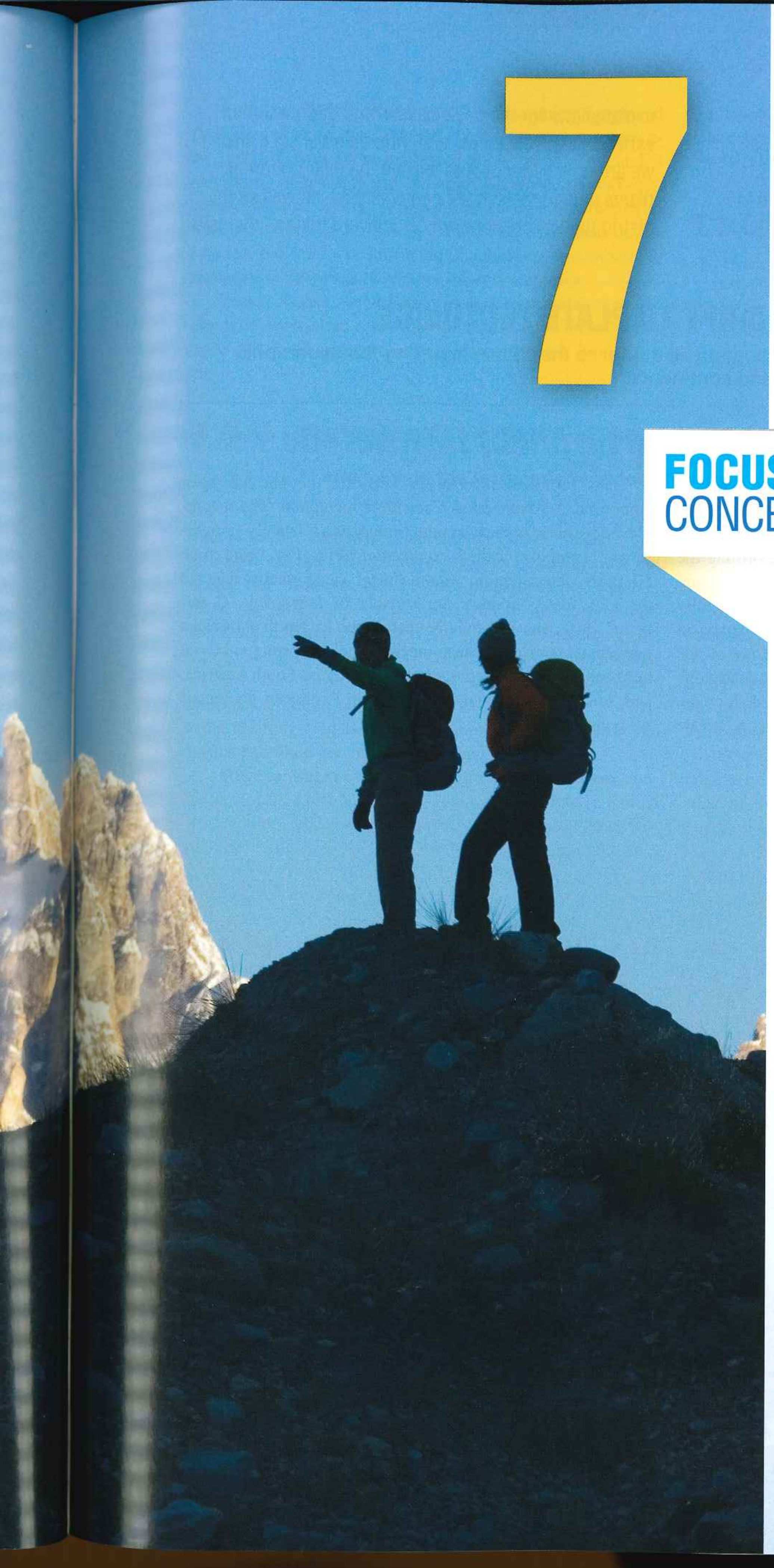
7

Plate Tectonics: A Scientific Revolution Unfolds



FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

7.1 Discuss the view that most geologists held prior to the 1960s regarding the geographic positions of the ocean basins and continents.

7.2 List and explain the evidence Wegener presented to support his continental drift hypothesis.

7.3 Discuss the two main objections to the continental drift hypothesis.

7.4 List the major differences between Earth's lithosphere and asthenosphere and explain the importance of each in the plate tectonics theory.

7.5 Sketch and describe the movement along a divergent plate boundary that results in the formation of new oceanic lithosphere.

7.6 Compare and contrast the three types of convergent plate boundaries and name a location where each type can be found.

7.7 Describe the relative motion along a transform plate boundary and locate several examples on a plate boundary map.

7.8 Explain why plates such as the African and Antarctic plates are getting larger, while the Pacific plate is getting smaller.

7.9 List and explain the evidence used to support the plate tectonics theory.

7.10 Describe two methods researchers use to measure relative plate motion.

7.11 Summarize what is meant by plate–mantle convection and explain two of the primary driving forces of plate motion.

Climber ascending Chang Zheng Peak near Mount Everest.
(Photo by Stock Connection/SuperStock)

Plate tectonics is the first theory to provide a comprehensive view of the processes that produced Earth's major surface features, including the continents and ocean basins. Within the framework of this theory, geologists have found explanations for the basic causes and distribution of earthquakes, volcanoes, and mountain belts. Further, we are now better able to explain the distribution of plants and animals in the geologic past, as well as the distribution of economically significant mineral deposits.

7.1

FROM CONTINENTAL DRIFT TO PLATE TECTONICS

Discuss the view that most geologists held prior to the 1960s regarding the geographic positions of the ocean basins and continents.

Prior to the late 1960s, most geologists held the view that the ocean basins and continents had fixed geographic positions and were of great antiquity. Researchers came to realize that Earth's continents are not static; instead, they gradually migrate across the globe. Because of these movements, blocks of continental material collide, deforming the intervening crust, thereby creating Earth's great mountain chains (**FIGURE 7.1**). Furthermore, landmasses occasionally split apart. As continental blocks separate, a new ocean basin emerges between them. Meanwhile, other portions of the seafloor plunge into the mantle. In short, a dramatically different model of Earth's tectonic processes emerged. Tectonic processes are processes that deform Earth's crust to create major structural features, such as mountains, continents, and ocean basins.

This profound reversal in scientific thought has been appropriately described as a *scientific revolution*. The revolution began early in the twentieth century as a relatively straightforward proposal called *continental drift*. For more than 50 years, the scientific establishment categorically rejected the idea that continents are capable of movement. Continental drift was particularly distasteful to North American geologists, perhaps because much of the supporting evidence had been gathered from the continents of Africa, South America, and Australia, with which most North American geologists were unfamiliar.

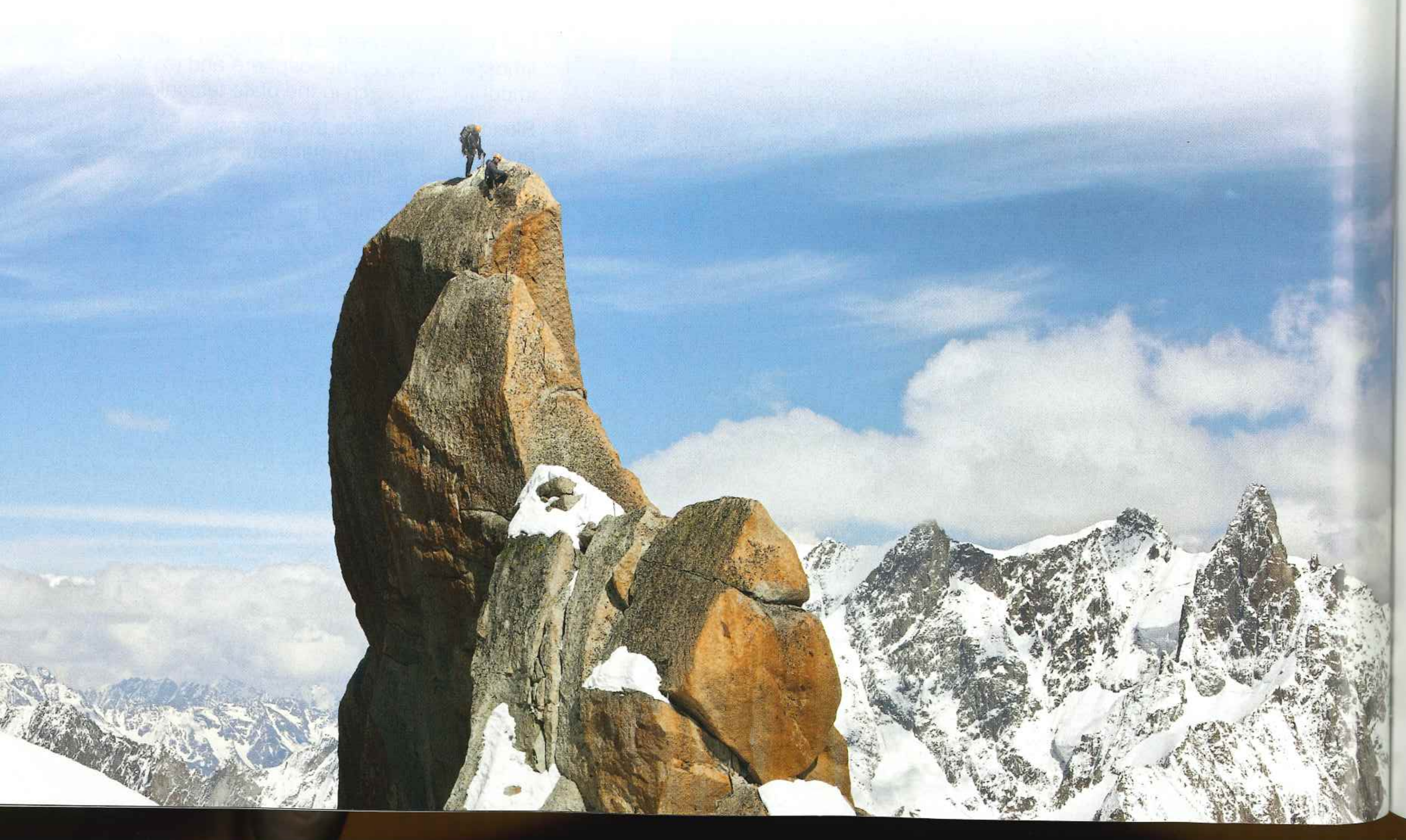


FIGURE 7.1 Rock Pinnacle near Mount Blanc The Alps were created by the collision of the African and Eurasian plates. (Photo by Bildagentur Walhaeus/AGE Fotostock)

Following World War II, modern instruments replaced rock hammers as the tools of choice for many researchers. Armed with more advanced tools, geologists and a new breed of researchers, including *geophysicists* and *geochemists*, made several surprising discoveries that began to rekindle interest in the drift hypothesis. By 1968 these developments had led to the unfolding of a far more encompassing explanation known as the *theory of plate tectonics.*

In this chapter, we will examine the events that led to this dramatic reversal of scientific opinion. We will also briefly trace the development of the *continental drift hypothesis*, examine why it was initially rejected, and consider the evidence that finally led to the acceptance of its direct descendant—the theory of plate tectonics.

7.1 CONCEPT CHECKS

1. Briefly describe the view held by most geologists regarding the ocean basins and continents prior to the 1960s.
2. What group of geologists were the least receptive to the continental drift hypothesis? Explain.

7.2 CONTINENTAL DRIFT: AN IDEA BEFORE ITS TIME

List and explain the evidence Wegener presented to support his continental drift hypothesis.

The idea that continents, particularly South America and Africa, fit together like pieces of a jigsaw puzzle came about during the 1600s, as better world maps became available. However, little significance was given to this notion until 1915, when Alfred Wegener (1880–1930), a German meteorologist and geophysicist, wrote *The Origin of Continents and Oceans.* This book set forth the basic outline of Wegener's hypothesis, called **continental drift**, which dared to challenge the long-held assumption that the continents and ocean basins had fixed geographic positions.

Wegener suggested that a single **supercontinent** consisting of all Earth's landmasses once existed.* He named this giant landmass **Pangaea** (pronounced "Pan-jee-ah," meaning "all lands") (**FIGURE 7.2**). Wegener further hypothesized that about 200 million years ago, during the early part of the Mesozoic era, this supercontinent began to fragment into smaller landmasses. These continental blocks then "drifted" to their present positions over a span of millions of years.

