17 Plate Tectonics

A spectacular example of the surface expression of plate movement is dramatically shown in this shaded relief map of Central America collected by astronauts on the Space Shuttle. The map spans a distance of almost 2000 km. A long linear trench lies parallel to the shore and marks the zone where the oceanic Cocos plate bends and dives back into the mantle. The area between the trench and the shore is underlain by strongly deformed sediment scraped off the downgoing plate. The system of ridges and valleys, high plateaus, grabens, and volcanoes is part of the great Cordilleran mountain chain formed by subduction beneath the American continents. The mountains furrowed with arcuate ridges (on the far right and left) are eroded fold and thrust belts formed by compression. On the left, you can see a series of long linear troughs and rugged ridges that cut diagonally across the region; this is a transform plate boundary that connects the Caribbean trench with the Middle American trench. Strike-slip movement has sheared continental and oceanic plates past one another. Huge ash-flow calderas are filled by lakes and smaller andesite volcanoes are aligned parallel to the trench. Magma is generated at a depth of about 100 km before rising,

intruding the crust to form vast batholiths, or erupting explosively. These volcanoes and innumerable earthquakes along the faults pose a direct threat to millions of people. All of these tectonic features have been extensively eroded by rivers to form short but delicate dendritic patterns. Wave action has shaped the shoreline and helped to create the wide continental shelf. Elsewhere coral reefs have shaped the Caribbean coastline.

Plate tectonics has done much more than explain the deformation of these mountains in Central America. It explains the San Andreas fault system and its relationship to the Gulf of California and how the Cascade Mountains are related to the far-off midocean ridge that traverses the Pacific. It explains many aspects of the interrelationships of volcanoes, earthquakes, climate change, and even of the evolution of life itself. In brief, it provides a single unifying theory of Earth's dynamics. Essentially everything about our planet is related either directly or indirectly to plate tectonics.

How did scientists develop such a revolutionary theory? A few decades ago, most geologists believed that continents and ocean basins were fixed, permanent features on Earth, and the theory of continental drift was considered a radical idea. What brought about the remarkable change in the entire science of geology? In this chapter we will consider how the theory of plate tectonics developed and the evidence upon which it is based. We will then consider the nature of the lithospheric plates, what causes them to move, and how we measure the rates and direction of plate motion.

Courtesy of NASA/JPL/NIMA.
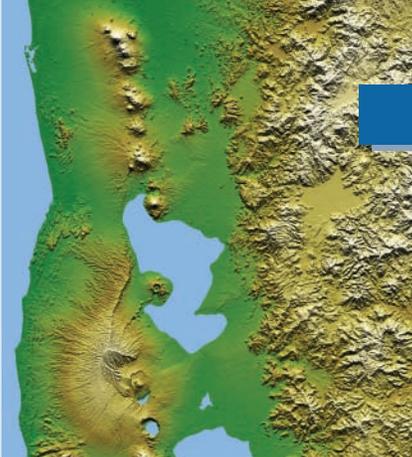
1. The theory of continental drift was proposed in the early 1900s and was supported by a variety of geologic evidence. Lack of knowledge of the nature of the oceanic crust, however, prevented a complete theory of Earth's dynamics from being developed.

2. A major breakthrough in the development of the plate tectonics theory occurred in the early 1960s, when the topography of the ocean floors was mapped and magnetic and seismic characteristics of the oceanic crust were determined.

3. Most tectonic activity occurs along plate boundaries. Divergent plate boundaries are zones where the plates split and spread apart. Convergent plate boundaries are zones where plates collide. Transform fault boundaries are zones where plates slide horizontally past each other.

4. The direction of the relative motion of plates is indicated by (a) the trend of the oceanic ridge and associated transform faults, (b) seismic data, (c) magnetic stripes on the seafloor, and (d) the ages of chains of volcanic islands and seamounts. The motion of a plate can be described in terms of rotation around a pole.

5. Heat from the mantle (generated by radioactivity) and from the core is probably the fundamental cause of Earth's internal convection.

6. The major forces acting on plates are (a) slab-pull, (b) ridge-push, (c) basal drag, and (d) friction along transform faults and in subduction zones. The most important forces that make the plates move are probably slab-pull and ridge-push.

CONTINENTAL DRIFT

The theory of continental drift was proposed in the early 1900s and was supported by a variety of impressive geologic data. Lack of an understanding of the nature of the oceanic crust, however, prevented the development of a complete theory of Earth's dynamics.

The theory of plate tectonics wrought a sweeping change in our understanding of Earth and the forces that shape it. Some scientists consider this conceptual change as profound as those that occurred when Darwin reorganized biology in the nineteenth century or when Copernicus, in the sixteenth century, determined that Earth is not the center of the universe.

The predecessor of the plate tectonic theory, the concept of **continental drift,** is an old idea. Soon after the first reliable world maps were made, scientists noted that the continents, particularly Africa and South America, would fit together like a jigsaw puzzle, if they could be moved. Antonio Snider-Pelligrini, a Frenchman, was one of the first to study the idea in some depth. In his book *Creation and Its Mysteries Revealed* (1858), he showed how the continents looked before they separated (Figure 17.1). He cited fossil evidence in North America and Europe but based his reasoning on the catastrophe of Noah's flood. The idea seemed too far-fetched for science or the general public, so it was forgotten, not to be revived for 50 years. The theory was first considered seriously in 1908, when American geologist Frank B. Taylor pointed out several geologic facts that could be explained by continental drift.

However, Alfred Wegener, a German meteorologist, was the first to exhaustively investigate the idea of continental drift and to convince others to take it seriously. In his book *The Origin of the Continents and Oceans* (1915), Wegener based his theory not only on the shapes of the continents, but also on geologic evidence, such as similarities in the fossils found in Brazil and Africa. He drew a series of maps showing three stages in the drifting process, beginning with an original large
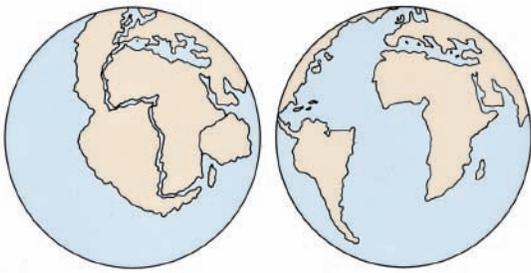
(A) Maps made by Antonio Snider-Pelligrini in 1858.

FIGURE 17.1 **Continental drift** was illustrated as early as 1858 by Antonio Snider-Pelligrini when he published these maps (A) in his book *Creation and Its Mysteries Revealed*. The idea seemed too far-fetched to the public and the scientific communities of the time and was forgotten, not to be revived for 50 years. Wegener published his series of maps (B) in 1915. His evidence, most of which was quite valid, was drawn from all of the sciences. Wegener called the original land mass Pangaea ("all lands") and believed that the continents somehow plowed through the oceanic crust as they drifted.

(B) Maps made by Alfred Wegener in 1915.

land mass, which he called **Pangaea** (meaning "all lands") (Figure 17.1). Wegener believed that the continents, composed of less dense silicic rock, somehow plowed through the denser rocks of the ocean floor, driven by forces related to the rotation of Earth.

Most geologists and geophysicists rejected Wegener's theory, although many scientific observations supporting it were known at the time. A few noted scholars, however, seriously considered the theory. Alexander L. du Toit, from South Africa, compared the landforms and fossils of Africa and South America and further expounded the theory in his book *Our Wandering Continents* (1937). Arthur Holmes, of England, later developed it in his textbook *Principles of Physical Geology* (1944). The early arguments concerning the breakup of the supercontinent Pangaea and the theory of continental drift were supported by some important and imposing evidence, most of which resulted from regional geologic studies as outlined below.

What evidence indicates that continents split and drift apart?

Paleontological Evidence

The striking similarity of certain fossils found on the continents on both sides of the Atlantic is difficult to explain unless the continents were once connected. The fossil record indicates that a new species appears at one point and disperses outward from there. Floating and swimming organisms could migrate in the ocean, from the shore of one continent to another, but the Atlantic Ocean would present an insurmountable obstacle for the migration of land-dwelling animals, such as reptiles and insects, and certain land plants. Consider the profound implications of the following examples (Figure 17.2).

Fossils of *Glossopteris,* a fernlike plant, have been found in rocks of the same age from South America, South Africa, Australia, India, and Antarctica. Mature seeds of this plant were several millimeters in diameter, too large to have been dispersed across the ocean by winds. The simultaneous presence of *Glossopteris* on

Are marine fossils important in supporting the theory of continental drift?
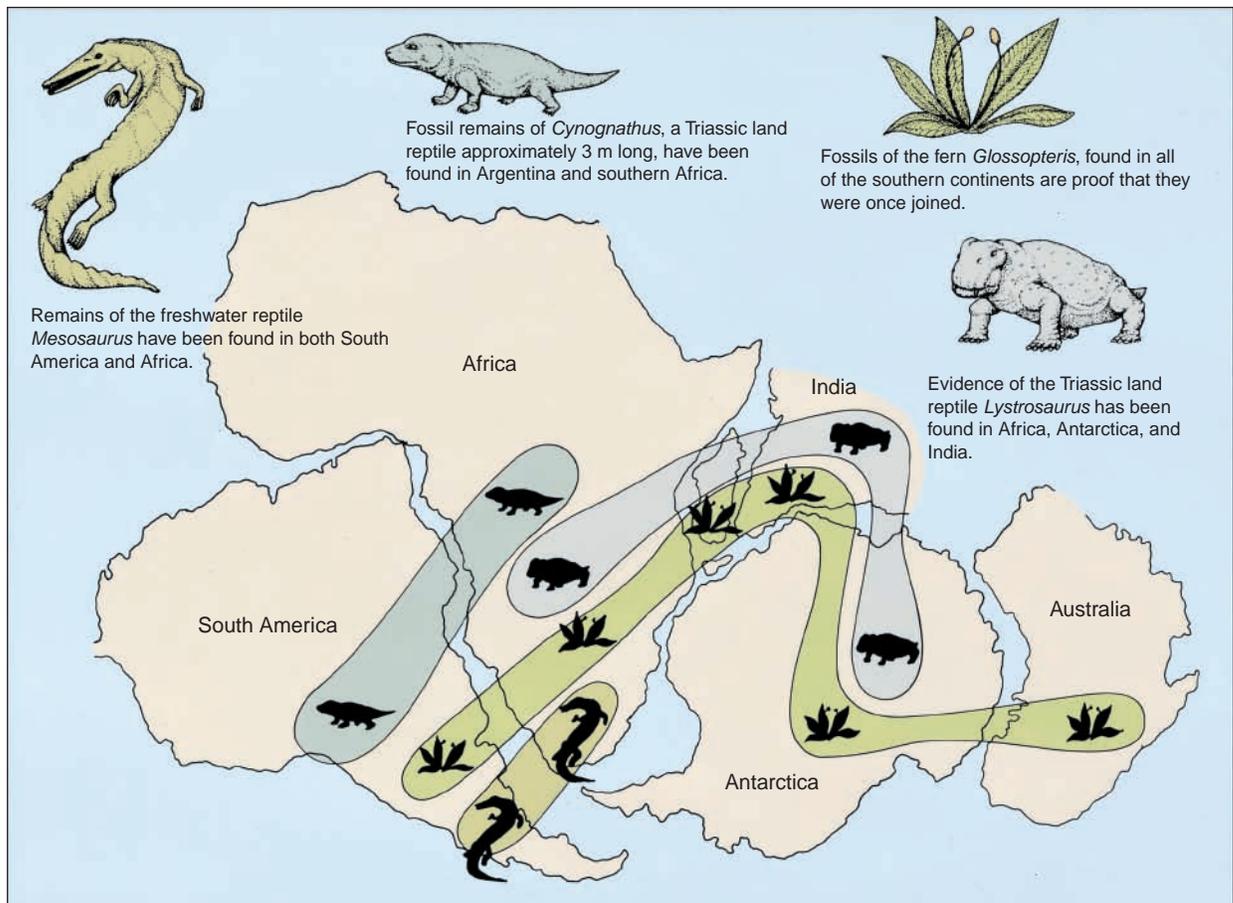
FIGURE 17.2 **Paleontologic evidence of continental drift** can be appreciated by considering the distribution of some fossil plants and animals found in South America, Africa, Madagascar, India, Antarctica, and Australia. *Mesosaurus,* a Permian freshwater reptile, is found in both Brazil and South Africa. *Glossopteris,* a fossil fern, is found on all of the southern continents in the zone shown on the map. *Lystrosaurus,* a Triassic land reptile, is found in South Africa, South America, India, and Antarctica. *Cynognathus,* an older Triassic reptile, is found in Argentina and South Africa. *(Modified from L. Motz)*

all of the southern continents, therefore, is strong supporting evidence that the continents were once connected.

The distribution of Paleozoic and Mesozoic reptiles provides similar evidence; fossils of several species have been found in the now-separated southern continents. An example is a mammal-like reptile belonging to the genus *Lystrosaurus.* This creature was strictly a land dweller. Its fossils are found in abundance in South Africa, South America, Asia, and in Antarctica. This genus thus inhabited all of the southern continents except Australia during the same geologic period. Clearly, these reptiles could not have swum thousands of kilometers across the Atlantic and Antarctic oceans, so some previous connection of the continents must be postulated. A former land bridge between the continents could explain the distribution of *Lystrosaurus* in distant parts of the world. Surveys of the ocean floor show no evidence for such a submerged land bridge like today's Central America.

