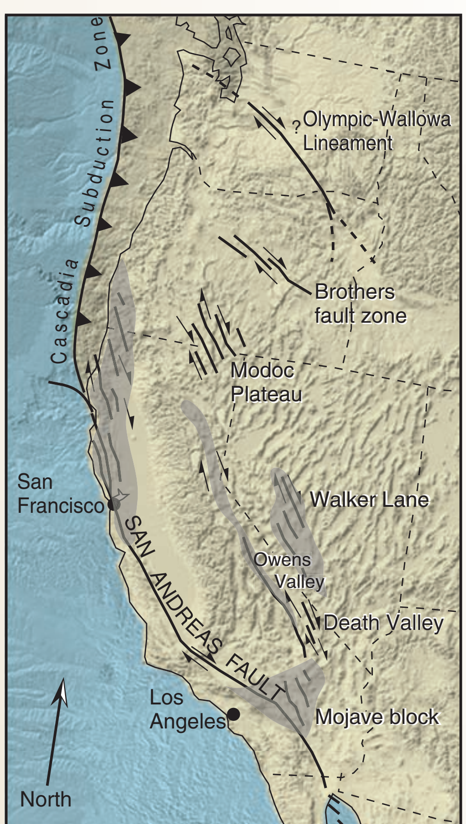



**BOX 19.1 ■ FIGURE 1**

Central Asia has adjusted to the broadside collision of India through uplift of the Tibetan plateau, and by stretching and slipping along major "intraplate" faults.

of total slip between the two places, the biggest plates on Earth, has taken place along the fault during its 25- to 30-million-year history. How then do the plates actually move past one another in this region? The answer is that the San Andreas belongs to a much larger system of related parallel faults. Other ruptures, such as the Death Valley fault in eastern California and the Brothers fault zone in Oregon, also take up components of plate motion, so that the plate boundary is actually a *zone* of slippage about 600 kilometers wide rather than the single line you see on a map in an introductory geology textbook (box figure 2). The western side of North America is sliced up like a giant stack of dominoes—in other words, each domino slides past another in a right-lateral sense.

The San Andreas itself bends in places, so that it is not always parallel to the vectors of plate movement. In southern California, local plate convergence along the fault has shoved up the mountains bordering Los Angeles. Here, the San Andreas is a dynamic, evolving structure that will almost certainly wane as new faults inland more efficiently ease the plates past one another in the not-so-distant geological future.




**BOX 19.1 ■ FIGURE 2**

Many faults participate in easing North America past the Pacific plate.

A mantle plume rising beneath a continent should heat the land and bulge it upward to form a dome marked by volcanic eruptions. As the dome forms, the stretched crust typically fractures in a three-pronged pattern (figure 19.33). Continued radial flow outward from the rising plume eventually separates the crust along two of the three fractures but leaves the third fracture inactive. In this model of continental breakup, the two active fractures become continental edges as new sea floor forms between the divergent continents. The third fracture is a *failed rift* (or *aulacogen*), an inactive rift that becomes filled with sediment.

An example of this type of fracturing may exist in the vicinity of the Red Sea (figure 19.34). The Red Sea and the Gulf of