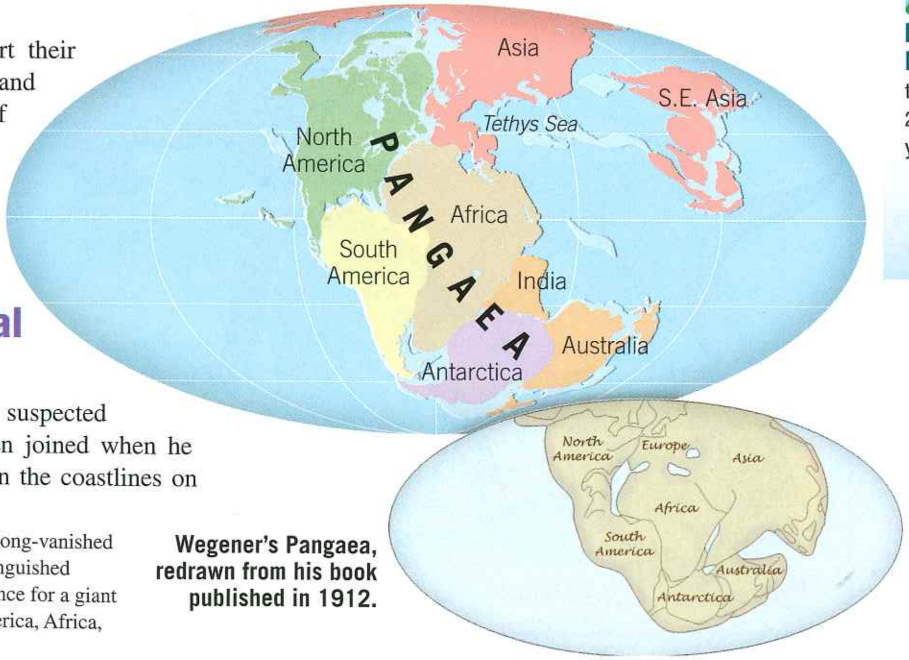
Wegener and others who advocated the continental drift hypothesis collected substantial evidence to support their point of view. The fit of South America and Africa and the geographic distribution of fossils and ancient climates all seemed to buttress the idea that these now separate landmasses were once joined. Let us examine some of this evidence.

Evidence: The Continental Jigsaw Puzzle

Like a few others before him, Wegener suspected that the continents might once have been joined when he noticed the remarkable similarity between the coastlines on opposite sides of the Atlantic Ocean. However, other Earth scientists immediately challenged Wegener's use of present-day shorelines to fit these continents together. These opponents correctly argued that shorelines are continually modified by wave erosion and depositional processes. Even if continental displacement had taken place, a good fit today would be unlikely. Because Wegener's original jigsaw fit of the continents was crude, it is assumed that he was aware of this problem (see Figure 7.2).

Scientists later determined that a much better approximation of the outer boundary of a continent is the seaward edge of its continental shelf, which lies submerged a few hundred meters below sea level. In the early 1960s, Sir Edward Bullard and two associates constructed a map that pieced together the edges of the continental shelves of South America and Africa at a depth of about 900 meters (3000 feet) (**FIGURE 7.3**). The remarkable fit that was obtained was more precise than even these researchers had expected.

Modern reconstruction of Pangaea



Wegener's Pangaea, redrawn from his book published in 1912.

SmartFigure 7.2 Reconstructions of Pangaea This is as it is thought to have appeared 200 million years ago.

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*Wegener was not the first person to conceive of a long-vanished supercontinent. Edward Suess (1831–1914), a distinguished nineteenth-century geologist, pieced together evidence for a giant landmass consisting of the continents of South America, Africa, India, and Australia.

FIGURE 7.3 Two of the Puzzle Pieces Best fit of South America and Africa along the continental slope at a depth of 500 fathoms (about 900 meters [3000 feet]).

Evidence: Fossils Matching Across the Seas

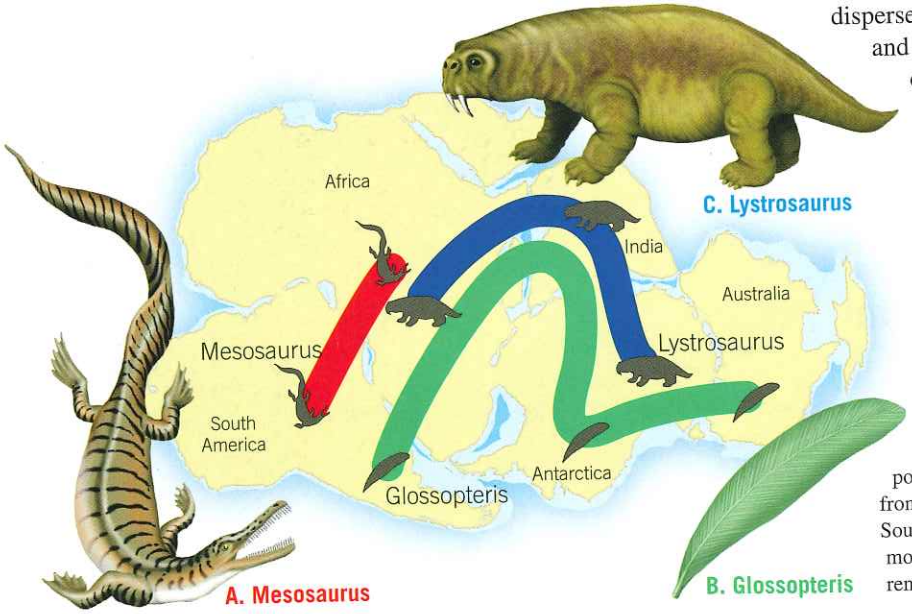
Although the seed for Wegener's hypothesis came from the remarkable similarities of the continental margins on opposite sides of the Atlantic, it was when he learned that identical fossil organisms had been discovered in rocks from both South America and Africa that his pursuit of continental drift became more focused. Through a review of the literature, Wegener learned that most paleontologists (scientists who study the fossilized remains of ancient organisms) were in agreement that some type of land connection was needed to explain the existence of similar Mesozoic age life-forms on widely separated landmasses. Just as modern life-forms native to North America are quite different from those of Africa and Australia, during the Mesozoic era, organisms on widely separated continents should have been distinctly different.

Mesosaurus To add credibility to his argument, Wegener documented cases of several fossil organisms found on different landmasses, despite the unlikely possibility that their living forms could have crossed the vast ocean presently separating them (**FIGURE 7.4**). A classic example is *Mesosaurus*, a small aquatic freshwater reptile whose fossil remains are limited to black shales of the Permian period (about 260 million years ago) in eastern South America and southwestern Africa. If *Mesosaurus* had been able to make the long journey across the South Atlantic, its remains would likely be more widely distributed. As this is not the case, Wegener asserted that South America and Africa must have been joined during that period of Earth history.

How did opponents of continental drift explain the existence of identical fossil organisms in places separated by thousands of kilometers of open ocean? Rafting, transoceanic land bridges (isthmian links), and island stepping stones were the most widely invoked explanations for these migrations (**FIGURE 7.5**). We know, for example, that during the Ice Age that ended about 8000 years ago, the lowering of sea level allowed mammals (including humans) to cross the narrow Bering Strait that separates Russia and Alaska. Was it possible that land bridges once connected Africa and South America but later subsided below sea level? Modern maps of the seafloor substantiate Wegener's contention that if land bridges of this magnitude once existed, their remnants would still lie below sea level.

Glossopteris Wegener also cited the distribution of the fossil "seed fern" *Glossopteris* as evidence for the existence of Pangaea (see Figure 7.4). This plant, identified by its tongue-shaped leaves and seeds that were too large to be carried by the wind, was known to be widely dispersed among Africa, Australia, India, and South America. Later, fossil remains of *Glossopteris* were also discovered in Antarctica.* Wegener also learned that these seed ferns and associated flora grew only in cool climates—similar to central Alaska. Therefore, he concluded that when these landmasses were joined, they were located much closer to the South Pole.

FIGURE 7.4 Fossil Evidence Supporting Continental Drift Fossils of identical organisms have been discovered in rocks of similar age in Australia, Africa, South America, Antarctica, and India—continents that are currently widely separated by ocean barriers. Wegener accounted for these occurrences by placing these continents in their pre-drift locations.



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*In 1912 Captain Robert Scott and two companions froze to death lying beside 35 pounds (16 kilograms) of rock on their return from a failed attempt to be the first to reach the South Pole. These samples, collected on the moraines of Beardmore Glacier, contained fossil remains of *Glossopteris*.

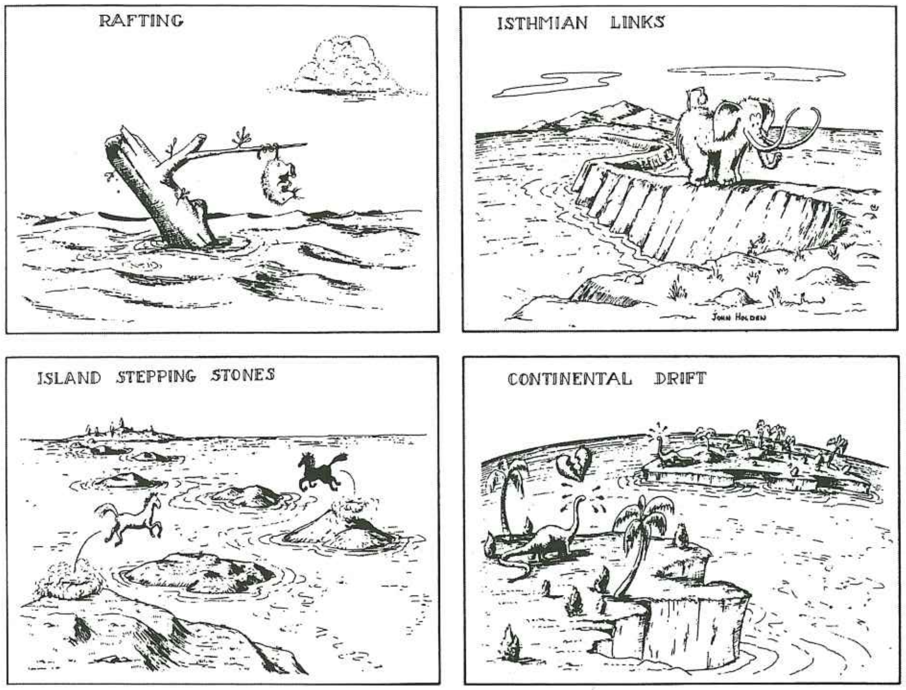

FIGURE 7.5 How Do Land Animals Cross Vast Oceans? These sketches illustrate various explanations for the occurrence of similar species on landmasses that are presently separated by vast oceans. (Reprinted with permission of John Holden)

Evidence: Rock Types and Geologic Features

Anyone who has worked a jigsaw puzzle knows that its successful completion requires that you fit the pieces together while maintaining the continuity of the picture. The "picture" that must match in the "continental drift puzzle" is one of rock types and geologic features such as mountain belts. If the continents were together, the rocks found in a particular region on one continent should closely match in age and type those found in adjacent positions on the once adjoining continent. Wegener found evidence of 2.2-billion-year-old igneous rocks in Brazil that closely resembled similarly aged rocks in Africa.

Similar evidence can be found in mountain belts that terminate at one coastline and reappear on landmasses across the ocean. For instance, the mountain belt that includes the Appalachians trends northeastward through the eastern United States and disappears off the coast of Newfoundland (**FIGURE 7.6A**). Mountains of comparable age and structure are found in the British Isles, western Africa, and Scandinavia. When these landmasses are positioned as they were about 200 million years ago, as shown in **FIGURE 7.6B**, the mountain chains form a nearly continuous belt.

Wegener described how the similarities in geologic features on both sides of the Atlantic linked these landmasses when he said, "It is just as if we were to refit the torn pieces of a newspaper by matching their edges and then check whether the lines of print run smoothly across. If they do, there is nothing left but to conclude that the pieces were in fact joined in this way."*

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*Alfred Wegener, *The Origin of Continents and Oceans*, translated from the 4th revised German ed. of 1929 by J. Birman (London: Methuen, 1966).