Evidence from Structure and Rock Type

Several geologic features end abruptly at the coast of one continent and reappear on the facing continent across the Atlantic (Figure 17.3). The folded mountain ranges at the Cape of Good Hope, at the southern tip of Africa, trend from east to west and terminate sharply at the coast. An equivalent structure, of the same age and style of deformation, appears near Buenos Aires, Argentina (Figure 17.3). The folded Appalachian Mountains are another excellent example. The deformed structures of the mountain belt extend northeastward across the eastern United States and through Newfoundland, terminating abruptly at the ocean. The mountain belt

with a similar age, rock sequence, fossils, and structural style reappears on the coasts of Ireland, Scotland, and Norway.
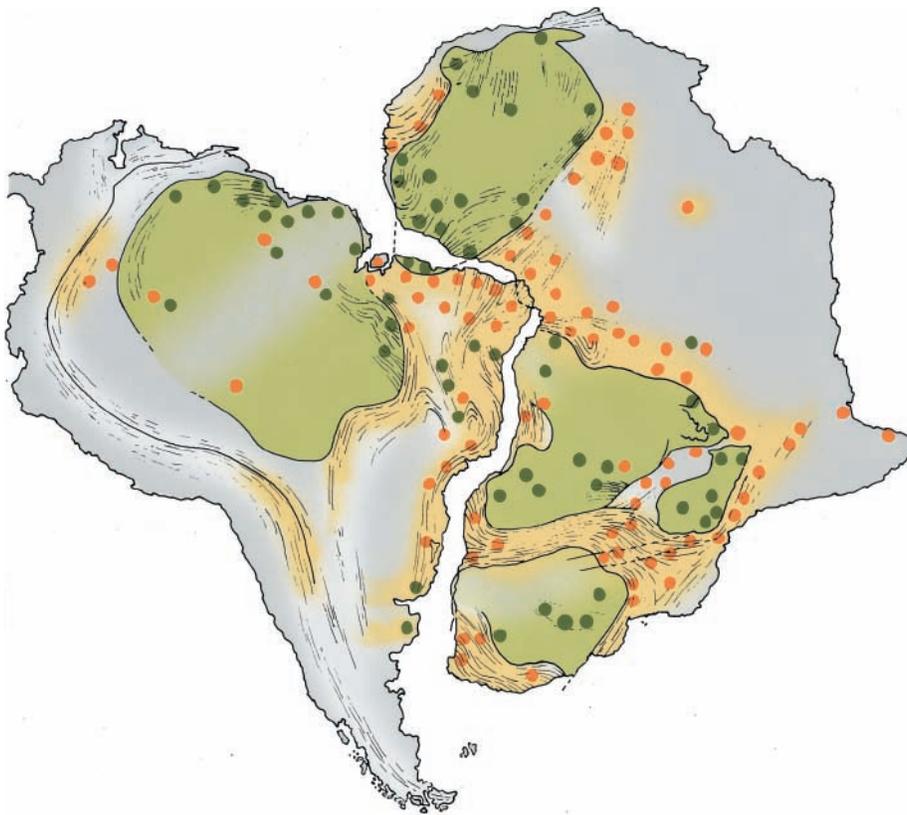
Other examples could be cited, but the important point is that the continents on both sides of the Atlantic fit together, not only in outline, but in rock type and structure. They are related much like matching pieces of a torn newspaper (Figure 17.4). The jagged edges fit, and the printed lines (structure and rock types) join in a coherent unit. One important point needs emphasis. The geologic similarities on opposite sides of the South Atlantic are found only in rocks older than the Cretaceous Period, which began about 145 million years ago. The southern continents are believed to have split and begun drifting apart in Jurassic time, about 200 million years ago.

Evidence from Glaciation

During the latter part of the Paleozoic Era (about 300 million years ago), glaciers covered large portions of the continents in the Southern Hemisphere. The deposits left by these ancient glaciers are distinct and can be readily recognized, and they cannot be mistaken for other types of sediment. In addition, striations and grooves on the underlying rock show the direction in which the ice moved (Figure 17.5A). Except for Antarctica, all of the continents in the Southern Hemisphere now lie close to the equator, far removed from a latitude that could produce glaciation. In contrast, the present-day continents in the Northern Hemisphere show no trace of glaciation during this time. In fact, fossil plants in North America and Europe indicate a tropical climate in those areas. This evidence is difficult to explain in the context of immovable continents because the climatic belts are determined by latitude.

Even more difficult to explain is the direction in which the glaciers moved. Regional mapping of striations and grooves indicates that in South America, India, and Australia, the ice accumulated in the oceans and moved inland. Such movement of ice would be impossible unless there was a land mass where the
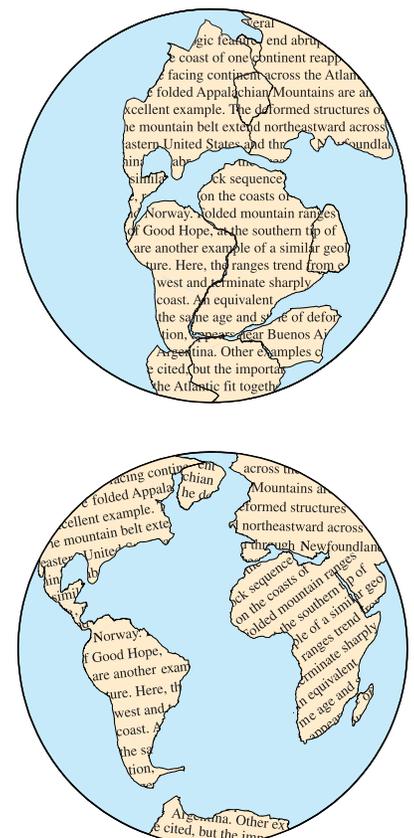
FIGURE 17.4   When reconstructed, the continents fit together like a jigsaw puzzle or pieces of a torn newspaper. Not only do the outlines of the torn pieces fit together, but the printing on them (analogous to the ages and structural features of the continents) also matches across their edges.
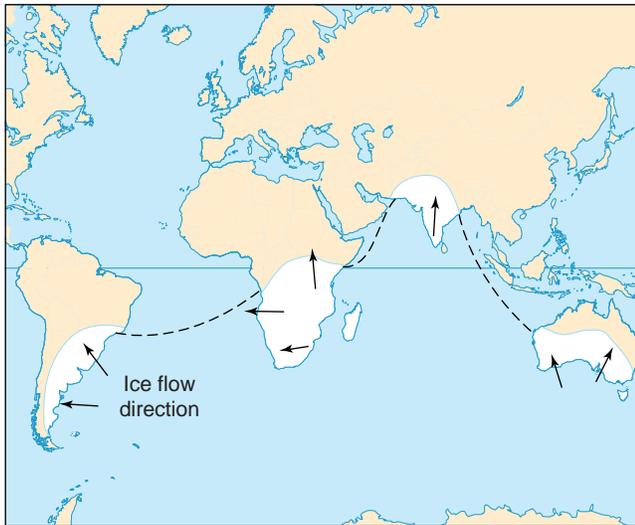
(A) Late Paleozoic glacial deposits are found only in the Southern Hemisphere and India, areas now close to the tropics. The present-day cold latitudes in the Northern Hemisphere show no evidence of glaciation at this time. Arrows show the direction of ice movement was from the sea toward the land. This flow direction is impossible; glaciers flow from centers of accumulation on the continents *outward toward* the sea.
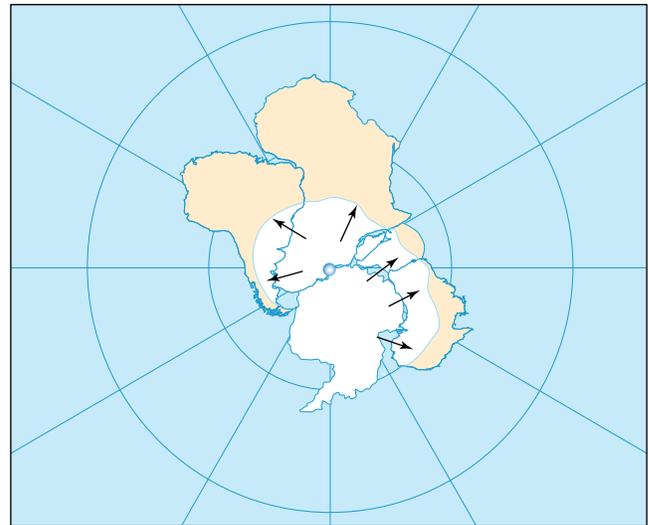
(B) If the continents were restored to their former positions according to Wegener's theory of continental drift, and if the former South Pole were located approximately where South Africa and Antarctica meet, the location of late Paleozoic glacial deposits and the directions in which the ice flowed would be explained nicely.

FIGURE 17.5   The distribution and flow direction of late Paleozoic glaciers provide further evidence of continental drift.

Why is the distribution of Paleozoic glacial features such powerful evidence for continental drift?

oceans now exist. As we saw in Chapter 14, glaciers do not form in the ocean. If glaciers could form in the sea, a large permanent glacier would exist in the Arctic Ocean. Instead, glaciers originate on land and move *toward* the edge of a continent.

However, if the continents were grouped together as Wegener proposed, the glaciated areas would have made up a neat package near the South Pole (Figure 17.5B), and Paleozoic glaciation could be explained nicely. The pattern of glaciation was considered strong evidence of continental drift, and many geologists who worked in the Southern Hemisphere became ardent supporters of the theory because they could see the evidence with their own eyes.

Evidence from Other Paleoclimatic Records

Other evidence of striking climatic changes recorded in the geologic record tends to support the drift theory. Great coal deposits in Antarctica show that abundant plant life once flourished on that continent, now covered with ice more than a kilometer thick (see Figure 14.19).

On the other continents, thick deposits of salt, formations of wind-blown sandstone, and extensive fossil coral reefs provide additional clues that permit us to reconstruct the climatic zones of the past. The paleoclimatic patterns shown by these rocks are baffling with the continents in their present positions, but if the continents are grouped together in their predrift positions, the patterns are easily explained (Figure 17.6).

The evidence for the theory of continental drift was considered and debated for years. Wegener was criticized for failing to explain what forces would permit continents of granite to plow through oceans of rock. The idea of a moving lithosphere was yet to come. In the absence of a reasonable mechanism for drift, there was little further development of the theory until after World War II. An explosion of knowledge then provided renewed support for the drift hypothesis and also led to the discovery of a possible mechanism.
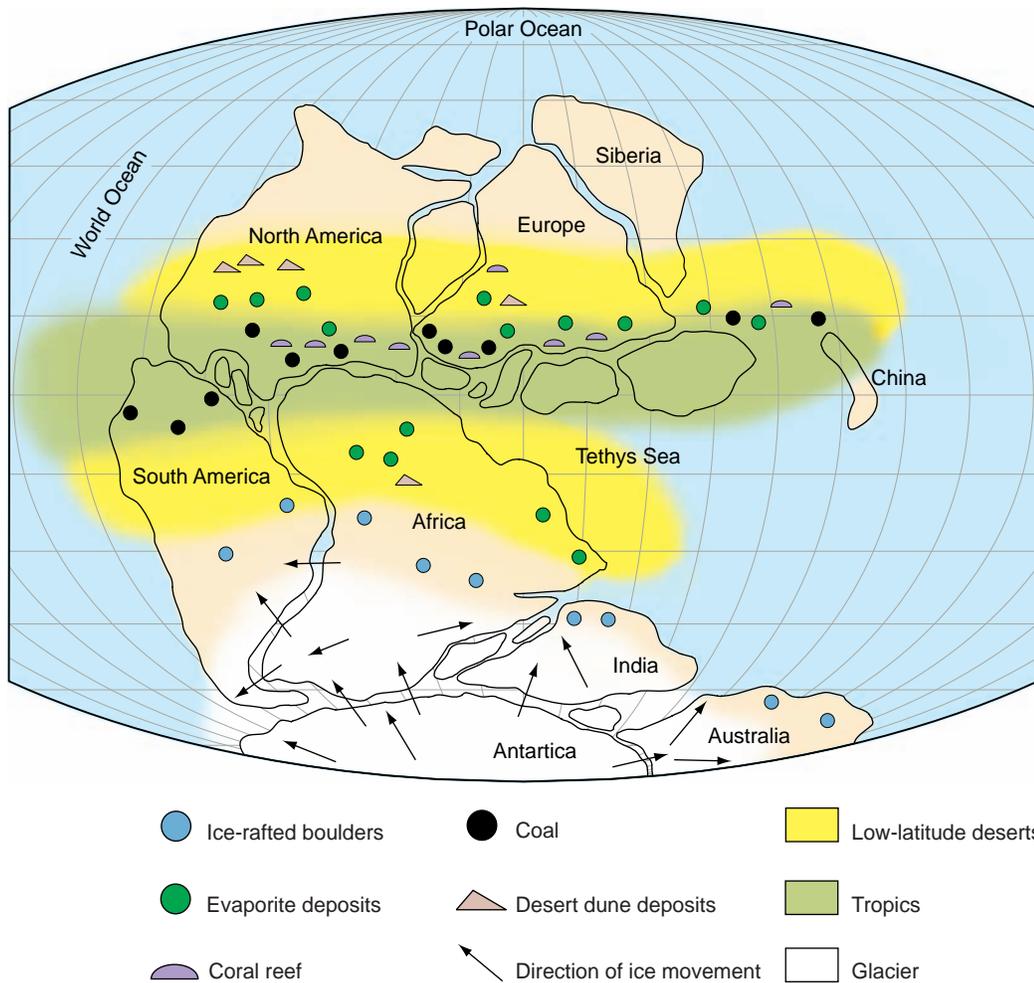
FIGURE 17.6   Paleoclimatic evidence for continental drift includes deposits of coal, desert sandstone, rock salt, wind-blown sand, gypsum, and glacial deposits about 300 million years ago near the end of the Paleozoic Era. Each indicates a specific climatic condition at the time of its formation. The distribution of these deposits is best explained if we assume that the continents were grouped together at the end of the Paleozoic Era, as shown in this diagram. *(After American Association of Petroleum Geologists)*

DEVELOPMENT OF THE THEORY OF PLATE TECTONICS

> The plate tectonics theory was developed during the early 1960s, when new instruments permitted scientists to map the topography of the ocean floor and to study its geologic and paleomagnetic characteristics.