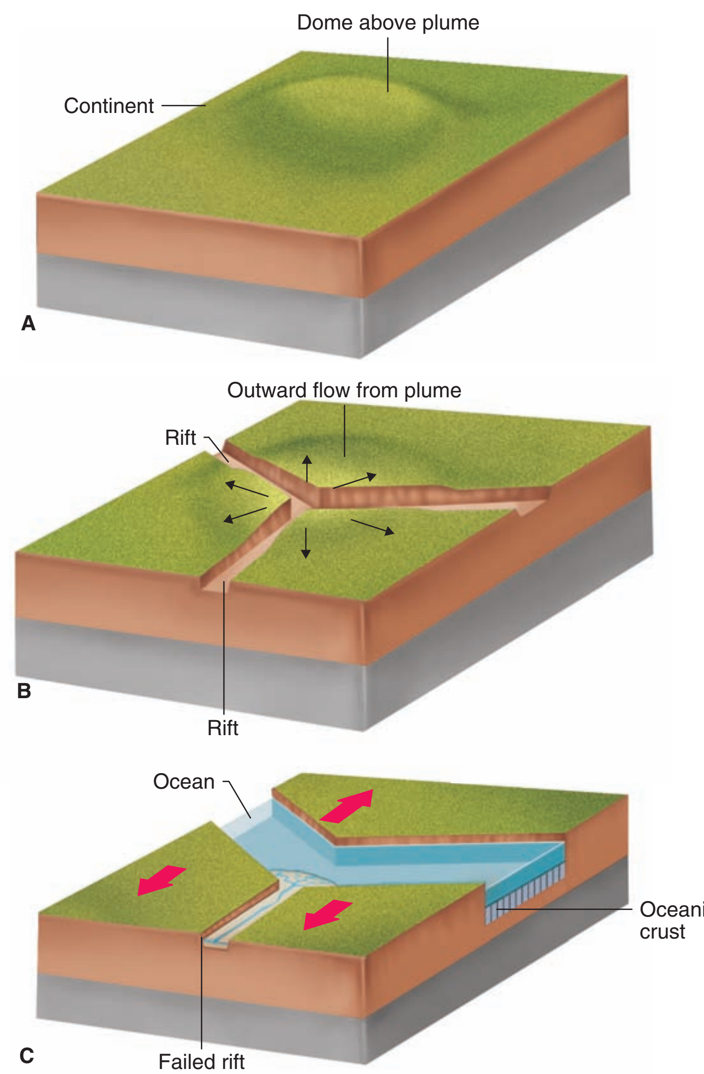



**FIGURE 19.33**

Continental breakup caused by a mantle plume. (*A*) A dome forms over a mantle plume rising beneath a continent. (*B*) Three radial rifts develop due to outward radial flow from the top of the mantle plume. (*C*) Continent separates into two pieces along two of the three rifts, with new ocean floor forming between the diverging continents. The third rift becomes an inactive "failed rift" (or aulacogen) filled with continental sediment.

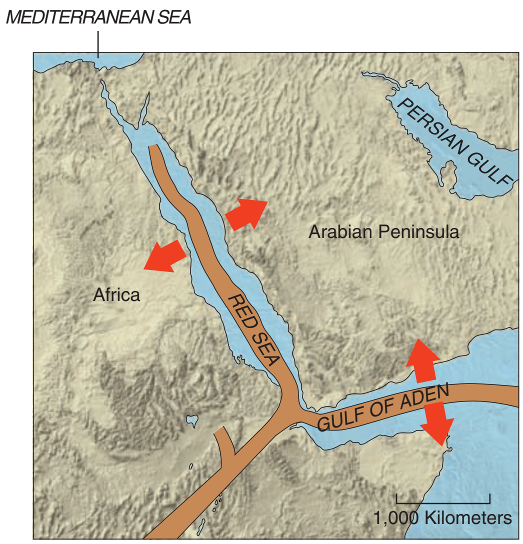



**FIGURE 19.34**

An example of radial rifts. The Red Sea and the Gulf of Aden are the active rifts, as the Arabian peninsula moves away from Africa. The Gulf of Aden contains a mid-oceanic ridge and central rift valley. The less active, failed rift (aulacogen) is the rift valley shown in Africa.

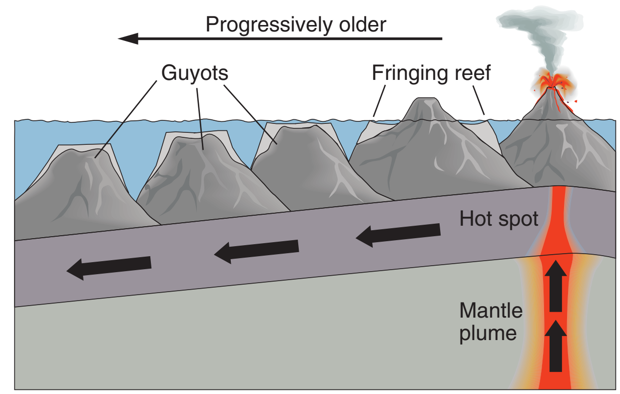



**FIGURE 19.35**

Fringing reef forms around volcanic island as it moves off hot spot. Waves erode and flatten top of volcanic islands to form guyots that progressively sink and become submerged away from hot spot.