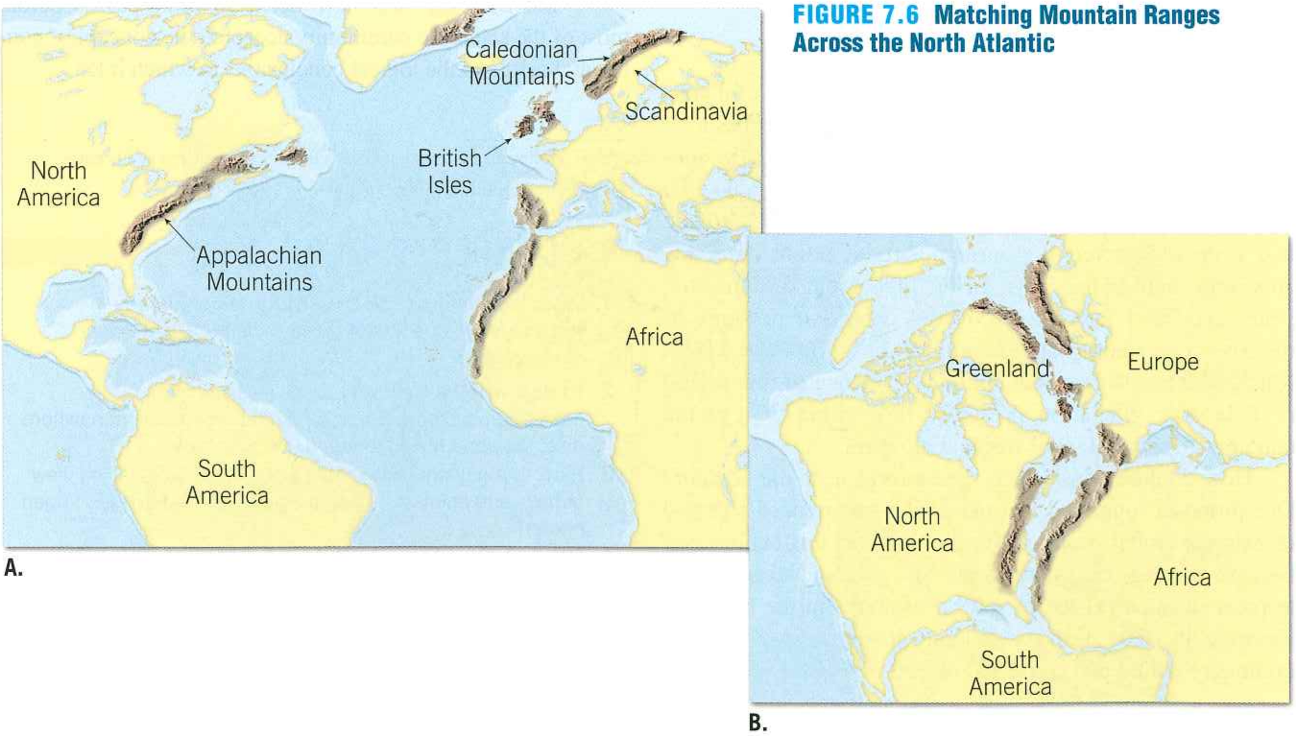
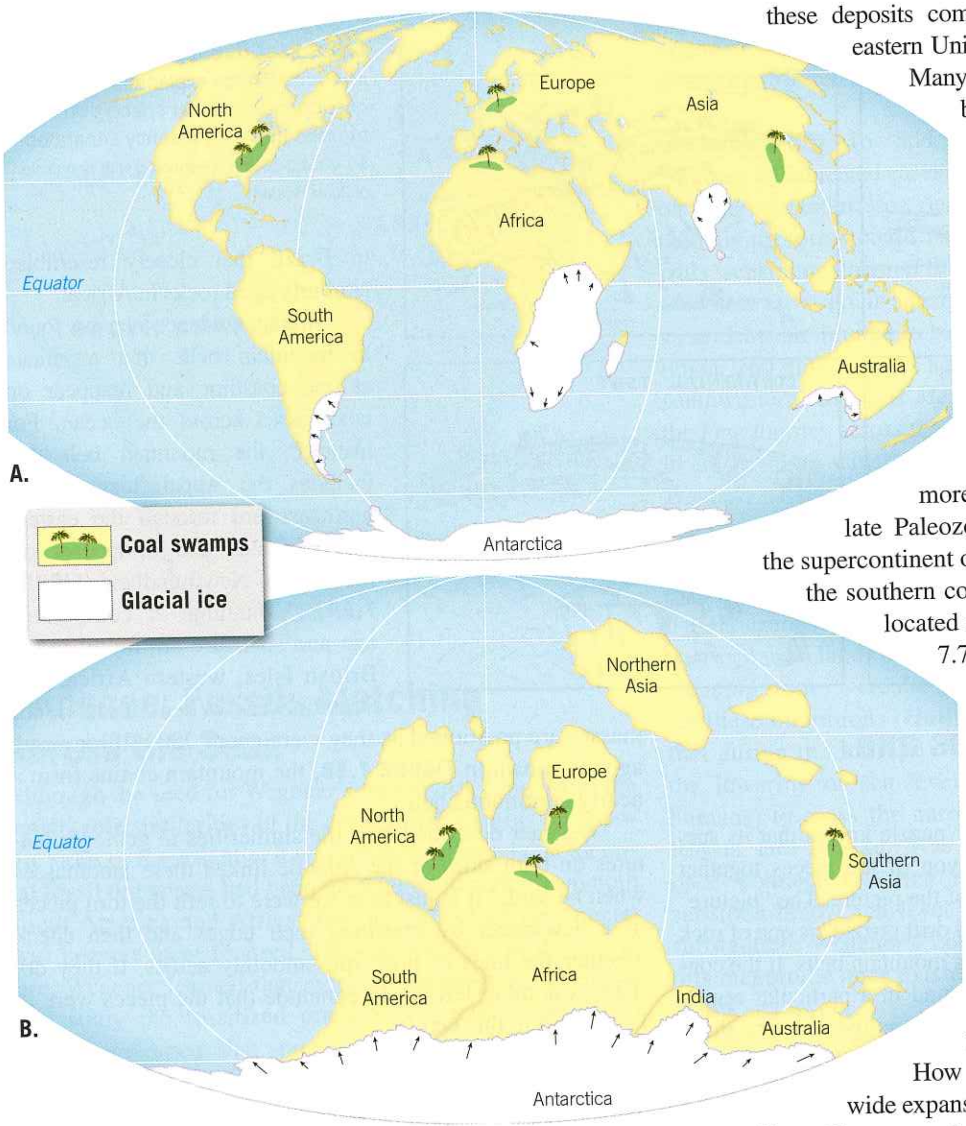


FIGURE 7.6 Matching Mountain Ranges Across the North Atlantic

FIGURE 7.7 Paleoclimatic Evidence for Continental Drift **A.** About 300 million years ago, ice sheets covered extensive areas of the Southern Hemisphere and India. Arrows show the direction of ice movement that can be inferred from the pattern of glacial striations and grooves found in the bedrock. **B.** The continents restored to their pre-drift positions accounts for tropical coal swamps that existed in areas presently located in temperate climates.



Evidence: Ancient Climates

Because Alfred Wegener was a student of world climates, he suspected that paleoclimatic (*paleo* = ancient, *climatic* = climate) data might also support the idea of mobile continents. His assertion was bolstered when he learned that evidence for a glacial period that dated to the late Paleozoic had been discovered in southern Africa, South America, Australia, and India. This meant that about 300 million years ago, vast ice sheets covered extensive portions of the Southern Hemisphere as well as India (**FIGURE 7.7A**). Much of the land area that contains evidence of this period of Paleozoic glaciation presently lies within 30° of the equator, in subtropical or tropical climates.

How could extensive ice sheets form near the equator? One proposal suggested that our planet experienced a period of extreme global cooling. Wegener rejected this explanation because during the same span of geologic time, large tropical swamps existed in several locations in the Northern Hemisphere. The lush vegetation in these swamps was eventually buried and converted to coal (**FIGURE 7.7B**). Today these deposits comprise major coal fields in the eastern United States and Northern Europe. Many of the fossils found in these coal-bearing rocks were produced by tree ferns that possessed large fronds—a feature consistent with warm, moist climates.** The existence of these large tropical swamps, Wegener argued, was inconsistent with the proposals that extreme global cooling caused glaciers to form in what are currently tropical areas.

Wegener suggested that a more plausible explanation for the late Paleozoic glaciation was provided by the supercontinent of Pangaea. In this configuration, the southern continents are joined together and located near the South Pole (see Figure 7.7B). This would account for the conditions necessary to generate extensive expanses of glacial ice over much of these landmasses. At the same time, this geography would place today's northern continents nearer the equator and account for the tropical swamps that generated the vast coal deposits.

How does a glacier develop in hot, arid central Australia? How do land animals migrate across wide expanses of the ocean? As compelling as this evidence may have been, 50 years passed before most of the scientific community accepted the concept of continental drift and the logical conclusions to which it led.

7.2 CONCEPT CHECKS

1. What was the first line of evidence that led early investigators to suspect that the continents were once connected?

2 Explain why the discovery of the fossil remains of *Mesosaurus* in both South America and Africa, but nowhere else, supports the continental drift hypothesis.

3 Early in the twentieth century, what was the prevailing view of how land animals migrated across vast expanses of open ocean?

4 How did Wegener account for the existence of glaciers in the southern landmasses at a time when areas in North America, Europe, and Asia supported lush tropical swamps?

**It is important to note that coal can form in a variety of climates, provided that large quantities of plant life are buried.

7.3 THE GREAT DEBATE

Discuss the two main objections to the continental drift hypothesis.

Wegener's proposal did not attract much open criticism until 1924, when his book was translated into English, French, Spanish, and Russian. From that point until his death in 1930, the drift hypothesis encountered a great deal of hostile criticism. The respected American geologist R. T. Chamberlain stated, "Wegener's hypothesis in general is of the foot-loose type, in that it takes considerable liberty with our globe, and is less bound by restrictions or tied down by awkward, ugly facts than most of its rival theories."

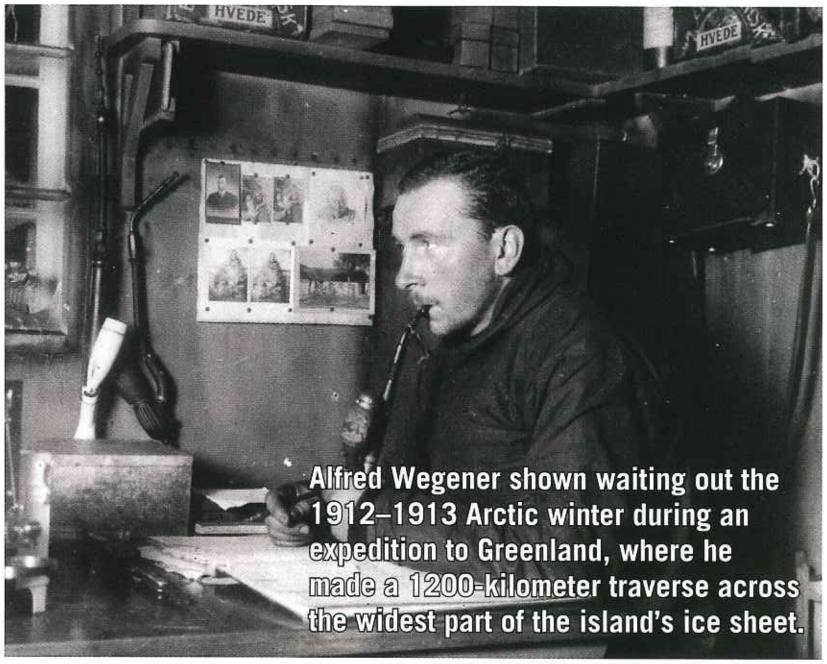

Alfred Wegener shown waiting out the 1912–1913 Arctic winter during an expedition to Greenland, where he made a 1200-kilometer traverse across the widest part of the island's ice sheet.

FIGURE 7.8 Alfred Wegener During an Expedition to Greenland (Photo courtesy of Archive of Alfred Wegener Institute for Polar and Marine Research)

Rejection of the Drift Hypothesis

One of the main objections to Wegener's hypothesis stemmed from his inability to identify a credible mechanism for continental drift. Wegener proposed that gravitational forces of the Moon and Sun that produce Earth's tides were also capable of gradually moving the continents across the globe. However, the prominent physicist Harold Jeffreys correctly countered that tidal forces strong enough to move Earth's continents would have resulted in halting our planet's rotation, which, of course, has not happened.