Although the theory of continental drift was supported by some convincing evidence, the data on which it was originally based came only from the continents because, before the 1950s, there was no effective means of studying the ocean floor. Before 1950, therefore, geologists faced an almost total absence of data about the geology of three-fourths of Earth's surface; then, in the 1950s and 1960s, new technology resulted in a burst of new data and new ideas about the geology of the ocean floor and about paleomagnetism.

Geology of the Ocean Floor

In the 1950s and 1960s, newly developed echo-sounding devices enabled marine geologists and geophysicists to map in considerable detail the topography of the ocean floor. When the results of these studies were compiled, they revealed that

several ocean basins are divided by a great ridge, approximately 65,000 km long and about 1500 km wide. Moreover, at the crest of the ridge is a central valley, from 1 to 3 km deep. This feature appears to be a **rift valley** that is splitting apart under tension. No one could imagine why the ridge was there, but no one could dispute that it was the longest mountain range on the planet, and along its crest was the longest valley.

Other evidence showed a multitude of differences between continental and oceanic crust. Decades of research have shown that the oceanic crust is much younger than continental crust. Drilling and dredging have established that the oceanic crust is composed largely of basalt and, therefore, has a completely different composition from the granitic continental crust. Seismic studies reveal that oceanic crust is also much thinner. Furthermore, the oceanic crust is not deformed into folded mountain structures and apparently is not subjected to strong compressional forces.

In 1960 H. H. Hess, a noted geologist from Princeton University, proposed a theory of **seafloor spreading** that took into account the new data from echo soundings and suggested a possible mechanism for continental drift. Hess postulated that the ocean floors are spreading apart, propelled by convection currents in the mantle, and are moving symmetrically away from the oceanic ridge. According to his theory, this continuous spreading produces fractures in the rift valley, into which magma from the mantle is injected to become new oceanic crust. He proposed that convection currents in the mantle carry the continents away from the oceanic ridge and toward deep-sea trenches. There, the oceanic crust descends into the mantle, with the descending convection current, and is reabsorbed. In this way, the entire ocean floor is completely regenerated in 200 or 300 million years.

In the light of fresh knowledge, Hess thus elaborated on the theory of continental drift and redefined it in the scheme of seafloor spreading. A test of his ideas, using new studies in paleomagnetism, was soon to follow.

Paleomagnetism

Like most planets, Earth has an internally generated magnetic field. In many ways, Earth's magnetic field resembles that of a simple bar magnet with a distinct north and south magnetic pole. The axis of the magnetic field is inclined 11° from the spin axis (Figure 17.7A). However, Earth's mantle and core are far too hot to retain a permanent magnetic field. Earth's magnetism, therefore, must be constantly generated electromagnetically. Geophysicists still lack a complete understanding of how the field forms. The electromagnetic, or dynamo, theory postulates that the outer core of liquid iron convects and the motion generates electrical currents that establish a magnetic field (Figure 17.7B).

The study of rock magnetism developed during the 1950s with the perfection of new, highly sensitive magnetometers. Certain rocks, such as basalt, are fairly rich in iron and become weakly magnetized by Earth's magnetic field as they cool. In a sense, the mineral grains in the rock become "fossil" magnets that show the orientation of Earth's magnetic field at the time when the minerals crystallized and cooled; they thus preserve a record of **paleomagnetism.** Similarly, the iron-oxide grains in some red sandstones become oriented in Earth's magnetic field as the sediment is deposited, so some sedimentary rocks also can show the orientation of the paleomagnetic fields. These rocks therefore retain an imprint of Earth's magnetic field at the time of their formation.

Apparent Polar Wandering.   Some of the first paleomagnetic studies were conducted in Europe. Paleomagnetism in these rocks of widely different ages appears to show that Earth's north magnetic pole has steadily changed its position. As illustrated in Figure 17.8, the north magnetic pole appears to have slowly migrated northward and westward to its present position. The change in position was systematic, not random. Migration of the magnetic pole was found from

The plate tectonics theory is simple, clear, and straightforward. Why wasn't it developed earlier?

FIGURE 17.7 **Earth's magnetic field** is like that of a simple bar magnet because it has a north and a south pole. The temperature in the core and mantle, however, is far too high for permanent magnetism. Earth's magnetism must therefore be generated electromagnetically.

Magnetic field lines

Solid inner core
Convection cells
Mantle
Rotation speed

Magnetic field lines

(A) Lines of force in Earth's magnetic field are shown by arrows. If a magnetic needle were free to move in space, it would be deflected by Earth's magnetic field. Close to the equator, the needle would be horizontal and would point toward the poles. At the magnetic poles, the needle would be vertical. Field lines are shown for a reverse polarity time period.
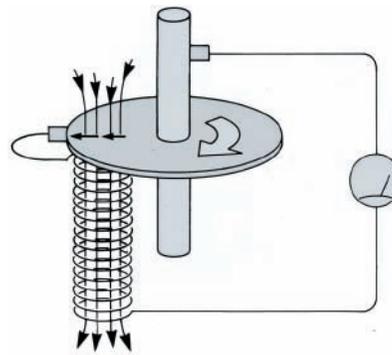
(B) Theoretically, convection in Earth's core can generate an electrical current (in a manner similar to the operation of a dynamo), which produces a magnetic field

paleomagnetic work in North America, and although the path of migration was systematically different, it paralleled that of the European shift. Soon, paleomagnetic results collected from the southern continents were reported. Again, a systematic change in the position of the magnetic pole through time was documented—but with different paths for different continents.

It is impossible that there were numerous magnetic poles migrating systematically and eventually merging. The most logical explanation is that there has always been only one magnetic pole, which has remained fixed, while the continents moved with respect to it. Consequently, students of paleomagnetism became leading proponents of the theory of continental drift.

The results of paleomagnetic studies make sense if the continents were once arranged as shown in Figure 17.8B and then drifted to their present positions. This discovery brought renewed interest in the theory of continental drift and lent support to the conclusion that the Atlantic Ocean opened relatively recently.

How does apparent polar wandering support the theory of plate tectonics?

Patterns of Magnetic Reversals on the Seafloor. Studies of the magnetic properties of numerous layers of volcanic rock, from many parts of the world, demonstrate that the polarity of Earth's magnetic field has reversed many times over its history. Epochs of **normal polarity** (that is, periods when the magnetic field was oriented as it is today with the north magnetic pole in the north and close to its present location) have been followed by periods during which the locations of the north magnetic pole and the south magnetic pole were reversed. At least a dozen magnetic reversals have occurred in the last 4.0 million years (Figure 17.9).

(A) The magnetic properties of rocks in North America show that the north magnetic pole has apparently migrated in a sinuous path over the last 500 hundred million years (red). Other continents show "polar" migration along different paths. How could different continents show different paths of polar wander? The paleomagnetic evidence implies that different continents would have had different magnetic poles at the same time, but that would be impossible.

(B) The question can be answered if the location of the magnetic pole was fixed while the continents drifted. Thus when the continents are moved back to a past positions, they show that there was only one magnetic pole at that specific time. The apparent polar wander paths of Europe (blue) and North America (red) in (A) show they were separate (before about 400 million years ago), then joined, and then diverged again. (after about 180 million years ago).

FIGURE 17.8   **Apparent changes in the locations of the magnetic poles in the geologic past** are shown by paleomagnetic studies of rocks.

How do patterns of magnetic reversals support the plate tectonics theory?

The present period of normal polarity began about 780,000 years ago. It was preceded by a major period of **reversed polarity,** which began about 2.5 million years ago. That period of generally reversed polarity contained two short episodes of normal polarity. The major intervals of alternating polarity (about 1 million years apart) are termed **polarity chrons.**

The pattern of alternating polarities has been clearly defined, and evidence of the occurrence of polarity reversals has been found in widely separated places. From the sequence of **magnetic anomalies** and their radiometric ages, a reliable chronology of **magnetic reversals** has been established for the last 4 million years (Figure 17.9). The paleomagnetic time scale is gradually being extended back in time.

In 1963 Fred Vine and D. H. Matthews saw a way to use paleomagnetism to test the idea of seafloor spreading put forth by Hess. If seafloor spreading has occurred, they suggested, it should be recorded in the magnetism of the basalts in the oceanic crust. (The same idea was developed independently by L. W. Morley.) If Earth's magnetic field reversed intermittently, new basalt forming at the crest of the oceanic ridge would be magnetized according to the polarity at the time it cooled. As the ocean floor spreads, a symmetrical series of magnetic stripes, with alternating normal and reversed polarities, would be preserved in the crust along either side of the oceanic ridge. Subsequent investigations have conclusively proved this theory.

To understand the origin of these magnetic patterns better, consider how the seafloor could have evolved during the last few million years. Figure 17.10A shows the seafloor as it is considered to have been about 2.75 million years ago, during the Gauss normal polarity chron (named for German mathematician Karl Friedrich Gauss). Basalt was injected into dikes below the ocean ridge or was extruded over the seafloor as submarine flows. As it crystallized and cooled, it became magnetized in the direction of the existing (normal) magnetic field, and thus, basalt extruded along the oceanic ridge formed a zone of new crust with normal magnetic polarity.