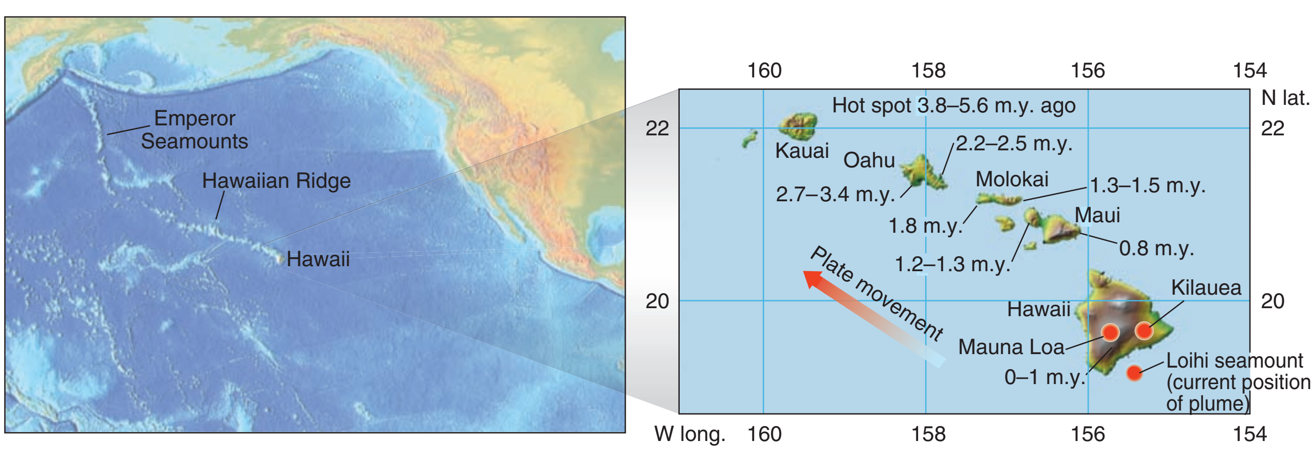



**FIGURE 19.36**

Ages of volcanic rock of the Hawaiian island group. Ages increase to northwest. Two active volcanoes on Hawaii are shown by red dots. The plume is currently offshore under the Loihi seamount (red dot), where recent underwater eruptions have been documented.

Aden are active diverging boundaries along which the Arabian Peninsula is being separated from northeastern Africa. The third, less-active rift is the northernmost African Rift Valley, lying at an angle about 120 degrees to each of the narrow seaways.

Some plumes rise beneath the centers of oceanic plates. A plume under Hawaii rises in the center of the Pacific plate. As the plate moves over the plume, a line of volcanoes forms, creating an aseismic ridge (figure 19.35). The volcanoes are gradually carried away from the eruptive center, isostatically sinking as they go because of cooling. The result is a line of extinct volcanoes (seamounts and guyots) increasing in age away from an active volcano directly above the plume.

In the Hawaiian island group, the only two active volcanoes are in the extreme southeastern corner (figure 19.36). The isotopic ages of the Hawaiian basalts increase regularly to the northwest, and a long line of submerged volcanoes forms an aseismic ridge to the northwest of Kauai. Most aseismic ridges on the sea floor appear to have active volcanoes at one end, with ages increasing away from the eruptive centers. Deep-sea drilling has shown, however, that not all aseismic ridges increase in age along their lengths. This evidence has led to alternate hypotheses for the origin of aseismic ridges. It may pose difficulties for the plume hypothesis itself.

EARTH SYSTEMS 19.2

## The Relationship between Plate Tectonics and Ore Deposits

The plate-tectonic theory provides an overall model for the origin of metallic ore deposits that has been used to explain the occurrence of known deposits and to explore for new deposits. Because many ore deposits are associated with igneous activity, a close relationship exists between plate boundaries and metallic ore deposits.

As discussed in chapter 18, *divergent plate boundaries* are often marked by lines of active hot springs in rift valleys that carry and precipitate metallic minerals in mounds around the hot springs. The metals in rift-valley hot springs are predominantly iron, copper, and zinc, with smaller amounts of manganese, gold, and silver. Although the mounds are nearly solid metal sulfide, they are small and widely scattered on the sea floor, so commercial mining of them may not be practical. Occasionally, the ore minerals may be concentrated in richer deposits. On the floor of the Red Sea, metallic sediments have precipitated in basins filled with hot-spring solutions. Although the solutions are hot (up to 60°C or 140°F), they are very dense because of their high salt content (they are seven times saltier than seawater), so they collect in seafloor depressions instead of mixing with the overlying seawater. Although not currently mined, the metallic sediments have an estimated value of $25 billion.