Wegener also incorrectly suggested that the larger and sturdier continents broke through thinner oceanic crust, much as ice breakers cut through ice. However, no evidence existed to suggest that the ocean floor was weak enough to permit passage of the continents without the continents being appreciably deformed in the process.

FIGURE 7.9 Plate Movement Causes Destructive Earthquakes Photo of Pisco, Peru, following a powerful earthquake on August 16, 2007. (Sergio Urday/epa/Corbis)

In 1930 Wegener made his fourth and final trip to the Greenland Ice Sheet (**FIGURE 7.8**). Although the primary focus of this expedition was to study this great ice cap and its climate, Wegener continued to test his continental drift hypothesis. While returning from Eismitte, an experimental station located in the center of Greenland, Wegener perished along with his Greenland companion. His intriguing idea, however, did not die.

Why was Wegener unable to overturn the established scientific views of his day? Foremost was the fact that, although the central theme of Wegener's drift hypothesis was correct, it contained some incorrect details. For example, continents do not break through the ocean floor, and tidal energy is much too weak to cause continents to be displaced. Moreover, in order for any comprehensive scientific theory to gain wide acceptance, it must withstand critical testing from all areas of science. Despite Wegener's great contribution to our understanding of Earth, not *all* of the evidence supported the continental drift hypothesis as he had proposed it.

Although many of Wegener's contemporaries opposed his views, even to the point of open ridicule, some considered his ideas plausible. For those geologists who continued the search, the exciting concept of continents adrift held their interest. Others viewed continental drift as a solution to previously unexplainable observations such as the cause of earthquakes (**FIGURE 7.9**). Nevertheless, most of the scientific community, particularly in North America, either categorically rejected continental drift or treated it with considerable skepticism.

7.3 CONCEPT CHECKS

1 What two aspects of Wegener's continental drift hypothesis were objectionable to most Earth scientists?

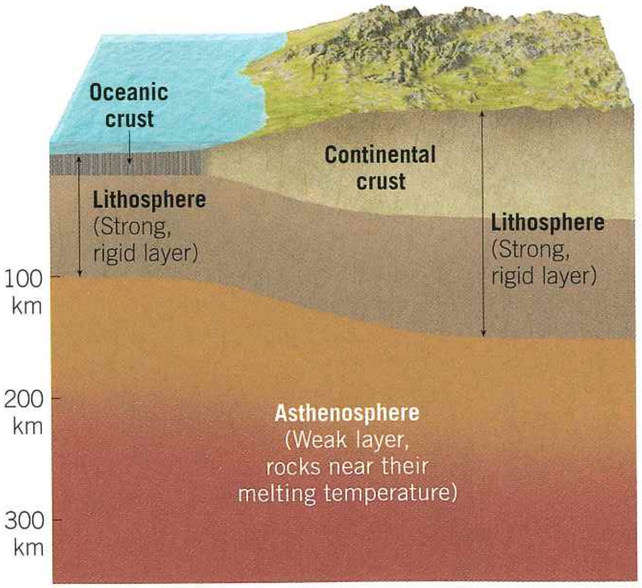
7.4 THE THEORY OF PLATE TECTONICS

List the major differences between Earth's lithosphere and asthenosphere and explain the importance of each in the plate tectonics theory.

Following World War II, oceanographers equipped with new marine tools and ample funding from the U.S. Office of Naval Research embarked on an unprecedented period of oceanographic exploration. Over the next two decades, a much better picture of large expanses of the seafloor slowly and painstakingly began to emerge. From this work came the discovery of a global **oceanic ridge system** that winds through all the major oceans in a manner similar to the seams on a baseball.

In other parts of the ocean, more new discoveries were being made. Studies conducted in the western Pacific demonstrated that earthquakes were occurring at great depths beneath deep-ocean trenches. Of equal importance was the fact that dredging of the seafloor did not bring up any oceanic crust that was older than 180 million years. Further, sediment accumulations in the deep-ocean basins were found to be thin, not the thousands of meters that were predicted. By 1968 these developments, among others, had led to the unfolding of a far more encompassing theory than continental drift, known as the **theory of plate tectonics** (*tekto* = to build).

SmartFigure 7.10 Rigid Lithosphere Overlies the Weak Asthenosphere



Rigid Lithosphere Overlies Weak Asthenosphere

According to the plate tectonics model, the crust and the uppermost, and therefore coolest, part of the mantle constitute Earth's strong outer layer, known as the **lithosphere** (*lithos* = stone, *sphere* = ball). The lithosphere varies in both thickness and density, depending on whether it is oceanic lithosphere or continental lithosphere (**FIGURE 7.10**). Oceanic lithosphere is about 100 kilometers (60 miles) thick in the deep-ocean basins but is considerably thinner along the crest of the oceanic ridge system—a topic we will consider later. By contrast, continental lithosphere averages about 150 kilometers (90 miles) thick but may extend to depths of 200 kilometers (125 miles) or more beneath the stable interiors of the continents. Further, the composition of both the oceanic and continental crusts affects their respective densities. Oceanic crust is composed of rocks that have a mafic (basaltic) composition, and therefore oceanic lithosphere has a greater density than continental lithosphere. Continental crust is composed largely of less dense felsic (granitic) rocks, making continental lithosphere less dense than its oceanic counterpart.

The **asthenosphere** (*asthenos* = weak, *sphere* = ball) is a hotter, weaker region in the mantle that lies below the lithosphere (see Figure 7.10). The temperatures and pressures in the upper asthenosphere (100 to 200 kilometers in depth) are such that rocks at this depth are very near their melting temperatures and, hence, respond to forces by *flowing*, similarly to the way a thick liquid would flow. By contrast, the relatively cool and rigid lithosphere tends to respond to forces acting on it by *bending or breaking but not flowing*. Because of these differences, Earth's rigid outer shell is effectively detached from the asthenosphere, which allows these layers to move independently.

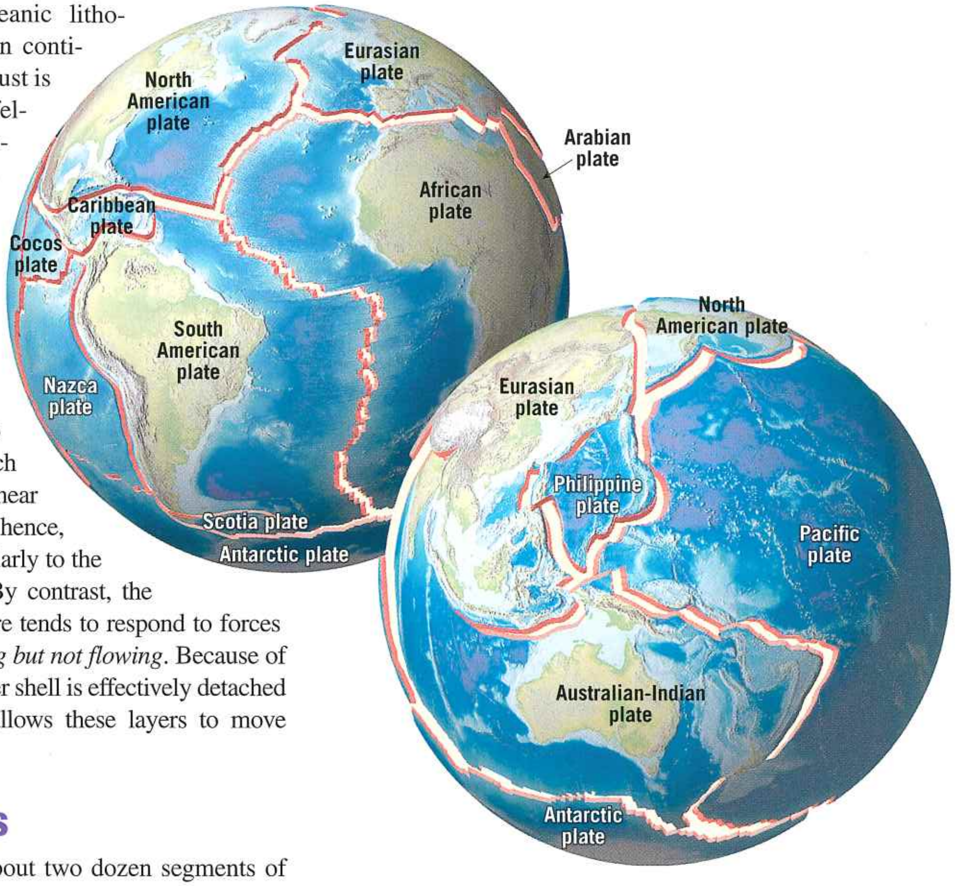


FIGURE 7.11 Earth's Major Lithospheric Plates

Earth's Major Plates

The lithosphere is broken into about two dozen segments of irregular size and shape called **lithospheric plates**, or simply **plates**, that are in constant motion with respect to one another (**FIGURE 7.11**). Seven major lithospheric plates are recognized and account for 94 percent of Earth's surface area: the *North American*, *South American*, *Pacific*, *African*, *Eurasian*, *Australian-Indian*, and *Antarctic plates.* The largest is the Pacific plate, which encompasses a significant portion of the Pacific basin. Each of the six other large plates includes an entire continent plus a significant amount of ocean floor. Notice in **FIGURE 7.12** that the South American plate encompasses almost all of South America and about one-half of the floor of the South Atlantic. This is a major departure from Wegener's continental drift hypothesis, which proposed that the continents move through the ocean floor, not with it. Note also that none of the plates are defined entirely by the margins of a single continent.

Intermediate-sized plates include the *Caribbean*, *Nazca*, *Philippine*, *Arabian*, *Cocos*, *Scotia*, and *Juan de Fuca plates.* These plates, with the exception of the Arabian plate, are composed mostly of oceanic lithosphere. In addition, several smaller plates (*microplates*) have been identified but are not shown in Figure 7.12.

Plate Boundaries

One of the main tenets of the plate tectonics theory is that plates move as somewhat rigid units relative to all other plates. As plates move, the distance between two locations on different plates, such as New York and London, gradually changes, whereas the distance between sites on the same plate—New York and Denver, for example—remains relatively constant. However, parts of some plates are comparatively "soft," such as southern China, which is literally being squeezed as the Indian subcontinent rams into Asia proper.

Because plates are in constant motion relative to each other, most major interactions among them (and, therefore, most deformation) occur along their *boundaries.* In fact, plate boundaries were first established by plotting the locations of earthquakes and volcanoes. Plates are bounded by three distinct types of boundaries, which are differentiated by the type of movement they exhibit. These boundaries are depicted in Figure 7.12 and are briefly described here:

1. Divergent plate boundaries (*constructive margins*)—where two plates move apart, resulting in upwelling of hot material from the mantle to create new seafloor (**FIGURE 7.12A**).
2. Convergent plate boundaries (*destructive margins*)—where two plates move together, resulting in oceanic lithosphere descending beneath an overriding plate, eventually to be reabsorbed into the mantle or possibly in the collision of two continental blocks to create a mountain belt (**FIGURE 7.12B**).