(A) Normal polarity

(B) Reverse polarity

(C) Magnetic polarity time scale
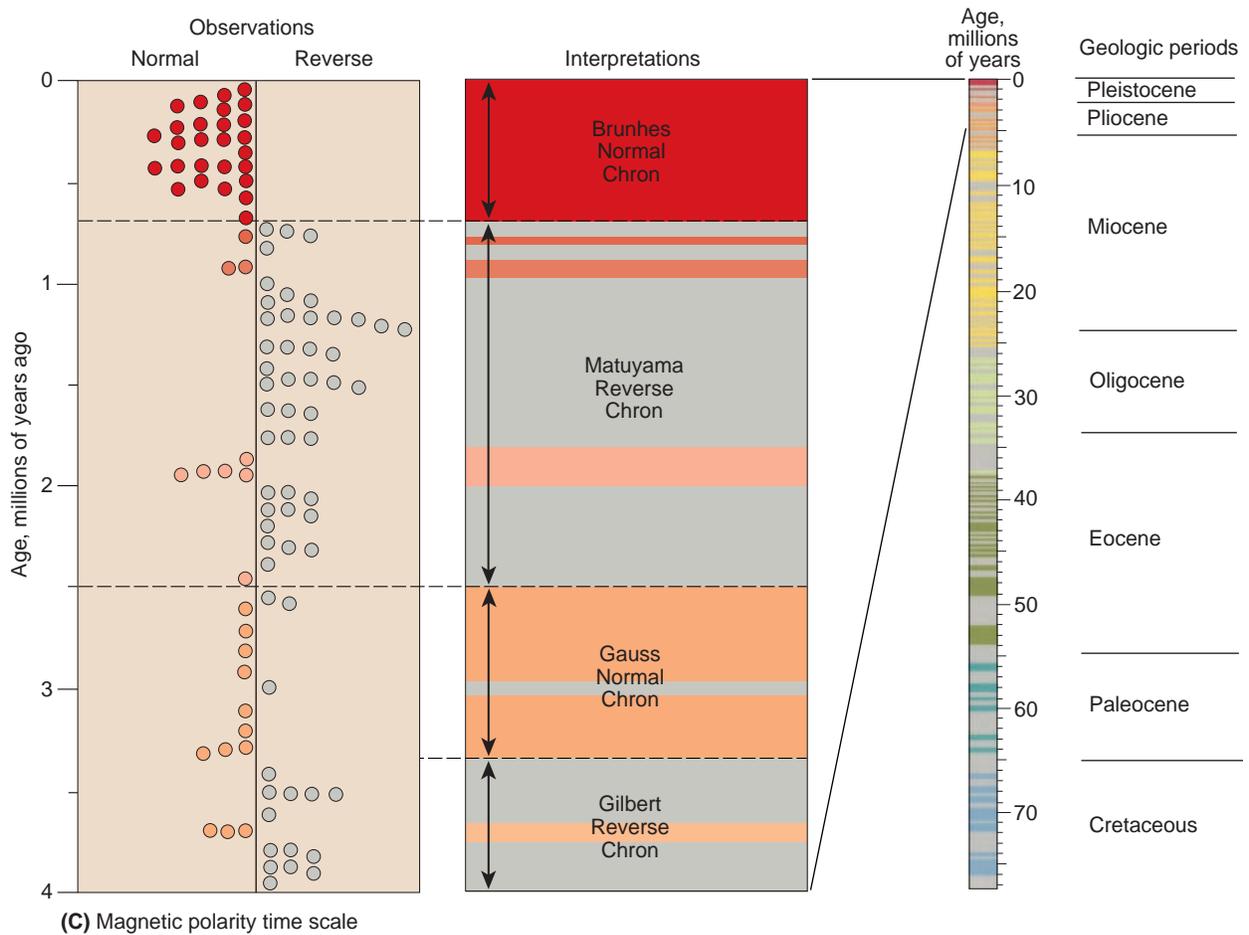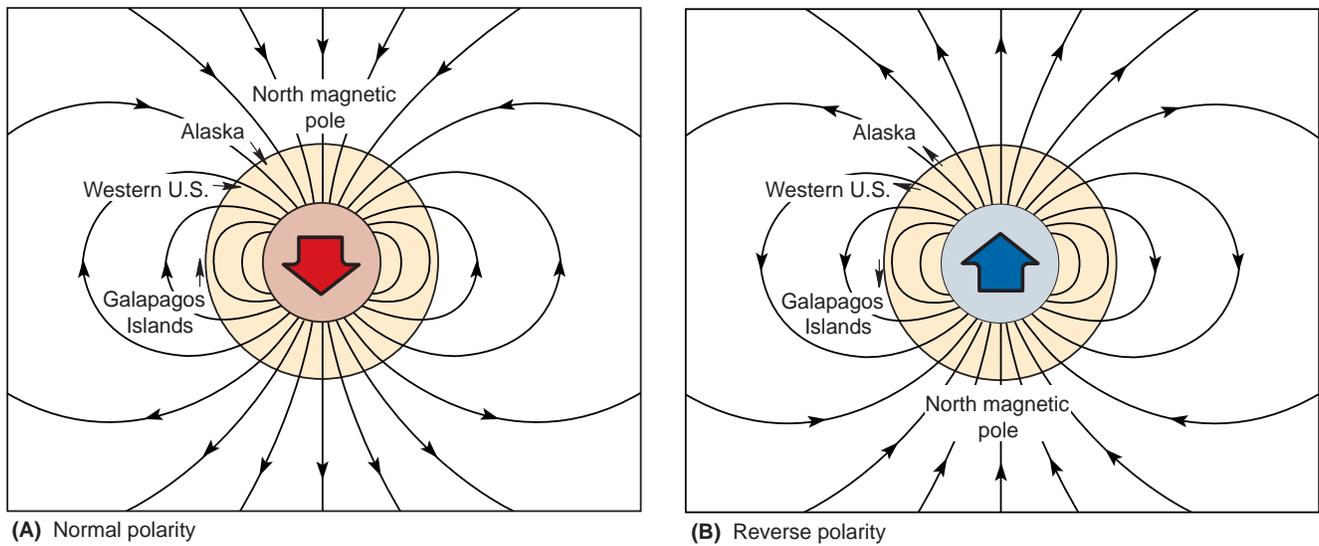
FIGURE 17.9   **Reversals of lines of force in Earth's magnetic field** are documented by paleomagnetic studies of numerous rock samples from throughout the world. Lines of force with normal polarity are shown in (A). With reverse polarity (B), the lines of force are oriented in the opposite direction. (C) shows the patterns of changing polarity with time. The pattern of change during a period of 1 or 2 million years is distinctive, and it can be used to help establish the age of a rock sequence. *(After A. Cox, G. B. Dalrymple, and R. R. Doell)*
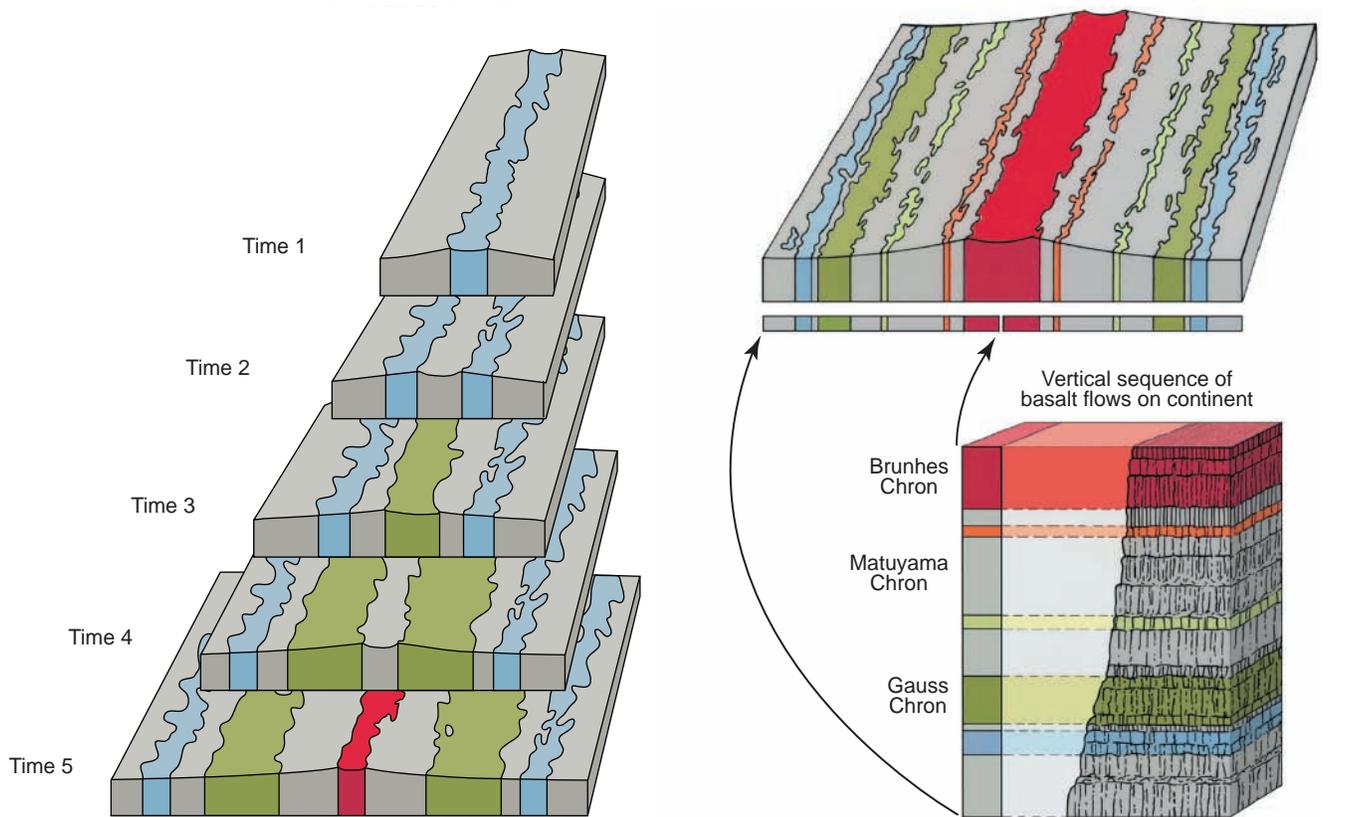
(A) As magma cools and solidifies along the ridge in dikes and flows (top), it becomes magnetized in the direction of the magnetic field existing at that time (normal polarity). As seafloor spreading continues, the magnetized crust formed during earlier periods separates into two blocks. Each block is transported laterally away from the ridge, as though on a conveyor belt. New crust, formed at the ridge, becomes magnetized in the opposite direction.

(B) Patterns of magnetic reversals in a vertical sequence of basalts on the continents. Note that the pattern of magnetic reversals away from the ridge is the same as the pattern found in this sequence of basalt flows. The youngest (upper) continental rocks correlate with the youngest oceanic crust (at the center of the oceanic ridge).

FIGURE 17.10   Specific patterns of magnetism are preserved in the newly formed crust generated at the oceanic ridge as the lithosphere moves laterally. The patterns of magnetic reversals away from the ridge are identical to the patterns of magnetic reversals in a vertical sequence of rocks on the continents.

Magnetic Stripes

As the seafloor spread, this zone of crust split and migrated away from the ridge but remained parallel to it. About 2.5 million years ago, Earth's magnetic polarity reversed. New crust generated at the oceanic ridge was then magnetized in this new direction (Figure 17.10B), producing a zone of crust with reverse polarity. When the polarity changed to normal again, the newest crustal material was magnetized in the normal direction. In this way, the sequence of polarity reversals became imprinted like a bar code on the oceanic crust.

Note that the patterns of magnetic stripes on the ocean floor, on either side of the ridge, match the patterns found in a sequence of recent basalts on the continents (Figure 17.10A and B; see also Figure 17.9C); that is, the crest of the ridge shows normal polarity and is flanked by a broad stripe of rocks with reversed polarity (formed during a reversed chron) and containing two narrow bands of rocks with normal polarity (formed during normal chrons). Then follows a stripe with normal polarity, containing one narrow band with reversed polarity, and so on. In brief, the patterns of magnetic reversals away from the ridge crest are the same as those found in a vertical sequence of rocks on the continents, from youngest to oldest. These data provide compelling evidence that the seafloor is spreading and that continents drift.

An important aspect of these reversal patterns is that they enable us to determine the age of the seafloor and to measure rates of plate movement. Magnetic re-

■ Holocene to Pliocene (0–5 MY)	■ Paleocene (56–65 MY)
■ Miocene (5–23 MY)	■ Cretaceous (65–146 MY)
■ Oligocene (23–35 MY)	■ Late Jurassic (146–157 MY)
■ Eocene (35–56 MY)	■ Middle Jurassic (157–178 MY)
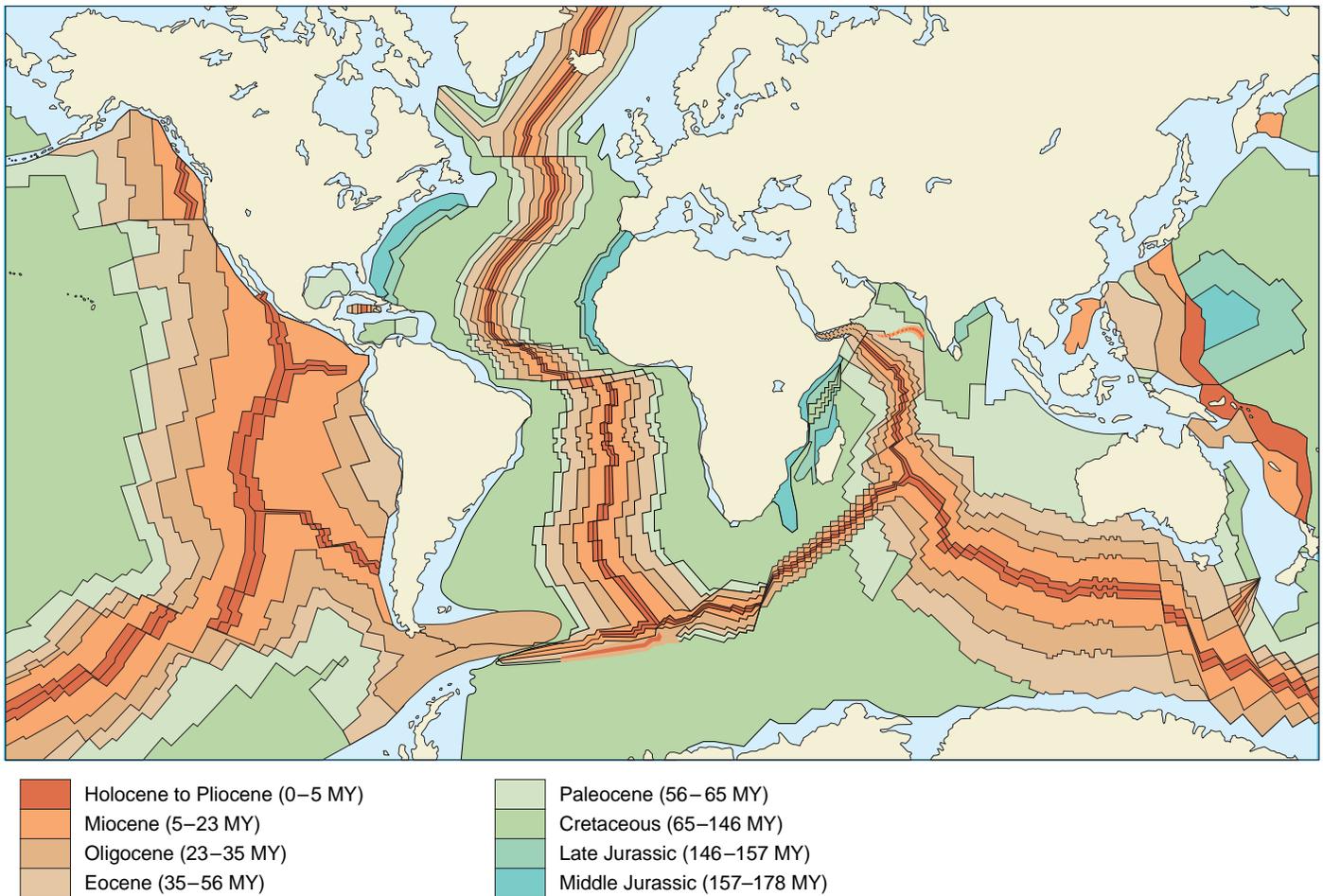
FIGURE 17.11   Ages of the rocks on the seafloor are symmetrical with respect to the oceanic ridge. By correlating magnetic reversals with the age of rocks found on the continents, we can estimate the age of the seafloor. The youngest crust is along the crest of the ridge. Away from the ridge, the crust is progressively older. The oldest oceanic crust is found in the Pacific Ocean and is less than 200 million years old.

versals in rock sequences on the continents have been radiometrically dated. These studies show that the present normal polarity has existed for the last 700,000 years and was preceded by the pattern of reversals shown in Figure 17.9C. Because the same pattern exists in the oceanic crust, we can assign provisional ages to the magnetic anomalies on the ocean floor based on known ages of continental rocks. Magnetic surveys have now determined patterns of magnetic reversal for most of the ocean floor, and from these patterns, the age of various segments of the seafloor has been established (Figure 17.11). These studies show that most of the deep seafloor was formed during the Cenozoic Era (the last 65 million years). It now seems probable that very little or none of the present ocean basin was formed before the Jurassic. From the pattern of magnetic reversals, the rate of seafloor spreading appears to range from 1 to 17 cm/yr.

Evidence from Sediment on the Ocean Floor

To many geologists, some of the most convincing evidence for the plate tectonics theory comes from recent drilling in the sediment on the ocean floor. The Deep-Sea Drilling Project is truly a remarkable example of scientific exploration. It began in 1968 with the *Glomar Challenger,* a special ship designed by a California offshore drilling company. The *Challenger* can lower more than 6000 m of drilling pipe into the open ocean, bore a hole in the seafloor, and bring up bottom cores and samples. The project was funded by the National Science Foundation and is under the direction of the Scripps Institution of Oceanography. Since 1968, the *Challenger* and its successors have drilled hundreds of holes in the seafloor and

penetrated more than a kilometer into the oceanic crust. These drilling projects have provided considerable data in support of the theory of plate tectonics.