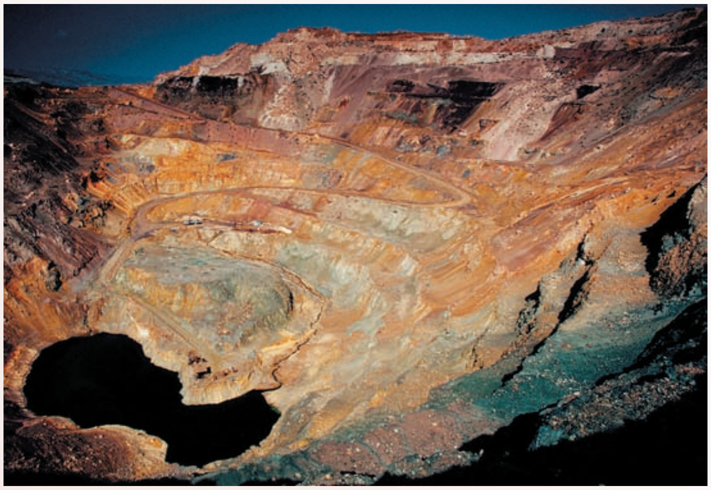
Hot metallic solutions are also found along some divergent continental boundaries. Near the Salton Sea in southern California, which lies along the extension of the mid-oceanic ridge inland, hot water very similar to the Red Sea brines has been discovered underground. The hot water is currently being used to run a geothermal power plant. The high salt and metal content is corrosive to equipment, but metals such as copper and silver may one day be recovered as valuable by-products.

Seafloor spreading carries the metallic ores away from the ridge crest (box figure 1), perhaps to be subducted beneath island arcs or continents at *convergent plate boundaries*. Slivers of *ophiolite* on land may contain these rich ore minerals in relatively intact form. A notable example of such ores occurs on the island of Cyprus in the Mediterranean Sea (box figure 2). Banded chromite ores may also be contained in the serpentinized ultramafic rock at the bottom of ophiolites.

Volcanism at *island arcs* can also produce hot-spring deposits on the flanks of the andesitic volcanoes. Pods of very rich ore collect above local bodies of magma, and the ore is sometimes distributed as sedimentary layers in shallow basins (box figure 3).

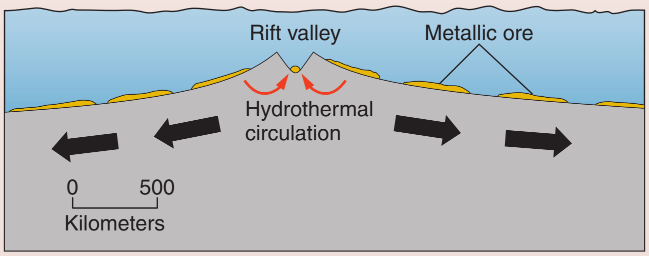
Many important ore deposits are also found at *convergent plate boundaries,* where metals from the subducting plate or overlying mantle are released and are concentrated in magmas or hydrothermal fluids. More than half of the world's supply of copper is mined from deposits associated with plate convergence.

It is tempting to think that *mantle plumes* might cause ore deposition, for plumes provide a source of both magma and hydrothermal solutions. The locations of supposed plumes, however, such as Yellowstone and Hawaii, are notable for their *lack* of ore deposits.



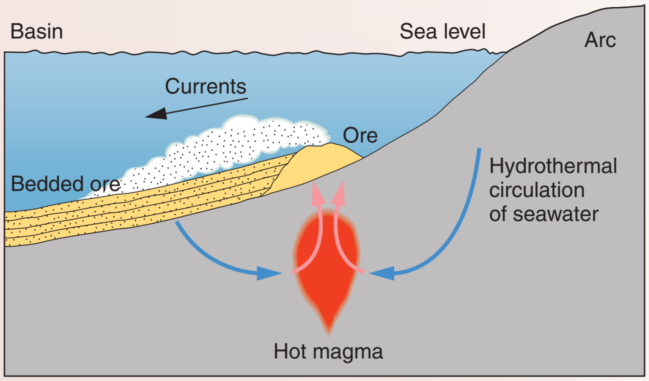
**BOX 19.2 ■ FIGURE 2**

Second-largest copper mine in Cyprus, Greece, mines copper from the Troodos ophiolite. Copper deposits were initially formed on the sea floor where active hot springs precipitated metallic minerals in rift valleys where the oceanic lithosphere was being pulled apart. *Photo © Jonathan Blair/Corbis*




**BOX 19.2 ■ FIGURE 1**

Divergent oceanic plates carry metallic ores away from rift valley. (Size of ore deposits is exaggerated.)




**BOX 19.2 ■ FIGURE 3**

On island arcs, metallic ores can form over hot springs and be redistributed into layers by currents in shallow basins.

## A FINAL NOTE

Objections were raised to plate tectonics after it was proposed in the late 1960s. Some seafloor features did not seem compatible with a moving sea floor. The geology of many continental regions did not seem to fit into the theory of plate tectonics—in some cases, not even slightly. But a revolutionary idea in science is always controversial. As it progresses from an "outrageous hypothesis" to a more widely accepted theory, after much discussion and testing, a new idea evolves and changes. The newness of the idea wears off, and successful tests and predictions convert skeptics to supporters (sometimes grudgingly). Perhaps equally important, dissenters die off.