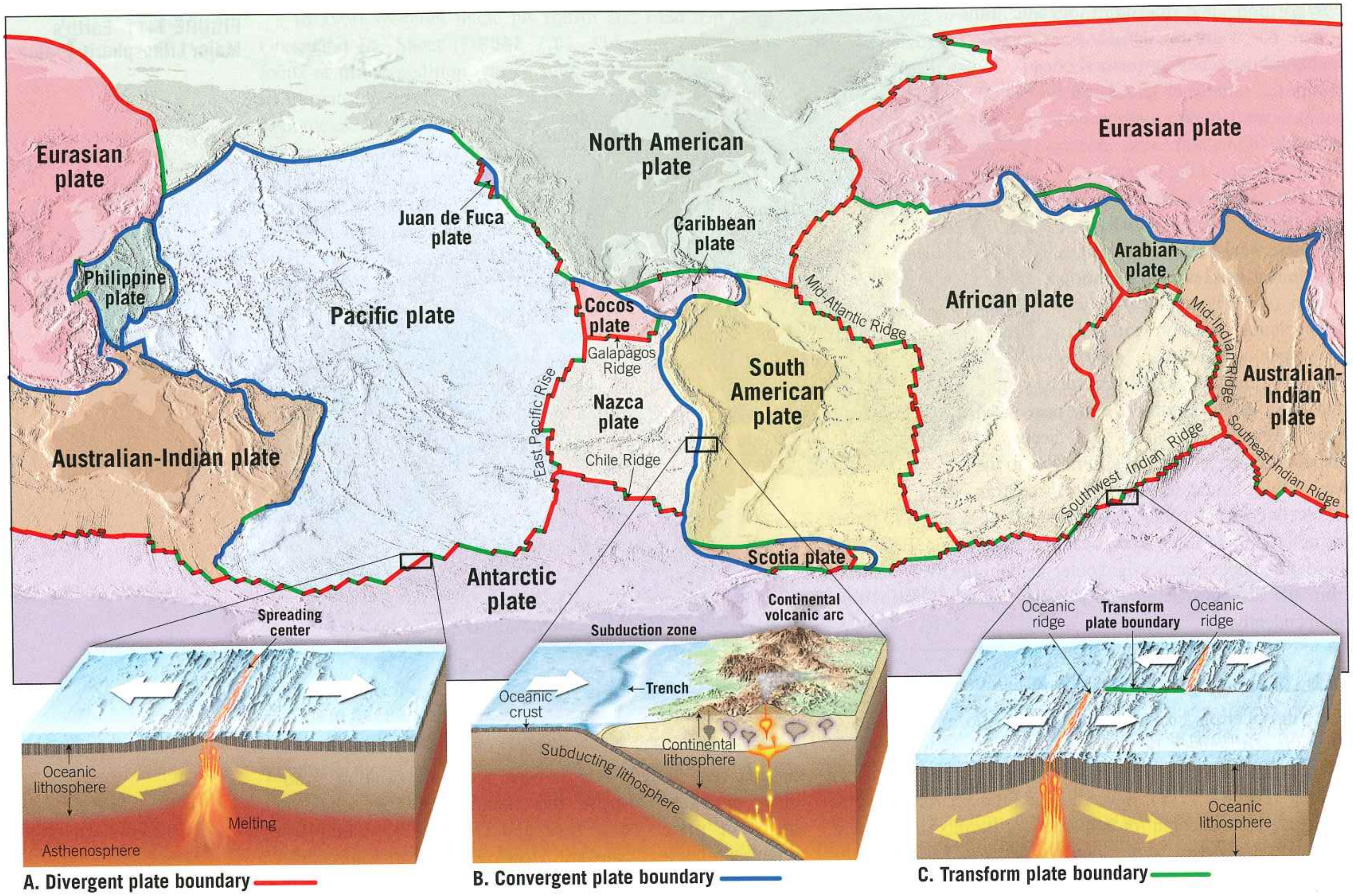


FIGURE 7.12 Divergent, Convergent, and Transform Plate Boundaries

3. Transform plate boundaries (*conservative margins*)—where two plates grind past each other without producing or destroying lithosphere (**FIGURE 7.12C**).

Divergent and convergent plate boundaries each account for about 40 percent of all plate boundaries. Transform faults account for the remaining 20 percent. In the following sections we will summarize the nature of the three types of plate boundaries.

7.4 CONCEPT CHECKS

1. What major ocean floor feature did oceanographers discover after World War II?
2. Compare and contrast the lithosphere and the asthenosphere.
3. List the seven largest lithospheric plates.
4. List the three types of plate boundaries and describe the relative motion at each of them.

7.5 DIVERGENT PLATE BOUNDARIES AND SEAFLOOR SPREADING

Sketch and describe the movement along a divergent plate boundary that results in the formation of new oceanic lithosphere.

Most **divergent plate boundaries** (*di* = apart, *vergere* = to move) are located along the crests of oceanic ridges and can be thought of as *constructive plate margins* because this is where new ocean floor is generated (**FIGURE 7.13**). Here, two adjacent plates move away from each other, producing long, narrow fractures in the ocean crust. As a result, hot rock from the mantle below migrates upward and fills the voids left as the crust is being ripped apart. This molten material gradually cools, producing new slivers of seafloor. In a slow and unending manner, adjacent plates spread apart, and new oceanic lithosphere forms between them. For this reason, divergent plate boundaries are also referred to as **spreading centers**.

Oceanic Ridges and Seafloor Spreading

The majority of, but not all, divergent plate boundaries are associated with *oceanic ridges*: elevated areas of the seafloor characterized by high heat flow and volcanism. The global ridge system is the longest topographic feature on Earth's surface, exceeding 70,000 kilometers (43,000 miles) in length. As shown in Figure 7.12, various segments of the global ridge system have been named, including the Mid-Atlantic Ridge, East Pacific Rise, and Mid-Indian Ridge.

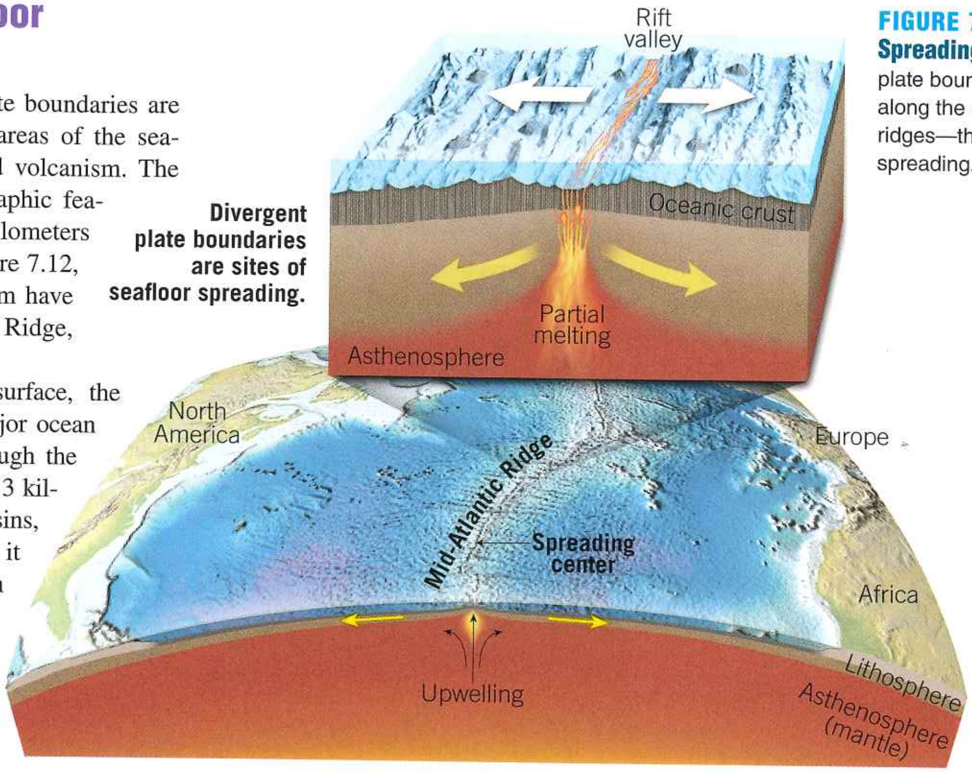


FIGURE 7.13 Seafloor Spreading Most divergent plate boundaries are situated along the crests of oceanic ridges—the sites of seafloor spreading.

Representing 20 percent of Earth's surface, the oceanic ridge system winds through all major ocean basins like the seams on a baseball. Although the crest of the oceanic ridge is commonly 2 to 3 kilometers higher than the adjacent ocean basins, the term *ridge* may be misleading because it implies "narrow" when, in fact, ridges vary in width from 1000 kilometers (600 miles) to more than 4000 kilometers (2500 miles). Further, along the crest of some ridge segments is a deep canyonlike structure called a **rift valley** (**FIGURE 7.14**). This structure is evidence that tensional forces are actively pulling the ocean crust apart at the ridge crest.

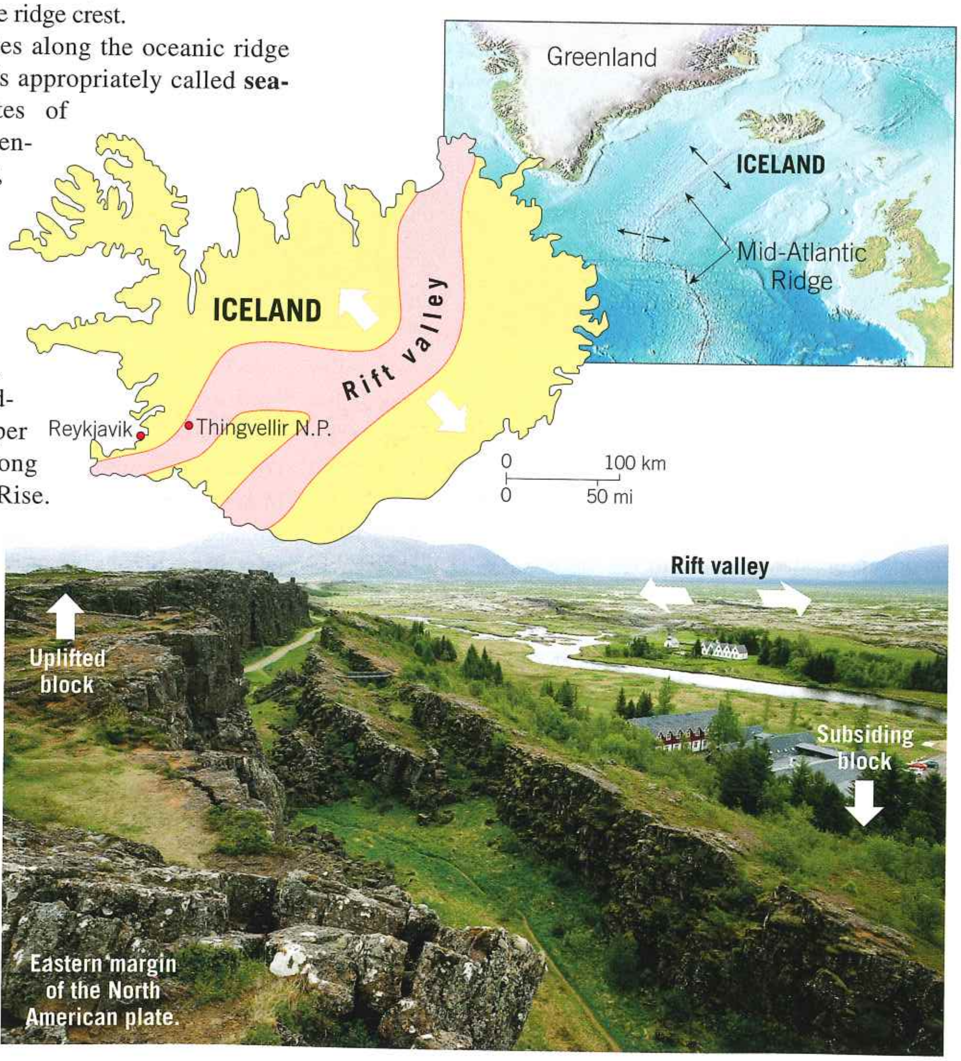
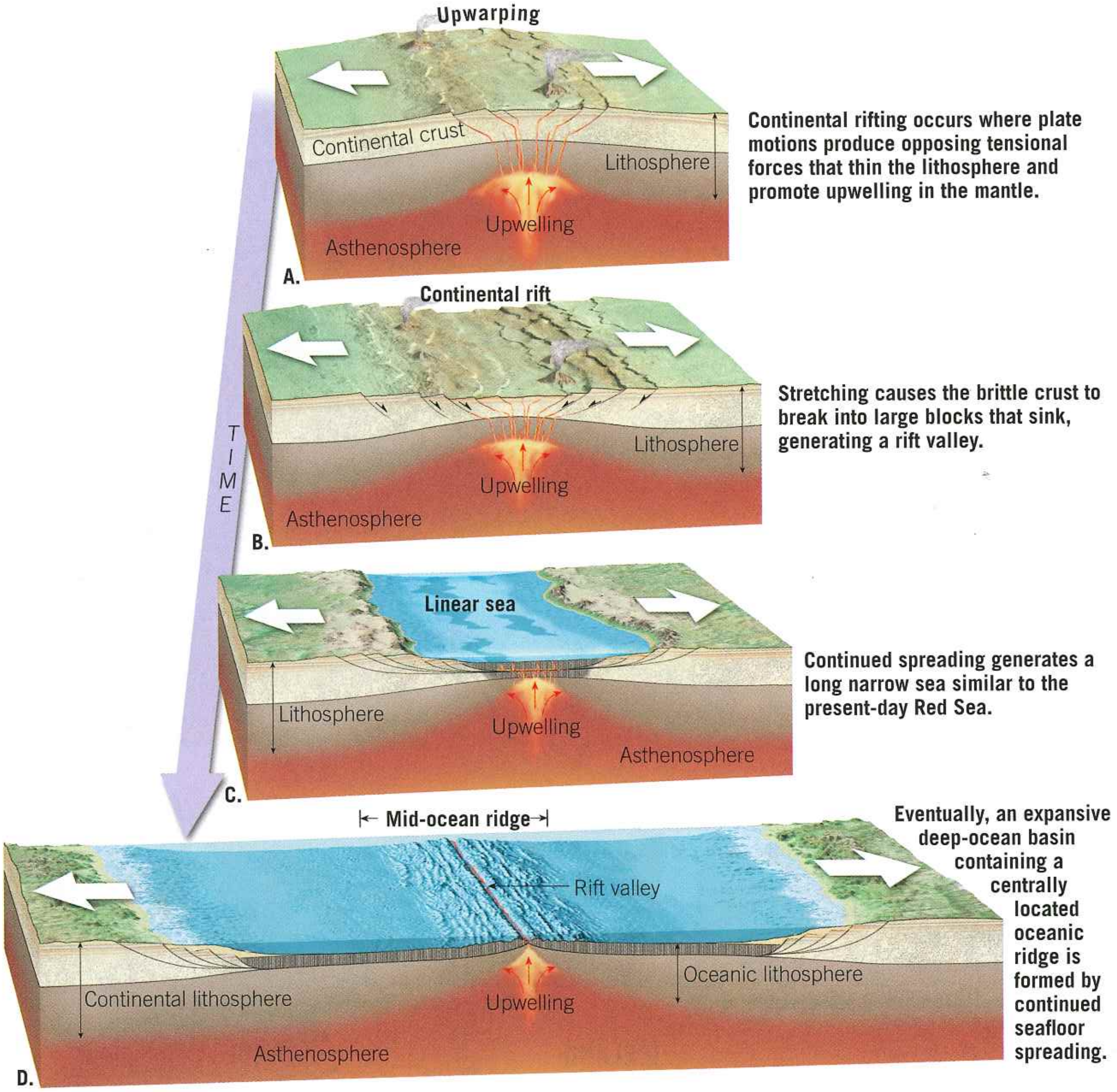