Deep-sea drilling confirms the conclusions drawn from paleomagnetic studies by providing samples of the fossils that accumulated on different portions of the ocean floor. As is predicted by the plate tectonics theory, the *youngest sediment resting on the basalt* of the ocean floor is found near the oceanic ridge (Figure 17.12), where new crust is being created. Away from the ridge, the sediments that lie directly above the basalt become progressively older, with the oldest sediment nearest the continental borders.

Measurements of rates of sedimentation in the open ocean show that about 3 mm of red clay accumulates every 1000 years. If the present ocean basins were old enough to have existed since Cambrian time, for example, the sediments would be 1.5 km thick (Figure 17.12A); however, the average thickness of deep-ocean sediments measured to date is only 300 m, suggesting that the ocean basins are young geologic features (Figure 17.12B). In fact, the oldest sediments yet found on any ocean floor are only about 200 million years old. In contrast, the metamorphic rocks of the continental shields are as much as 3.8 billion years old.

Not only do the thickness and age of the deepest sediments increase away from the crest of the oceanic ridge, but certain types of sediment also indicate seafloor spreading. For example, plankton thrive in the upwelling, warm, nutrient-rich water of the Pacific equatorial zone. As the creatures die, their tiny skeletons rain down unceasingly to build a layer of soft, white chalk on the seafloor. The chalk can form only in the equatorial belt, as plankton do not flourish in the colder waters of higher latitudes; yet, drilling by the *Glomar Challenger* has shown that the chalk layer on the Pacific floor extends north of today's equator. The only logical conclusion is that the Pacific seafloor has been migrating northward for at least 100 million years, carrying its load of chalk formed anciently when the plate was farther south.

The theory of plate tectonics is now firmly established and accepted as the fundamental theory of Earth's dynamics. It was first used to explain the meaning of features on the ocean floor. Now the emphasis has switched to the continents, and most previous geologic observations of the continents are being reexamined in light of plate tectonics theory.

Seafloor Spreading

(A) With no seafloor spreading, the entire ocean floor would be covered with a thick sequence of oceanic sediment, with alternating polarity preserving a record of Earth's magnetism since Precambrian time.
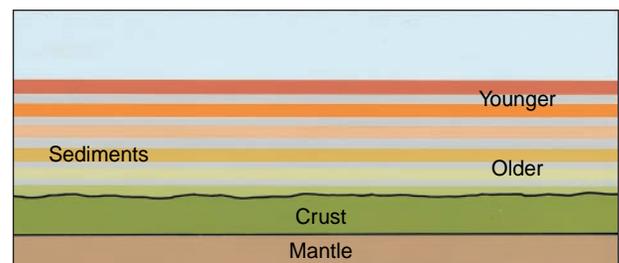
(B) With seafloor spreading, the blanket of oceanic sediment thins progressively toward the crest of the oceanic ridge and is almost nonexistent on the ridge. The edge of each layer of magnetized sediment lies upon basaltic crust, which was generated at the spreading ridge during the same time interval the sediment was deposited.
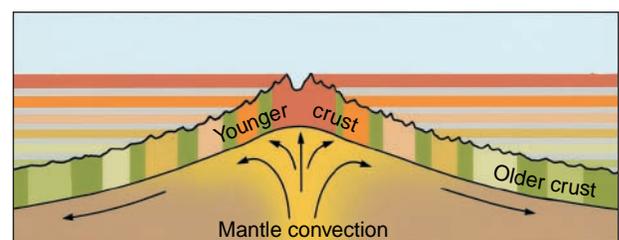
FIGURE 17.12 **The thickness of sediment and magnetic reversals on the oceanic ridge** confirms the theory of seafloor spreading. *(After P. J. Wylie)*

PLATE GEOGRAPHY

Plate boundaries are the most significant structural elements of Earth because they reflect the planet's internal dynamics.

The shorelines of the continents are major geographic features but have little significance from the standpoint of Earth's tectonics. Plate boundaries are the planet's most significant geologic elements, and to understand plate tectonics, you must learn a new geography: the geography of plate boundaries. This should not be difficult because plate boundaries generally are marked by major topographic features. You only need to focus your attention on Earth's structural features, rather than on the boundaries between land and ocean.

The new geography of **tectonic plates** is illustrated in Figure 17.13. Earth's outer rigid layer—the lithosphere—is divided into a mosaic of seven major plates and several smaller subplates. The major plates are outlined by oceanic ridges, trenches, and young mountain systems. These include the Pacific, Eurasian, North American, South American, African, Australian, and Antarctic plates.

The largest is the Pacific plate, which is composed almost entirely of oceanic crust and covers about one-fifth of Earth's surface. The other large plates contain both continental crust and oceanic crust. No major plate is composed entirely of continental crust. Smaller plates include the Philippine, Arabian, Juan de Fuca, Cocos, Nazca, Caribbean, and Scotia plates, plus others that have not been defined precisely.

Individual plates are not permanent features. They are in constant motion and continually change in size and shape. Plates that do not contain continental crust

How does the geography of tectonic plates differ from classical physical geography?
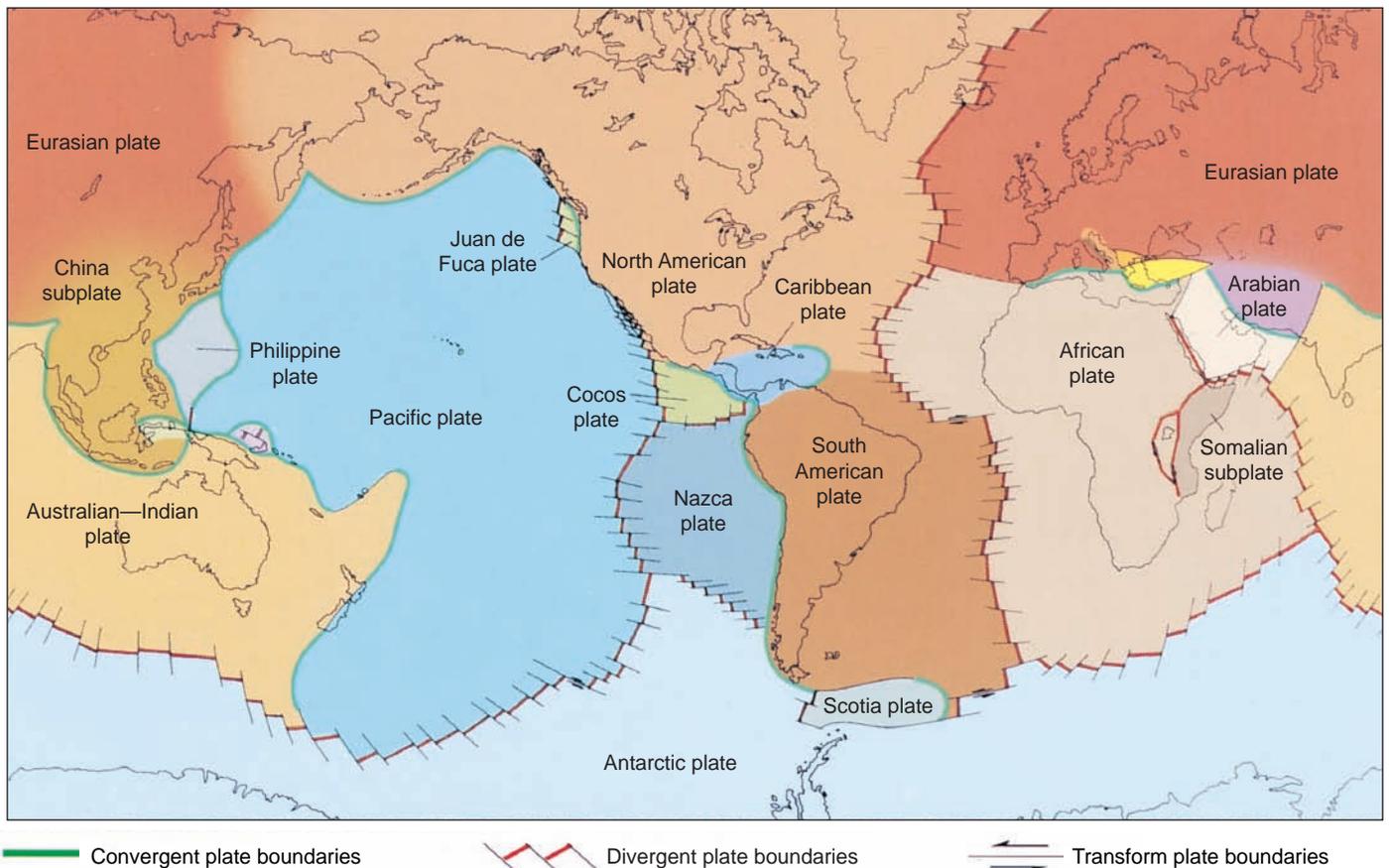
FIGURE 17.13   **The major tectonic plates** are delineated by the major tectonic features of the globe: (1) the oceanic ridge, (2) deep-sea trenches, and (3) young mountain belts. Plate boundaries are outlined by earthquake belts and volcanic activity. Most plates (such as the North American, African, and Australian) contain both continental and oceanic crust. The Pacific, Cocos, and Nazca plates contain predominantly oceanic crust.

can be completely consumed in a subduction zone. Even plate margins are not fixed. A plate can change its shape by splitting along new lines, by welding itself to another plate, or by the accretion of new oceanic crust along its passive margin. The movement and modification of a plate margin can change its size and shape across the entire plate.

PLATE BOUNDARIES

> Three kinds of plate boundaries are recognized and define three fundamental kinds of deformation and geologic activity: (1) divergent plate boundaries—zones of tension, where plates split and spread apart, (2) convergent plate boundaries—zones where plates collide and one plate moves down into the mantle, and (3) transform fault boundaries—zones of shearing, where plates slide past each other without diverging or converging.

How are plate boundaries expressed at the surface?

Each tectonic plate is rigid and moves as a single mechanical unit—that is, if one part moves, the entire plate moves. It can be warped or flexed slightly as it moves, but relatively little change occurs in the middle of a plate. Nearly all major tectonic activity occurs along the plate boundaries, and thus, geologists and students of geology focus their attention on the plate margins, the ones that are active as well as the ancient plate boundaries preserved on the continents (Figure 17.14).

Divergent Plate Boundaries

A **divergent plate boundary** forms where a plate splits and is pulled apart. Except for a few rift zones in Africa and western North America, essentially all present divergent plate margins are submerged beneath the sea. Where a zone of spreading extends into a continent, rifting occurs, and the continent splits (Figure 17.15). The separate continental fragments drift apart with the diverging plates, so a new and continually enlarging ocean basin is formed at the site of the initial rift zone. Divergent plate boundaries are thus characterized by tensional stresses that produce normal faults along the margins of the separating plates. Basaltic magma, derived from the partial melting of the mantle, is injected into the fissures or extruded as fissure eruptions. The magma then cools and becomes part of the moving plates.

Divergent plate boundaries are some of the most active volcanic areas on Earth; they are, however, generally characterized by unspectacular, quiet fissure eruptions, most of which are concealed beneath the sea. The importance of volcanism along this zone is underlined by the fact that during the last 200 million years, more

FIGURE 17.14   Types of plate margins are depicted in this idealized diagram. Constructive margins (divergent plate boundaries) occur along the oceanic ridge, where plates move apart. Destructive margins (convergent plate boundaries) occur along the deep trenches. Margins with no change in seafloor area during displacement occur along transform faults. *(After B. Isaks, J. Oliver, and L. R. Sykes)*
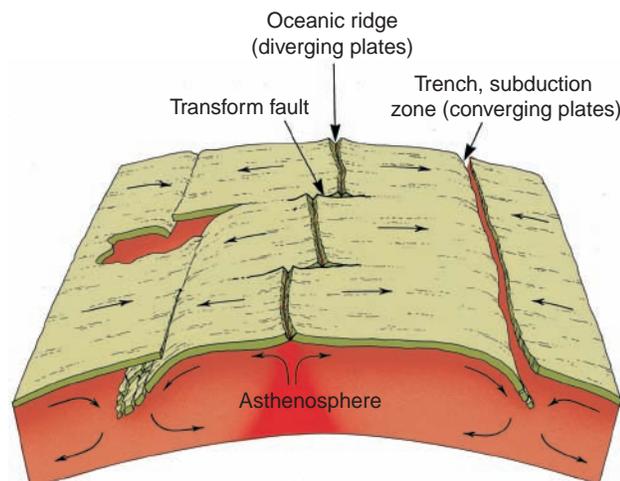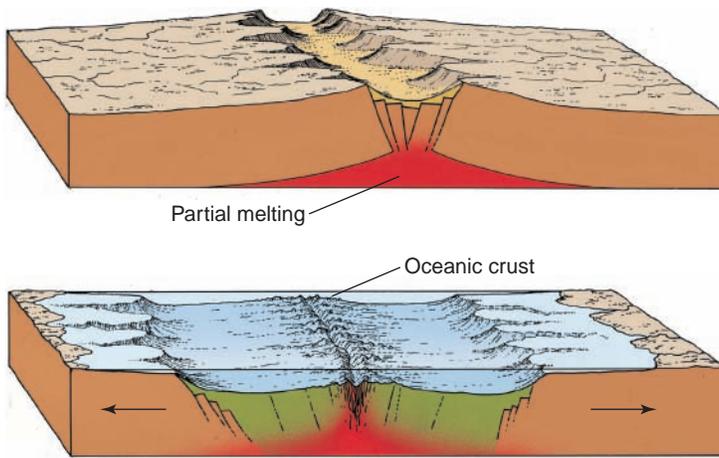
(A) Continental rifting begins when the crust is uparched and stretched, so that block faulting occurs. Continental sediment accumulates in the depressions of the downfaulted blocks, and basaltic magma is injected into the rift system.