As refinements were made to plate tectonics and as more was learned about the puzzling seafloor features and continental regions, they began to seem more compatible with plate tectonics. Objections died out, and plate tectonics became widely accepted.

It is wise to remember that at the time of Wegener, most geologists vehemently disagreed with continental drift. Because Wegener proposed that continents plow through seafloor rock and because his proposed forces for moving continents proved inadequate, most geologists thought that continental drift was wrong. Although these geologists had sound reasons for their dissent, we now know, due to overwhelming evidence, that lithospheric plates move and the early geologists were wrong.

The evidence for plate tectonics is very convincing. The theory has been rightly called a revolution in the Earth sciences. It has been an exciting time to be a geologist. Our whole concept of Earth dynamics has changed in the last fifty years.

## Summary

Plate tectonics is the idea that Earth's surface is divided into several large plates that change position and size. Intense geologic activity occurs at plate boundaries.

Plate tectonics combines the concepts of *seafloor spreading* and *continental drift.*

Alfred Wegener proposed continental drift in the early 1900s. His evidence included coastline fit, similar fossils and rocks in now-separated continents, and paleoclimatic evidence for *apparent polar wandering.* Wegener proposed that all continents were once joined together in the supercontinent *Pangaea.*

Wegener's ideas were not widely accepted until the 1950s, when work in paleomagnetism revived interest in polar wandering.

Evidence for continental drift includes careful fits of continental edges and detailed rock matches between now-separated continents. The positions of continents during the past 200 million years have been mapped.

Hess's hypothesis of *seafloor spreading* suggests that the sea floor moves away from the ridge crest and toward trenches as a result of mantle convection.

According to the concept of seafloor spreading, the high heat flow and volcanism of the ridge crest are caused by hot mantle rock rising beneath the ridge. Divergent *convection* currents in the mantle cause the rift valley and earthquakes on the ridge crest, which is a *spreading axis* (or *center*). New sea floor near the rift valley has not yet accumulated pelagic sediment.

Seafloor spreading explains trenches as sites of seafloor *subduction,* which causes low heat flow and negative gravity anomalies. Benioff zones and andesitic volcanism are caused by interaction between the subducting sea floor and the rocks above.

Seafloor spreading also explains the young age of the rock of the sea floor as caused by the loss of old sea floor through subduction into the mantle.

Plates are composed of blocks of *lithosphere* riding on a ductile *asthenosphere.* Plates move away from spreading axes, which add new sea floor to the trailing edges of the plates.

An apparent confirmation of plate motion came in the 1960s with the correlation of marine *magnetic anomalies* to *magnetic reversals* by Vine and Matthews. The origin of magnetic anomalies at sea apparently is due to the recording of normal and reverse magnetization by dikes that intrude the crest of the mid-oceanic ridge, then split and move sideways to give anomaly patterns a mirror symmetry.

The Vine-Matthews hypothesis gives the rate of plate motion and can predict the age of the sea floor before it is sampled.

Deep-sea drilling has apparently verified plate motions and the age predictions made from magnetic anomalies.

Earthquake distribution and first-motion studies on *transform faults* on fracture zones also verify plate motions.

*Divergent plate boundaries* are marked by rift valleys, shallow-focus earthquakes, high heat flow, and basaltic volcanism.

*Transform boundaries* between plates sliding past one another are marked by strike-slip (transform) faults and shallow-focus earthquakes.

*Convergent plate boundaries* can cause *subduction* or *continental collision.* Subducting plate boundaries are marked by trenches, low heat flow, Benioff zones, andesitic volcanism, and young mountain belts or island arcs. Continental-collision boundaries have shallow-focus earthquakes and form young mountain belts in continental interiors.

The distribution and origin of most volcanoes, earthquakes, young mountain belts, and major seafloor features can be explained by plate tectonics.

Plate motion was once thought to be caused by *mantle convection* but is now also attributed to the cold, dense leading edge of a subducting plate pulling the rest of the plate along with it (*slab pull*). Plates near mid-oceanic ridges also slide down the sloping lithosphere-asthenosphere boundary at the ridge (*ridge push*). *Trench suction* may help continents diverge.

*Mantle plumes* are narrow columns of hot, rising mantle rock. They cause flood basalts and may split continents, causing plate divergence.

An aseismic ridge may form as an oceanic plate moves over a mantle plume acting as an eruptive center (hot spot).