FIGURE 7.14 Rift Valley Thingvellir National Park, Iceland, is located on the western margin of a rift valley that is roughly 30 kilometers (20 miles) wide in this region. This rift valley is connected to a similar feature that extends along the crest of the Mid-Atlantic Ridge. The cliff in the left half of the image approximates the eastern edge of the North American plate. (Photo by Ragnar ThSigurdsson/Alamy)

The mechanism that operates along the oceanic ridge system to create new seafloor is appropriately called **seafloor spreading**. Typical rates of spreading average around 5 centimeters (2 inches) per year, roughly the same rate at which human fingernails grow. Comparatively slow spreading rates of 2 centimeters per year are found along the Mid-Atlantic Ridge, whereas spreading rates exceeding 15 centimeters (6 inches) per year have been measured along sections of the East Pacific Rise. Although these rates of seafloor production are slow on a human time scale, they are nevertheless rapid enough to have generated all of Earth's ocean basins within the past 200 million years.

The primary reason for the elevated position of the oceanic ridge is that newly created oceanic lithosphere is hot, which means it is less dense than cooler rocks found away from the ridge axis. (Geologists use the term *axis* to refer to a line that follows the general trend of the ridge

SmartFigure 7.15
Continental Rifting
Formation of a new ocean basin.



Continental rifting occurs where plate motions produce opposing tensional forces that thin the lithosphere and promote upwelling in the mantle.

Stretching causes the brittle crust to break into large blocks that sink, generating a rift valley.

Continued spreading generates a long narrow sea similar to the present-day Red Sea.

Eventually, an expansive deep-ocean basin containing a centrally located oceanic ridge is formed by continued seafloor spreading.

crest.) As soon as new lithosphere forms, it is slowly yet continually displaced away from the zone of upwelling. Thus, it begins to cool and contract, thereby increasing in density. This thermal contraction accounts for the increase in ocean depths away from the ridge crest. It takes about 80 million years for the temperature of oceanic lithosphere to stabilize and contraction to cease. By this time, rock that was once part of the elevated oceanic ridge system is located in the deep-ocean basin, where it may be buried by substantial accumulations of sediment.

In addition, as the plate moves away from the ridge, cooling of the underlying asthenosphere causes it to become increasingly more rigid. Thus, oceanic lithosphere is generated by cooling of the asthenosphere from the top down. Stated another way, the thickness of oceanic lithosphere is age dependent. The older (cooler) it is, the greater its thickness. Oceanic lithosphere that exceeds 80 million years in age is about 100 kilometers (60 miles) thick—approximately its maximum thickness.

Continental Rifting

Divergent boundaries can develop within a continent, in which case the landmass may split into two or more smaller segments separated by an ocean basin. Continental rifting begins when plate motions produce opposing (tensional) forces that pull and stretch the lithosphere. Because the lower lithosphere is warm and weak it deforms without breaking. Stretching, in turn, thins the lithosphere, which promotes mantle upwelling and broad upwarping of the overlying lithosphere (**FIGURE 7.15A**). During this process the outermost crustal rocks, which are cool and brittle, break into large blocks. As the tectonic forces continue to pull apart the crust, the broken crustal fragments sink, generating an elongated depression called a **continental rift**, which eventually widens to form a narrow sea (**FIGURE 7.15B, C**) and then a new ocean basin (**FIGURE 7.15D**).

A modern example of an active continental rift is the East African Rift (**FIGURE 7.16**). Whether this rift will eventually result in the breakup of Africa is a topic of continued research. Nevertheless, the East African Rift is an excellent model of the initial stage in the breakup of a continent. Here, tensional forces have stretched and thinned the lithosphere, allowing molten rock to ascend from the mantle. Evidence for recent volcanic activity includes several large volcanic mountains, including Mount Kilimanjaro and Mount Kenya, the tallest peaks in Africa. Research suggests that if rifting continues, the rift valley will lengthen and deepen (see Figure 7.15C). At some point, the rift valley will become a narrow sea with an outlet to the ocean. The Red Sea, which formed when the Arabian Peninsula split from Africa, is a modern example of such a feature and provides us with a view of how the Atlantic Ocean may have looked in its infancy (see Figure 7.15D).

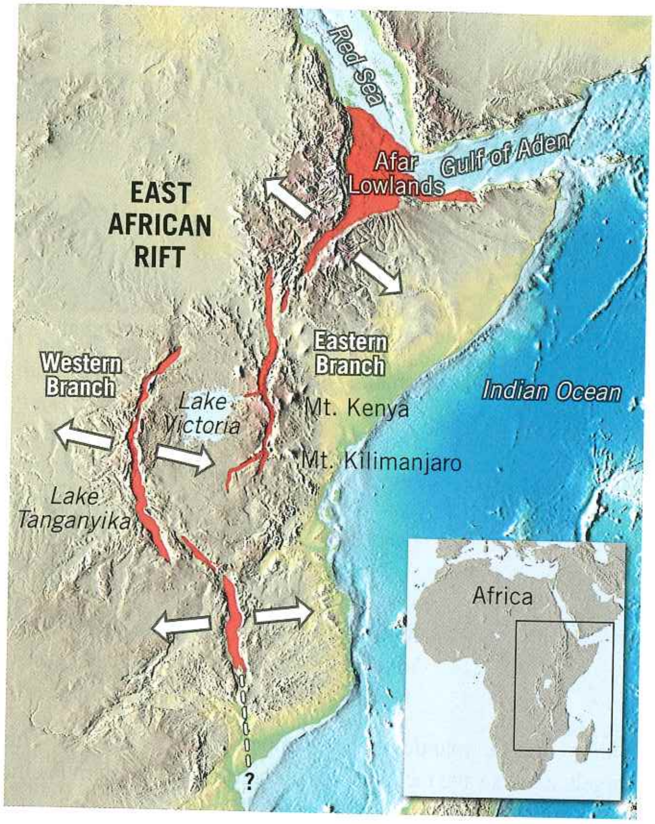


FIGURE 7.16 East African Rift Valley

7.5 CONCEPT CHECKS

1. Sketch or describe how two plates move in relation to each other along divergent plate boundaries.
2. What is the average rate of seafloor spreading in modern oceans?
3. List four facts that characterize the ocean ridge system.
4. Briefly describe the process of continental rifting. Where is it occurring today?

7.6 CONVERGENT PLATE BOUNDARIES AND SUBDUCTION

Compare and contrast the three types of convergent plate boundaries and name a location where each type can be found.

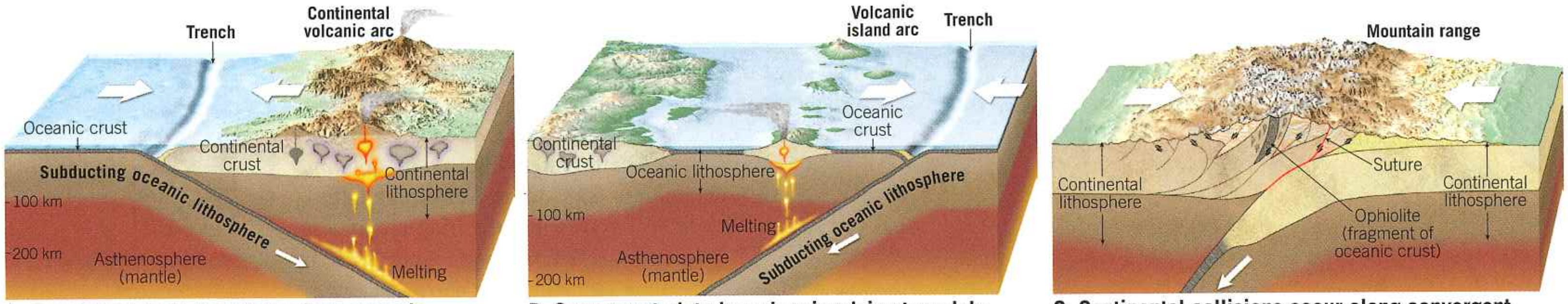
New lithosphere is constantly being produced at the oceanic ridges. However, our planet is not growing larger; its total surface area remains constant. A balance is maintained because older, denser portions of oceanic lithosphere descend into the mantle at a rate equal to seafloor production. This activity occurs along **convergent plate boundaries**, where two plates move toward each other and the leading edge of one is bent downward, as it slides beneath the other (**FIGURE 7.17**).

Convergent boundaries are also called **subduction zones** because they are sites where lithosphere is descending (being subducted) into the mantle. Subduction occurs because the density of the descending lithospheric plate is greater than the density of the underlying asthenosphere. In general, old oceanic lithosphere is about 2 percent more dense than the underlying asthenosphere, which causes it to subduct. Continental lithosphere, in contrast, is less dense and resists subduction. As a consequence, only oceanic lithosphere will subduct to great depths.

Deep-ocean trenches are the surface manifestations produced as oceanic lithosphere descends into the mantle (see Figure 1.20). These large linear depressions are remarkably long and deep. The Peru–Chile trench along the west coast of South America is more than 4500 kilometers (3000 miles) long, and its base is as much as 8 kilometers (5 miles) below sea level. The trenches in the western Pacific, including the Mariana and Tonga trenches, tend to be even deeper than those of the eastern Pacific.

Slabs of oceanic lithosphere descend into the mantle at angles that vary from a few degrees to nearly vertical (90 degrees). The angle at which an oceanic plate subducts depends largely on its age and therefore its density. For example, when seafloor spreading occurs near a subduction zone, as is the case along the coast of Chile, the subducting lithosphere is young and buoyant, which results in a low angle of descent. As the two plates converge, the overriding plate scrapes over the top of the subducting plate below—a type of forced subduction. Consequently, the region around the Peru–Chile trench experiences great earthquakes, including the 2010 Chilean earthquake—one of the 10 largest on record.