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

FIGURE 17.15 **Divergent plate boundaries** are found in the ocean basins and continents. The midocean ridge is one type of divergent plate boundary and has abundant normal faults, shallow earthquakes, and basaltic magmatism.

than half of Earth's surface has been created by volcanic activity along divergent plate boundaries. The mid-Atlantic ridge is a typical divergent plate boundary.

Convergent Plate Boundaries

Convergent plate boundaries, where the plates collide and one moves down into the mantle, are areas of complicated geologic processes, including igneous activity, earthquakes, metamorphism, crustal deformation, and mountain building.

The specific processes that are active along a convergent plate boundary depend on the types of crust involved in the collision of the converging plates (Figure 17.16). If both plates at a convergent boundary contain oceanic crust, one is thrust under the margin of the other in a process called **subduction. A subduction zone** is usually marked by a deep-sea trench, and the movement of the descending plate generates an inclined zone of seismic activity. The subducting plate descends into the asthenosphere, where it is heated and ultimately absorbed into the mantle. Layers of sediment may be scraped off the downgoing plate and accreted onto the continent. The island arcs of the western Pacific, including the islands of Tonga and the Marianas, formed at ocean-ocean convergent margins.

If one plate contains a continent, the lighter continental crust always resists subduction and overrides the oceanic plate. Compression may deform the continental margin into a folded mountain belt (Figure 17.16 and 17.17), and the deep roots of the mountains are intruded by magma and metamorphosed. The Cascadia subduction zone offshore of the northwestern United States is an ocean continent convergent margin.

If both converging plates contain continental crust, neither can subside into the mantle, although one can override the other for a short distance. Both continental masses are instead compressed, and the continents are ultimately "fused" into a single continental block, with a high mountain range marking the line of the suture. As a result of the collision and underthrusting, the thickness of the crust is greatly increased. The great Himalayan mountain chain formed when India and Asia collided, both of which are continental plates.

Magma is also produced at convergent plate margins. Magma extracted from the mantle above a subduction zone can differentiate to form relatively silicic magmas (like andesite and rhyolite) which have low densities. Ultimately much of this low density material is added to the continental crust as batholiths and volcanic extrusions at the surface In fact, most continental crust formed at ancient convergent plate boundaries. Steep-sided stratovolcanoes and large collapse calderas are the typical volcanoes found at convergent margins.

(A) The Philippine Islands represent the convergence of two oceanic plates.
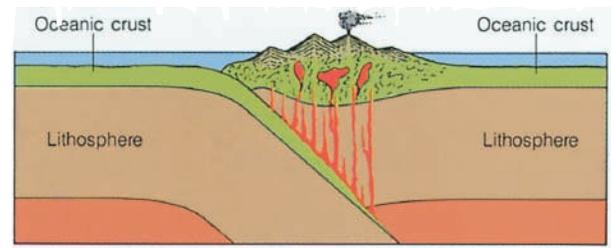
(B) South America represents the convergence of an oceanic plate and a continental plate.
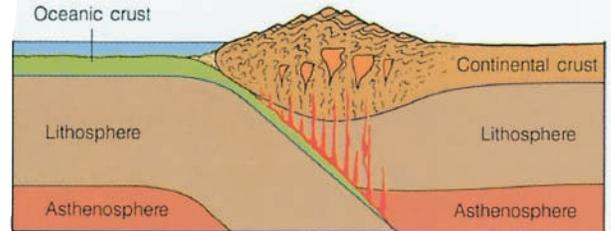
(C) The Himalaya Mountains represent the convergence of two continental plates.
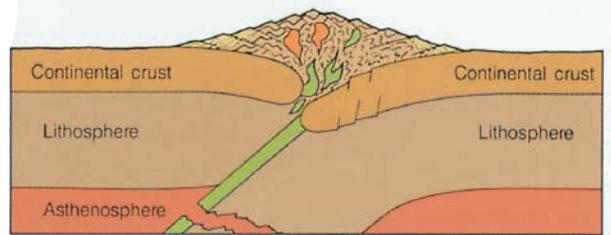
FIGURE 17.16   Examples of the main types of convergent plate boundaries can be found today in various parts of the world. The major geologic processes at convergent plate boundaries include the deformation of continental margins into folded mountain belts, metamorphism due to high temperatures and high pressures in the mountain roots, and partial melting of the mantle over the descending plate, which produces andesitic volcanism on the overriding plate.

Transform Fault Boundaries

Transform fault boundaries are zones of shearing where plates slide past each other without diverging or converging, and without creating or destroying lithosphere (Figure 17.18). These boundaries occur along a special type of fault, a **transform fault,** which is simply a **strike-slip fault** between plates (that is, movement along the fault is horizontal and parallel to the fault). The term *transform* is used because the kind of motion between plates is changed—transformed—at the ends of the active part of the fault. For example, the divergent motion between plates at an oceanic ridge can be transformed along the fault to the convergent motion between plates at a subduction zone.

Transform faults can join ridges to ridges, ridges to trenches, and trenches to trenches. In all cases, transform faults are parallel to the direction of relative plate motion. The plates simply slide past each other, but as the plates move, the crust is fractured and broken. This fracturing produces the shallow earthquakes that are characteristic of transform plate boundaries. However, volcanic activity usually is not abundant at transform faults.

The San Andreas fault system of western North America is a typical continental transform fault at the boundary between the North American plate and the Pacific plate (Figure 17.13). Southwestern California is actually on the Pacific plate. The fault connects a series of short spreading ridges in the Gulf of California, with the Cascadia subduction zone that starts in northern California and extends to Canada. Shallow earthquakes are common, and often devastating, along the boundary, but there are no active volcanoes along the fault system.
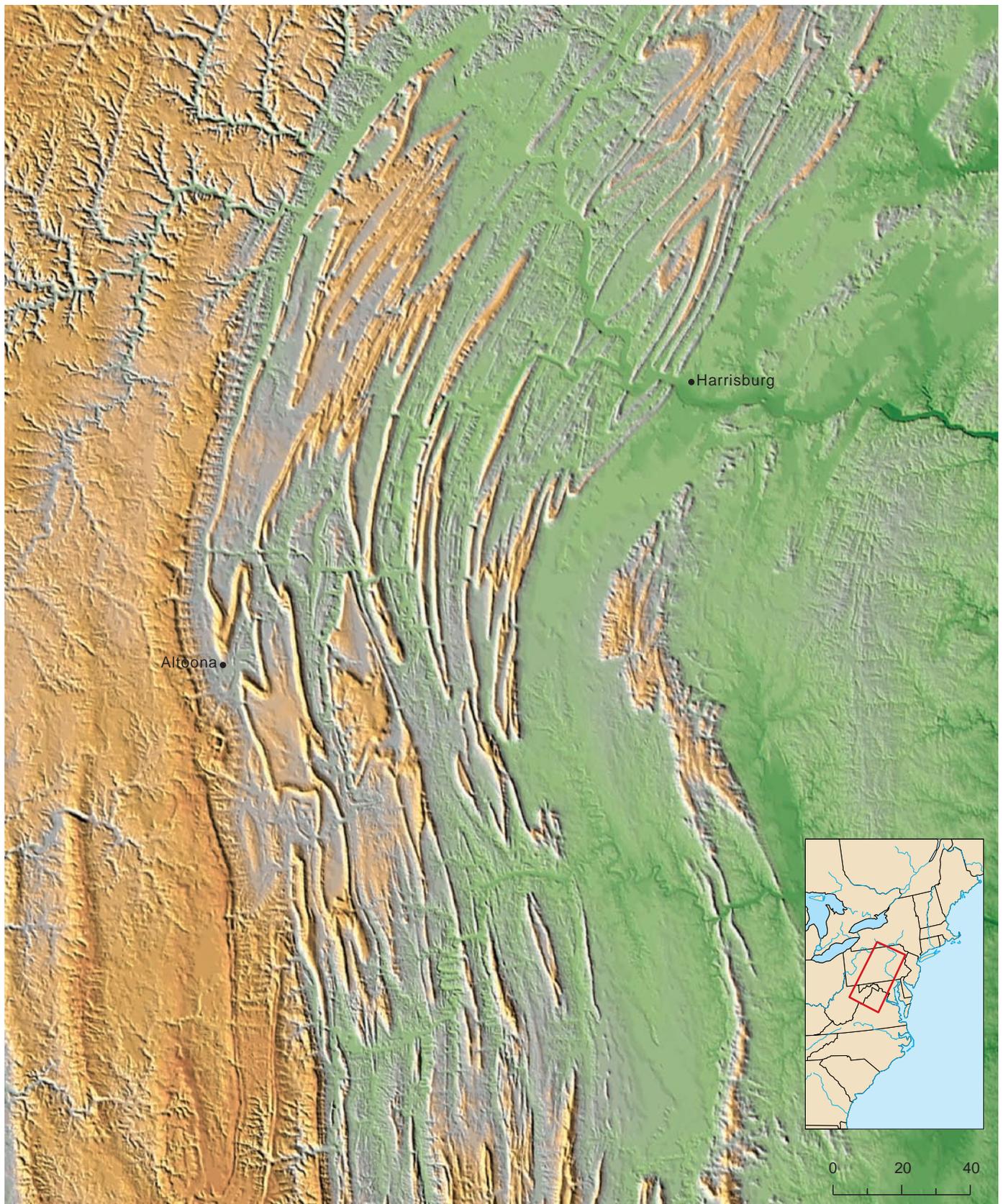
FIGURE 17.17   The spectacular fold belt of the Appalachian Mountains of the eastern United States, is one of the great surface expressions of a convergent plate boundary. The deformed strata form ridges that zigzag across the terrain, showing the style of deformation produced as the African plate drifted westward and impinged against the North American plate. Deformation dies out rapidly to the northeast. Small granitic plutons intruded the mountain belt, but are not obvious on this topographic map. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

Inactive
fracture
zone
(Both blocks move
in same direction)

Active fault zone
(Blocks move in
opposite directions)

Inactive
fracture
zone
(Both blocks move
in same direction)

FIGURE 17.18 **The relative movement of plates at a ridge-ridge transform fault** changes along the fracture zone. The plates are moving away from the ridge, but an active fault only lies between the two ridge segments. Here plates on opposite sides of the fault move in opposite directions. Beyond the spreading ridge, however, the plates move in the same direction on both sides of the fault.
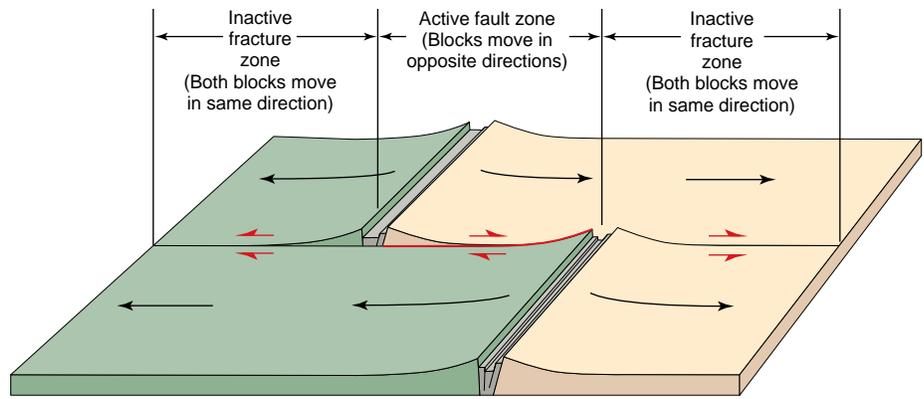
PLATE MOTION

> The motion of a series of rigid plates on a sphere can be complex. Each plate moves as an independent unit, in different directions and at different velocities than any other plates.

What is unique about the motion of plates on a sphere?

The geometry of a curved plate moving on a sphere was worked out more than 200 years ago by Swiss mathematician Leonhard Euler (1707–1783) and now provides the basis for analyzing plate motion. The basic analysis of this type of motion is illustrated in Figure 17.19A. In the figure, the motion of the yellow plate, with respect to the orange plate, is a rotation around the axis A_R (the **axis of plate rotation**), one pole of which is the point P (the **pole of rotation**). Note that the pole of the plate rotation is completely independent of Earth's spin axis and has no relation to the magnetic poles.

Several important facts about plate motion are immediately apparent from Figure 17.19A. First, different parts of a plate move with different velocities. Maximum
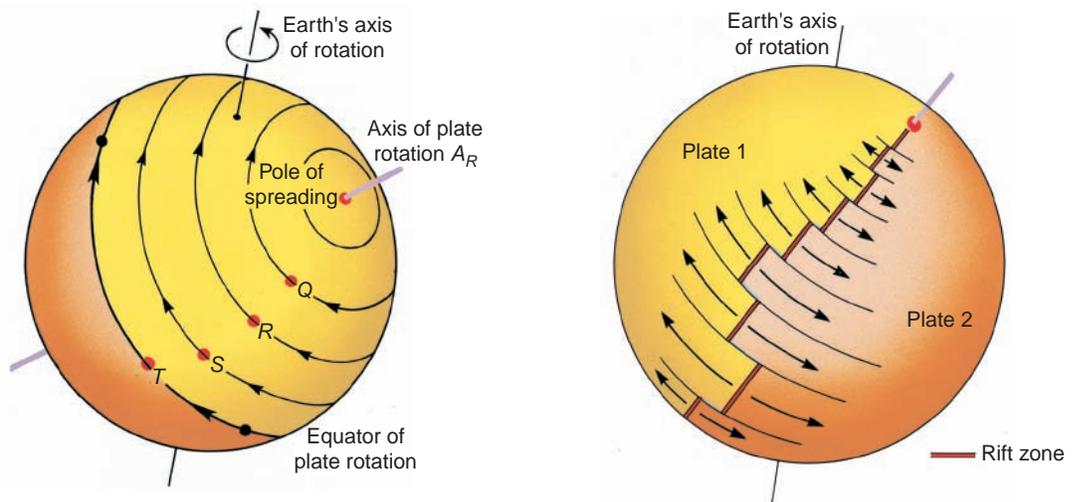
(A) Plate motion can be easily understood by considering a plate that covers an entire hemisphere. Each point on the plate would move along a line of latitude with respect to the pole of spreading, P.

(B) The motion of Plate 1 with respect to Plate 2 can be described as rotation around some imaginary axis. Segments of the oceanic ridge lie on lines of longitude that pass through the pole, and transform faults lie on lines of latitude. The rate of spreading is at a maximum at the equatorial line and zero at the pole.

FIGURE 17.19 **Plate motion on a sphere** requires that the plates rotate around an axis of spreading, the pole of which is called a pole of spreading. Plates always move parallel to the transform faults and along circles of latitude perpendicular to the spreading axis.
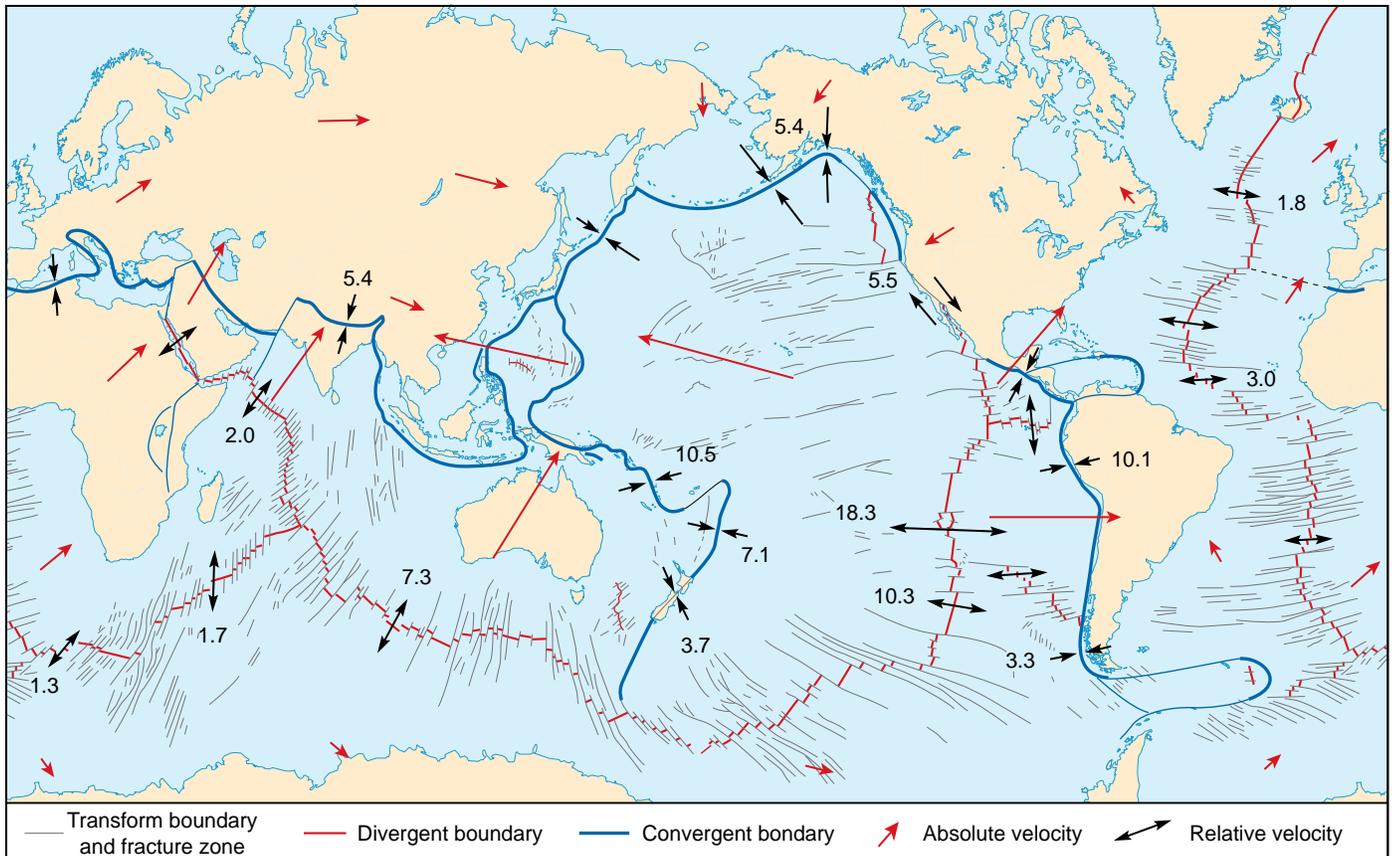
FIGURE 17.20 **Velocities and directions of plate movement** show how the major plates are currently interacting. Compare the absolute plate motions (red arrows) with the relative plate movements. The lengths of the arrows are proportional to the velocity of plate movement; the numbers represent velocity in centimeters per year.

velocity occurs at the equator of rotation and minimum velocity at the poles of rotation. This fact may best be understood by considering a plate so large that it covers an entire hemisphere. All motion occurs around the axis of plate rotation. The pole of rotation has zero velocity because it is a fixed point around which the hemispheric shell moves. Points *Q, R,* and *S* have progressively higher velocities, with a maximum velocity at point *T,* which lies on the equator of rotation.

Note also that transform faults lie on lines of latitude relative to a pole of rotation (Figure 17.19B). This condition holds for most transform faults in nature, as can be seen on a topographic map of the Atlantic. (See the inside covers of this book.) We can thus use the orientation of transform faults to locate the pole of rotation for each plate.

Spreading ridges are linear and are usually perpendicular to plate motion. They are commonly oriented along lines of longitude relative to the plate's pole of rotation. It is important to understand that the poles of rotation do not necessarily lie on the plate in question.

The direction of movement of the major plates, in relation to their neighbors, can be determined in several ways. As we have seen, the trends of the oceanic ridges and the associated transform faults are related to the location of the pole of rotation. Indications of movement are also drawn from seismic data (Chapter 18), from the relative ages of different regions of the seafloor (Figure 17.11 and Chapter 19), and from the ages of chains of volcanic islands and seamounts (Chapter 22). From these data, geologists have determined the motion of the present tectonic plates. This motion is summarized in Figure 17.20.

The Pacific plate is moving in a general northwesterly direction, from the East Pacific rise toward the system of trenches in the western Pacific. It is bordered by several small plates along the subduction zone, so the relative motion at each

What geologic features indicate direction and rates of plate motion?

trench differs from the general trend. The American plates are moving westward from the mid-Atlantic ridge, converging with the Pacific, Cocos, and Nazca plates. The Australian plate is moving northward.

Africa and Antarctica, however, present a different situation. Both are nearly surrounded by ridges, and they have no associated subduction zones to accommodate the new lithosphere generated along the ridges. Therefore, the ridges must be moving outward. The African and Antarctic plates illustrate a very important point: *Plate margins are not fixed but can move as much as the plates themselves can.* If two divergent plate margins are not separated by a subduction zone, new lithosphere is formed at each spreading axis, but none is destroyed between them. The plate between the ridges is continually enlarged, so the ridges themselves must move apart.

Another important change is in the lengths of plate margins. An oceanic ridge is essentially a fracture in the lithosphere that can grow longer. A good example is the ridge in the Atlantic Ocean. It has grown and lengthened considerably since spreading began to separate South America from Africa.

RATES OF PLATE MOTION

> Magnetic reversals on the ocean floor provide a timing mechanism to measure the relative velocity of plate motion. Absolute plate velocities can be measured compared to a fixed reference frame. The results show that plates move at different rates, ranging from 1 to 18 cm/yr.

Velocities of plates can be determined in two fundamentally different ways. The **relative velocity** compares the movement of one plate with respect to another plate. The **absolute velocity** compares plate movement to a fixed reference frame. The difference between the two measurements can be understood with a familiar example. Imagine you are standing on an overpass. Beneath you, two cars are traveling in opposite directions; Their speedometers say they are moving 50 km/hr. Compared to one another, their *relative velocity* is 100 km/hr, but compared to your fixed position, both cars have an *absolute velocity* of 50 km/hr.

To determine the relative velocity of a certain section of seafloor, all you need to know is its age and how far it is from the ridge. We described in a previous section how the age of the seafloor (Figure 17.11) can be estimated using the oscillation of Earth's magnetic field. The distance from the ridge axis and the age of the seafloor can then be used to calculate the velocity of plate movement. Transform faults show the direction of movement.

Absolute plate motion can be established in several ways. If we assume that hotspots are essentially stationary, then the tracks of hotspot volcanoes are tangible records of a plate's absolute velocity and its direction of movement. Absolute plate velocities can also be measured directly, using satellites and lasers. In one technique, a narrow beam of light is emitted from an Earth-bound laser and bounced off an orbiting satellite whose position is known precisely. The light is collected at the surface of Earth again, and the elapsed time is determined. This method allows the location of the laser to be determined to within a millimeter. If the location of the station is repetitively determined, the absolute motion of plate can be accurately measured. Global positioning satellites can be used in a similar way as described on p. 592.

The velocities and directions measured in this fashion are complementary records of plate movement (Figure 17.20). It is apparent that the plates are moving at significantly different rates, ranging from 1 to 20 cm/y. The Pacific, Nazca, Cocos, and Indian plates are moving faster than the slower moving North American, South American, and Antarctic plates. To better understand the significance of the difference between absolute and relative plate motions, compare the relative movement of Africa with respect to Europe with the absolute motion of
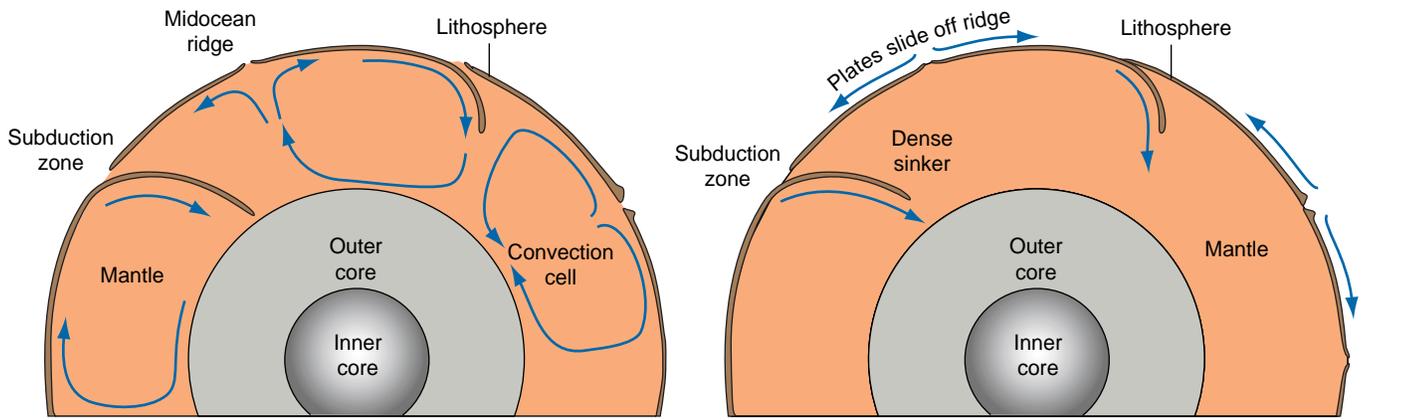
(A) Convection in the mantle drives the movement of the plates. Many characteristics of plate motion are inconsistent with this hypothesis.

(B) Forces generated by the plates themselves cause the plates to sink into the mantle because of their density and to slide off the midocean ridges.

FIGURE 17.21   **Two suggested models of plate tectonics** show how flow in the mantle might be related to plate movement.

both plates. The relative movement of Europe is south toward the African plate, since they are separated by a subduction zone. However, the absolute motion of both plates is northward. Europe is moving slower than Africa and consequently a convergent margin has developed between them. This can be likened to two cars traveling in the same direction, in the same lane, but with the trailing car going faster than the leading car. A collision is inevitable. Likewise, rifting is separating Arabia from Africa, but the absolute motion of both plates is northward, with Arabia moving faster than the African plate.

The fastest-moving plates are those in which a large part of the plate boundary is a subduction zone, and the slower-moving plates are those that lack subducting boundaries or that have large continental blocks embedded in them. This relation has been interpreted by some geologists as evidence that the tectonic plates are part of Earth's convection system and that plate motion is largely a result of cold, dense plates sinking into the mantle.

DRIVING MECHANISMS FOR PLATE TECTONICS

> Forces that influence the motion of a plate include (1) slab-pull, (2) ridge-push, (3) basal drag, (4) friction along transform faults, and (5) friction between the converging slabs of the lithosphere in a subduction zone. Slab-pull and ridge-push probably drive plate movement.

It should be clear by now that the tectonic plates move. But why do they move? Ultimately, the energy that drives plate tectonics is heat transported out of the hot core and mantle to Earth's surface. Plate tectonics is a type of convection and is the result of Earth's effort to cool and reach thermal equilibrium with cold space.

One of the first models to explain the driving mechanism of plate tectonics suggested that **convection cells** within the mantle carried the plates, and that the plates played little or no active part in the convection (Figure 17.21A). The rising limbs of the convecting cells in the mantle would therefore determine the positions of the oceanic ridges. The convecting mantle would cause the lithosphere to split, and the moving mantle would carry the lithosphere laterally toward the subduction zone. The descending cell would mark the location of the trench and would drag the lithosphere down into the mantle. Movements in the asthenosphere were thought to be coupled strongly to the lithosphere. In other words, convection cells in the mantle supposedly *caused* ridges, trenches, and the

Is convection of the mantle the only force responsible for plate movement?