As oceanic lithosphere ages (gets farther from the spreading center), it gradually cools, which causes it to thicken and increase in density. In parts of the western Pacific, some oceanic lithosphere is 180 million years old—the thickest and densest in today's oceans. The very dense slabs in this region typically



A. Convergent plate boundary where oceanic lithosphere is subducting beneath continental lithosphere.

B. Convergent plate boundary involving two slabs of oceanic lithosphere.

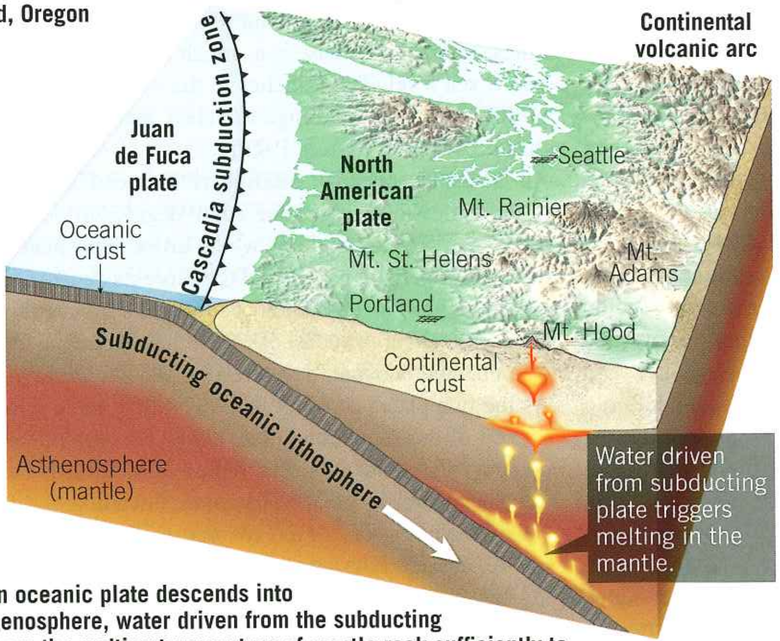
C. Continental collisions occur along convergent plate boundaries when both plates are capped with continental crust.

SmartFigure 7.17 Three Types of Convergent Plate Boundaries

FIGURE 7.18 Oceanic–continental Convergent Plate Boundary Mount Hood, Oregon, is one of more than a dozen large composite volcanoes in the Cascade Range.


Wallace Garrison/Getty Images

Mt. Hood, Oregon



Water driven from subducting plate triggers melting in the mantle.

When an oceanic plate descends into the asthenosphere, water driven from the subducting slab lowers the melting temperature of mantle rock sufficiently to generate magma. The Cascade Range is a continental volcanic arc formed by the subduction of the Juan de Fuca plate under the North American plate.

plunge into the mantle at angles approaching 90 degrees. This largely explains the fact that most trenches in the western Pacific are deeper than trenches in the eastern Pacific.

Although all convergent zones have the same basic characteristics, they may vary considerably, based on the type of crustal material involved and the tectonic setting. Convergent boundaries can form between *two oceanic plates*, *one oceanic plate and one continental plate*, or *two continental plates.*

Oceanic–Continental Convergence

When the leading edge of a plate capped with continental crust converges with a slab of oceanic lithosphere, the buoyant continental block remains "floating," while the denser oceanic slab sinks into the mantle (see Figure 7.17A). When a descending oceanic slab reaches a depth of about 100 kilometers (60 miles), melting is triggered within the wedge of hot asthenosphere that lies above it. But how does the subduction of a cool slab of oceanic lithosphere cause mantle rock to melt? The answer lies in the fact that water contained in the descending plates acts the way salt does to melt ice. That is, "wet" rock in a high-pressure environment melts at substantially lower temperatures than does "dry" rock of the same composition.

Sediments and oceanic crust contain large amounts of water, which is carried to great depths by a subducting plate. As the plate plunges downward,

FIGURE 7.19 Volcanoes of the Aleutian Islands

heat and pressure drive water from the voids in the rock. At a depth of roughly 100 kilometers (60 miles), the wedge of mantle rock is sufficiently hot that the introduction of water from the slab below leads to some melting. This process, called **partial melting**, is thought to generate some molten material, which is mixed with unmelted mantle rock. Being less dense than the surrounding mantle, this hot mobile material gradually rises toward the surface. Depending on the environment, these mantle-derived masses of molten rock may ascend through the crust and give rise to a volcanic eruption. However, much of this material never reaches the surface; rather, it solidifies at depth—a process that thickens the crust.

The volcanoes of the towering Andes are the product of molten rock generated by the subduction of the Nazca plate beneath the South American continent (see Figure 7.12). Mountain systems, such as the Andes, which are produced in part by volcanic activity associated with the subduction of oceanic lithosphere, are called **continental volcanic arcs**. The Cascade Range in Washington, Oregon, and California is another mountain system that consists of several well-known volcanic mountains, including Mount Rainier, Mount Shasta, Mount St. Helens, and Mount Hood (**FIGURE 7.18**). This active volcanic arc also extends into Canada, where it includes Mount Garibaldi, Mount Silverthrone, and others.

Oceanic–Oceanic Convergence

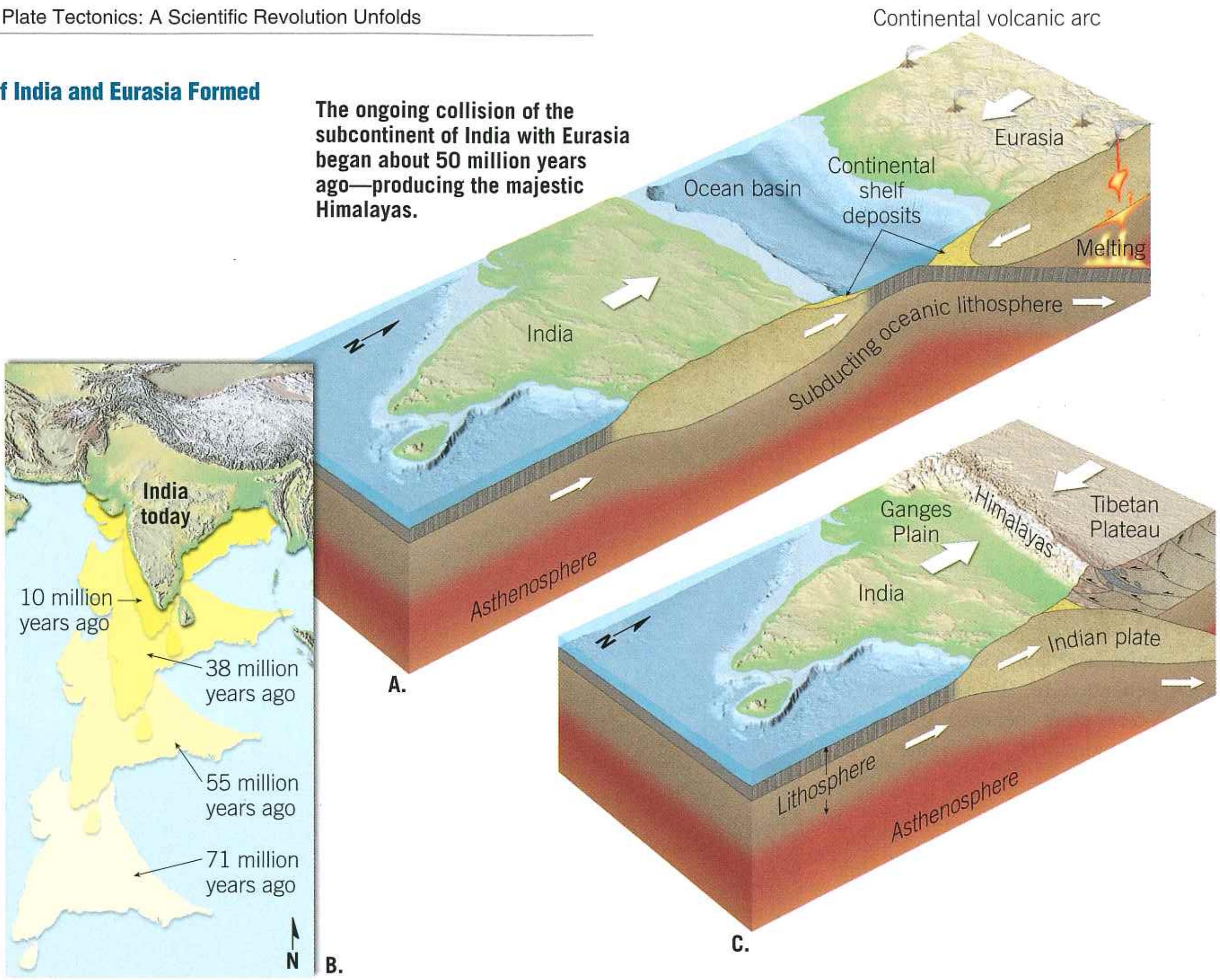
An *oceanic–oceanic convergent boundary* has many features in common with oceanic–continental plate margins. Where two oceanic slabs converge, one descends beneath the other, initiating volcanic activity by the same mechanism that operates at all subduction zones (see Figure 7.12). Water squeezed from the subducting slab of oceanic lithosphere triggers melting in the hot wedge of mantle rock above. In this setting, volcanoes grow up from the ocean floor rather than on a continental platform. When subduction is sustained, it will eventually build a chain of volcanic structures large enough to emerge as islands. The newly formed land consisting of an arc-shaped chain of volcanic islands is called a **volcanic island arc**, or simply an **island arc** (**FIGURE 7.19**).

The Aleutian, Mariana, and Tonga islands are examples of relatively young volcanic island arcs. Island arcs are generally located 100 to 300 kilometers (60 to 200 miles) from a deep-ocean trench. Located adjacent to the island arcs just mentioned are the Aleutian trench, the Mariana trench, and the Tonga trench.

Most volcanic island arcs are located in the western Pacific. Only two are located in the Atlantic—the Lesser Antilles arc, on the eastern margin of the Caribbean Sea, and the Sandwich Islands, located off the tip of South America. The Lesser Antilles are a product of the subduction of the Atlantic seafloor beneath the Caribbean plate. Located within this volcanic arc are the Virgin Islands of the United States and Britain as well as the island of Martinique, where Mount Pelée erupted in 1902, destroying the town of St. Pierre and killing an estimated 28,000 people. This chain of islands also includes Montserrat, where there has been recent volcanic activity. More on these volcanic events is found in Chapter 9.

Island arcs are typically simple structures made of numerous volcanic cones underlain by oceanic crust that is generally less than 20 kilometers (12 miles) thick. By contrast, some island arcs are more complex and are underlain by highly deformed crust that may reach 35 kilometers (22 miles) in thickness. Examples include Japan, Indonesia, and the Alaskan Peninsula. These island arcs are built on material generated by earlier episodes of subduction or on small slivers of continental crust that have rafted away from the mainland.

FIGURE 7.20 The Collision of India and Eurasia Formed the Himalayas



The ongoing collision of the subcontinent of India with Eurasia began about 50 million years ago—producing the majestic Himalayas.

Continental–Continental Convergence

The third type of convergent boundary results when one landmass moves toward the margin of another because of subduction of the intervening seafloor (**FIGURE 7.20A**). Whereas oceanic lithosphere tends to be dense and sink into the mantle, the buoyancy of continental material inhibits it from being subducted. Consequently, a collision between two converging continental fragments ensues (**FIGURE 7.20B**). This event folds and deforms the accumulation of sediments and sedimentary rocks along the continental margins as if they had been placed in a gigantic vise. The result is the formation of a new mountain belt composed of deformed sedimentary and metamorphic rocks that often contain slivers of oceanic crust.

Such a collision began about 50 million years ago, when the subcontinent of India "rammed" into Asia, producing the Himalayas—the most spectacular mountain range on Earth (see Figure 7.20B). During this collision, the continental crust buckled and fractured and was generally shortened horizontally and thickened vertically. In addition to the Himalayas, several other major mountain systems, including the Alps, Appalachians, and Urals, formed as continental fragments collided. This topic will be considered further in Chapter 10.