The magnetic character of rocks on the seafloor was a major factor in deciphering the reality of plate tectonics. But given the remoteness of the seafloor, how is this paleomagnetic data collected?

Specially designed *magnetometers* (instruments designed to measure the strength or orientation of the present-day magnetic field) are towed behind research ships. (These magnetometers were originally designed and used to detect submarines travelling below the surface during World War II.) The position of the magnetometer and the strength of the magnetic field are simultaneously recorded. The result is a long strip map showing where the strength of the magnetic field is higher or lower than normal, as shown in the illustration.

Note that the pattern of variation in the seafloor magnetism is not as regular as a simple sine wave. The highs and lows are not separated by equal distances. In spite of the irregular widths of the bands, you can see that the patterns are symmetrical on either side of the ridge axis.

One way to interpret the map was to claim that each band had fewer (the lows) or more (the highs) magnetic minerals. But this did little to explain the overall symmetry of the patterns or the correlation of the middle high with a midoceanic ridge. It was soon realized that a better interpretation was that the polarity of Earth's field changed. In addition, each band must have formed anciently at a ridge and was then split apart. According to this interpretation, the magnetic highs lie over regions where the volcanic rocks on the seafloor erupted when the orientation of the mag-

(Photograph by Lamont Doherty Earth Observatory/Columbia University)

netic field was the same as it is today. Thus, the modern magnetic field and the paleomagnetism stored in the rocks add to one another. The lows are areas where the paleomagnetic orientation is opposite that of the present field and cancels out part of the current magnetic field. To make a map like this one, the ship must traverse back and forth across the area many times. The strips are then laid side by side and interpreted as representing stripes of rocks with different polarities and therefore different ages.

Magnetic maps can also be constructed for areas above sea level and they reveal much about the structure of the crust (page 603). The magnetic field variations shown on these maps are strongly affected by the amount of magnetite in the rocks and to a lesser degree by the polarity of the magnetic field at the time the rocks formed.
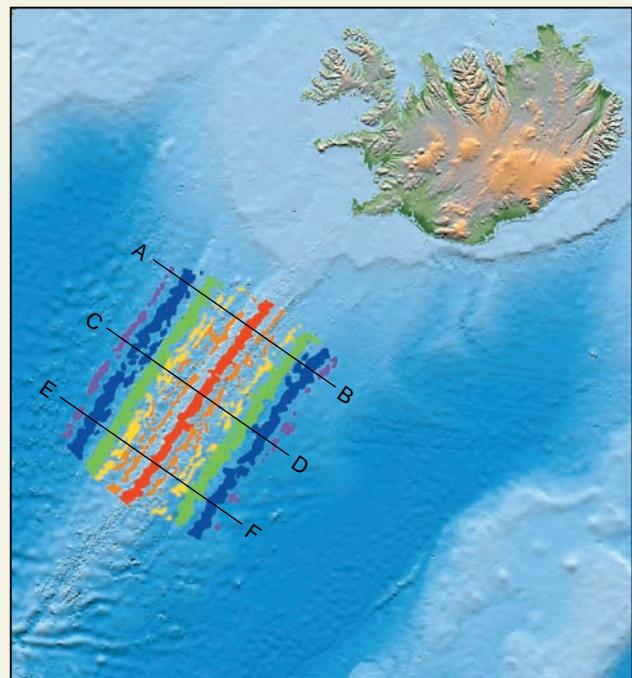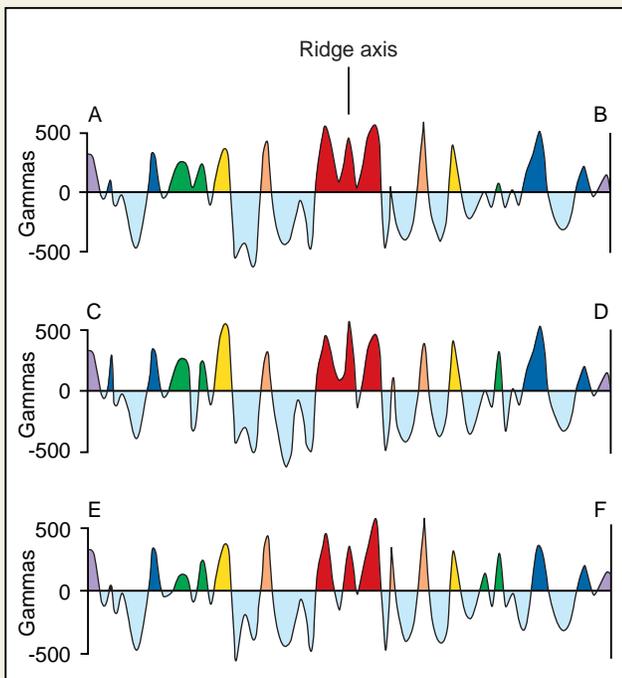
(Courtesy of Ken Perry, Chalk Butte, Inc.)
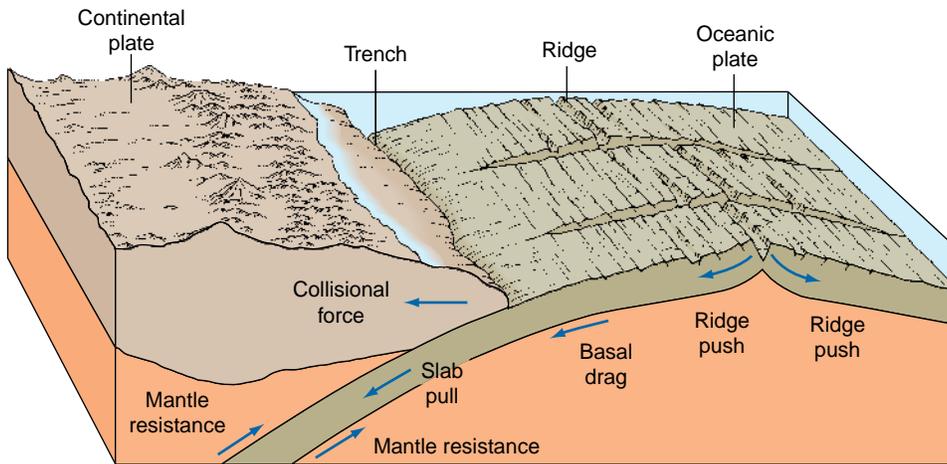
FIGURE 17.22   Forces active on the plates are shown with arrows on the front of this block diagram. They include slab-pull, ridge-push, basal drag, and friction along transform faults and in the subduction zone.

movement of plates. The distance between plate boundaries was thought to be caused by the size of the convection cell.

A more successful model of convection theory considers the plates themselves to be active participants in the convection process (Figure 17.21B), not passive passengers on a churning mantle. In this model, the lithosphere is the cold upper layer of the convection cell. Because of its greater density, the lithosphere eventually sinks. Subduction occurs *not* because the plate is pulled down by the descending mantle, but simply because the plate becomes denser than the underlying asthenosphere. In addition, the upward flow of the asthenosphere beneath a spreading ridge is *not* the cause of seafloor spreading, but a consequence of the plates moving apart. Thus, the plate may be moved by forces that are largely independent of the convection of the mantle beneath the plate.

To better understand why the plates move, let us examine the forces that act on them. The most important forces are shown diagrammatically in Figure 17.22.

The forces that influence motion of the plate include:

1. **Slab-pull**: A pull exerted on the plate as the dense oceanic slab descends under its own weight into the asthenosphere in a subduction zone. In essence, the slab sinks because it is denser than the asthenosphere, and it pulls the rest of the lithosphere along with it.

2. **Ridge-push**: Gravity makes the lithosphere slip off the elevated ridge.

3. **Basal drag**: Resistance to flow exerted on the bottom of the plate by the underlying asthenosphere; shear at the base of the plate. Depending on the direction of flow in the asthenosphere, this could aid or hinder plate movement.

4. **Mantle resistance**: Frictional resistance to the movement of the subducting plate through the asthenosphere and mesosphere.

5. **Friction:** Resistance along transform faults and between the converging slabs of lithosphere in a subduction zone; shear between two plates.

Inasmuch as each plate has a nearly constant velocity—is neither accelerating nor decelerating—most researchers believe that the forces that drive the plates are approximately balanced by forces that resist their movement. Thus, the driving forces provided by slab-pull and ridge-push are nearly balanced by resisting forces such as basal drag, mantle resistance, and friction at plate boundaries.

As noted in the last section, the absolute velocity of a plate is strongly related to the proportion of its margin that is subducting. For example, plates such as the Pacific and Cocos plates, which have about 40% of their margins represented by subduction zones, have high plate velocities (greater than 5 cm/yr). Plates such as the North American, which have smaller proportions of subducting margins, move more slowly (1 to 3 cm/yr). Hence, many researchers have concluded that

What is the difference between ridge-push and slab-pull?

FIGURE 17.23   Convection in a lava lake in Hawaii simulates convection and plate motion. As fresh, molten lava rises by convection, slightly older chilled lava (darker) is shoved aside to sink at some other zone in the crater (out of view). Note the transform fault near the middle of the view and the differential rate of spreading revealed by the different widths of recently chilled lava on either side of the spreading line. The front edge of the view is about 50 m wide. *(Courtesy of W. Duffield, U.S. Geological Survey)*

slab-pull is a major driving force. The correlation between the rate of plate motion and the proportion of subducting edges is so strong that other forces may be only minor. Slab-pull is aided by the metamorphic phase transitions that occur in subducting plates. As the plate moves deeper into the mantle, low-density phases convert into higher-density phases. These changes effectively create a sinker that pulls the plate deeper into the mantle.

Several examples illustrate the role of slab-pull in plate convection. If a large cauldron of molten metal is allowed to cool, a skin of solid metal forms on the surface and, because it is colder and denser than the liquid, the solid skin eventually founders and sinks into the molten liquid, thereby stirring the melt. The same process has been observed on a larger scale in lava lakes formed in the pit craters of Hawaiian volcanoes (Figure 17.23). As molten lava cools, a solid layer forms over the lake, but the rigid layer splits into slabs that move about. Eventually a slab sinks, because it is cooler and denser than the underlying liquid, pulling the solid crust apart. Large slabs of the crust break up and split, causing molten lava to rise from below and create a zone of new cooling crust. Many features of plate tectonics are exhibited in Figure 17.23. Spreading ridges, transform faults, and subduction zones are all observed.

Ridge-push is probably the next most important, motivator of tectonic plates. Ridge-push is related to the elevation of the ridge, which in turn is caused by the hot buoyant mantle that rises beneath it. The asthenosphere acts as a slippery layer beneath the slab, and the lithosphere simply slides downhill.

Observations of plate movement and theoretical calculations both suggest that the forces supplied by slab-pull and ridge-push are so large that the question may become, What slows the plates down? The major retarding force is probably resistance in the mantle to the sinking of a subducting slab. Friction at plate boundaries must also slow the movement of the plates. Basal drag, once thought to be the prime motivator of plate movement, is now relegated to a minor role. Basal drag may actually slow the movement of a plate.

From the perspective supplied by considering the forces acting on plates, you can think of the plates and the underlying mantle as forming a single, though complex system, with each portion of the system affecting the others. In fact, convective flow in the mantle may have a radically different aspect than the motion of lithospheric plates seen at the surface of Earth.

KEY TERMS

absolute velocity (p. 502)
axis of plate rotation (p. 500)
basal drag (p. 505)
continental drift (p. 482)
convection cell (p. 503)
convergent boundary (p. 497)
divergent boundary (p. 496)

friction (p. 505)
magnetic anomaly (p. 490)
magnetic reversal (p. 490)
mantle resistance (p. 505)
normal polarity (p. 489)
paleomagnetism (p. 489)
Pangaea (p. 483)

polarity chron (p. 490)
pole of rotation (p. 500)
relative velocity (p. 502)
reversed polarity (p. 490)
ridge-push (p. 505)
rift valley (p. 488)
seafloor spreading (p. 488)

slab-pull (p. 505)
strike-slip fault (p. 498)
subduction (p. 497)
subduction zone (p. 497)
tectonic plate (p. 495)
transform fault (p. 498)

REVIEW QUESTIONS

1. Briefly explain the theory of plate tectonics.
2. Distinguish between continental drift and plate tectonics.
3. List three major evidences for continental drift.
4. Why did it take so long for the scientific community to accept the movement of the continents?
5. Why are there paleomagnetic stripes on the ocean floor?
6. Where do you expect to find the youngest oceanic lithosphere?
7. In the Pacific Ocean basin, where is the oldest oceanic lithosphere? How is its location explained by plate tectonics?
8. Describe the types of plate boundaries, and give an example of each.
9. Sketch a simple map of a part of an oceanic ridge, and draw arrows to show the relative motion along ridge-to-ridge transform faults.
10. Describe the geometry of lithospheric plate motion over the planet.

11. How is the pattern of a series of transform faults along a plate boundary related to the pole of rotation?
12. Explain how plate margins, as well as the plate itself, can migrate.
13. Explain the origin of the following features in the context of plate tectonics: (a) the Ural Mountains, (b) the Alps, (c) the Mid-Atlantic Ridge, (d) Hawaii, (e) the San Andreas Fault, (f) the Andes Mountains, and (g) volcanoes in Italy.
14. How fast are the plates moving? How do we determine rates of plate motion?
15. Draw a cross section showing a tectonic plate with a divergent and a convergent boundary, and label the major forces acting on the plate.
16. Explain the difference between (a) the convection model of plate motion, in which the mantle carries the plates, and (b) a model in which the plates themselves drive plate tectonics.

ADDITIONAL READINGS

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MULTIMEDIA TOOLS

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

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

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

• Animations of plate movement
• Animations of the breakup of the continents
• Slide shows with examples of tectonic processes
• A direct link to the Companion Website