7.6 CONCEPT CHECKS

1. Explain why the rate of lithosphere production roughly balances with the rate of lithosphere destruction.
2. Compare a continental volcanic arc and a volcanic island arc.
3. Describe the process that leads to the formation of deep-ocean trenches.
4. Why does oceanic lithosphere subduct, while continental lithosphere does not?
5. Briefly describe how mountain belts such as the Himalayas form.

7.7 TRANSFORM PLATE BOUNDARIES

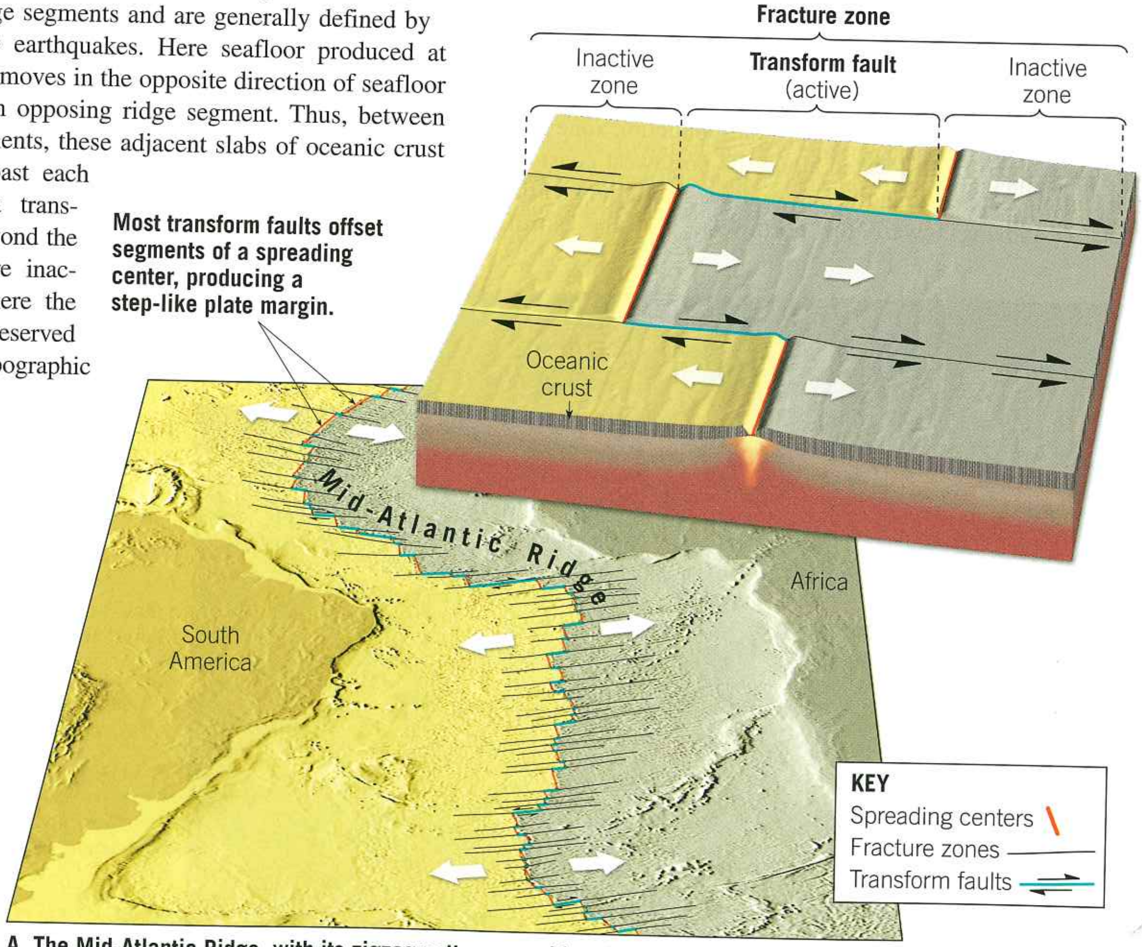
Describe the relative motion along a transform plate boundary and locate several examples on a plate boundary map.

Along a **transform plate boundary**, also called a **transform fault**, plates slide horizontally past one another without producing or destroying lithosphere. The nature of transform faults was discovered in 1965 by Canadian geologist J. Tuzo Wilson, who proposed that these large faults connect two spreading centers (divergent boundaries) or, less commonly, two trenches (convergent boundaries). Most transform faults are found on the ocean floor, where they offset segments of the oceanic ridge system, producing a steplike plate margin (**FIGURE 7.21A**). Notice that the zigzag shape of the Mid-Atlantic Ridge in Figure 7.12 roughly reflects the shape of the original rifting that caused the breakup of the supercontinent of Pangaea. (Compare the shapes of the continental margins of the landmasses on both sides of the Atlantic with the shape of the Mid-Atlantic Ridge.)

Typically, transform faults are part of prominent linear breaks in the seafloor known as **fracture zones**, which include both active transform faults and their inactive extensions into the plate interior (**FIGURE 7.21B**). Active transform faults lie *only between* the two offset ridge segments and are generally defined by weak, shallow earthquakes. Here seafloor produced at one ridge axis moves in the opposite direction of seafloor produced at an opposing ridge segment. Thus, between the ridge segments, these adjacent slabs of oceanic crust are grinding past each other along a transform fault. Beyond the ridge crests are inactive zones, where the fractures are preserved as linear topographic depressions. The trend of these fracture zones roughly parallels the direction of plate motion at the time of their formation. Thus, these structures are useful in mapping the direction of plate motion in the geologic past.

In another role, transform faults provide the means by which the oceanic crust created at ridge crests can be transported to a site of destruction—the deep-ocean trenches. **FIGURE 7.22** illustrates this situation. Notice that the Juan de Fuca plate moves in a southeasterly direction, eventually being subducted under the west coast of the United States. The southern end of this plate is bounded by a transform fault called the Mendocino Fault. This transform boundary connects the Juan de Fuca Ridge to the Cascadia subduction zone. Therefore, it facilitates the movement of the crustal material created at the Juan de Fuca Ridge to its destination beneath the North American continent.

B. Fracture zones are long, narrow scar-like features in the seafloor that are roughly perpendicular to the offset ridge segments. They include both the active transform fault and its "fossilized" trace.

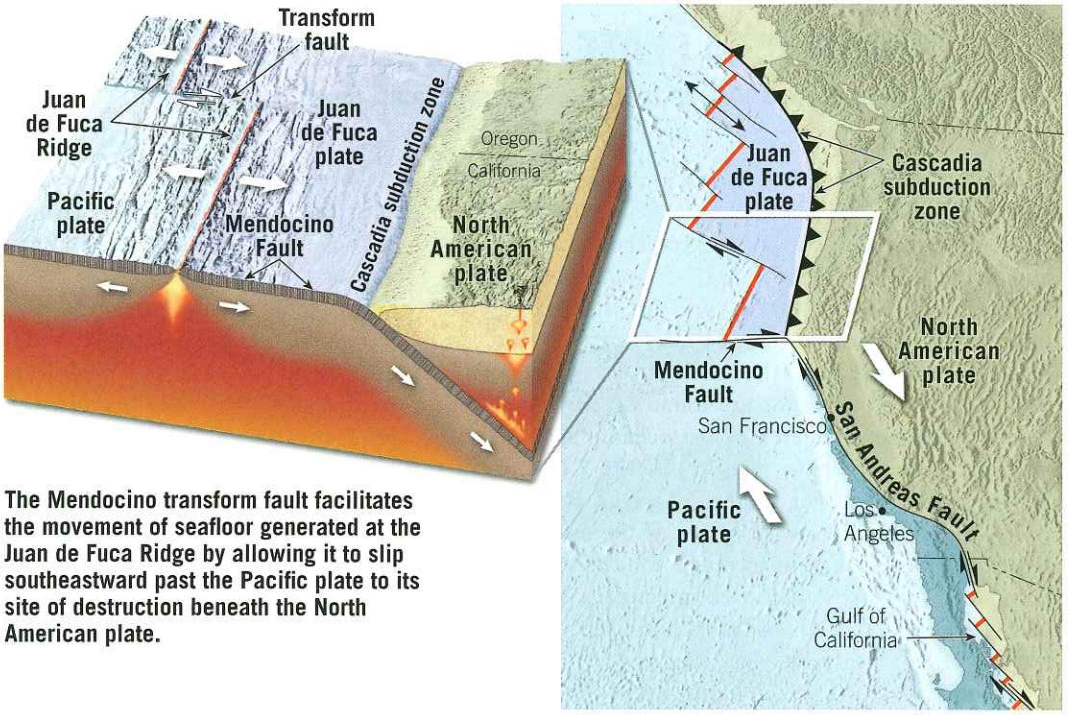


Most transform faults offset segments of a spreading center, producing a step-like plate margin.

A. The Mid-Atlantic Ridge, with its zigzag pattern, roughly reflects the shape of the rifting zone that resulted in the breakup of Pangaea.

SmartFigure 7.21 Transform Plate Boundaries

FIGURE 7.22 Transform Faults Facilitate Plate Motion Seafloor spreading generated along the Juan de Fuca Ridge moves southeastward, past the Pacific plate. Eventually it subducts beneath the North American plate. Thus, this transform fault connects a spreading center (divergent boundary) to a subduction zone (convergent boundary). Also shown is the San Andreas Fault, a transform fault that connects two spreading centers: the Juan de Fuca Ridge and a spreading center located in the Gulf of California.



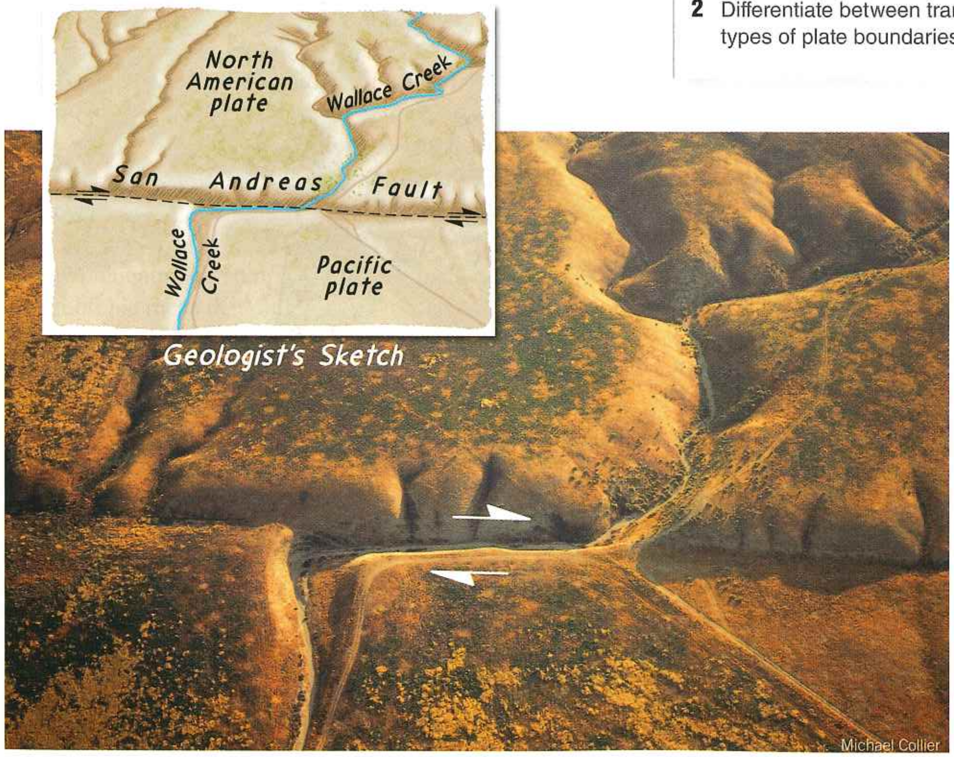
The Mendocino transform fault facilitates the movement of seafloor generated at the Juan de Fuca Ridge by allowing it to slip southeastward past the Pacific plate to its site of destruction beneath the North American plate.

Like the Mendocino Fault, most other transform fault boundaries are located within the ocean basins; however, a few cut through continental crust. Two examples are the earthquake-prone San Andreas Fault of California and New Zealand's Alpine Fault. Notice in Figure 7.22 that the San Andreas Fault connects a spreading center located in the Gulf of California to the Cascadia subduction zone and the Mendocino Fault located along the northwest coast of the United States. Along the San Andreas Fault, the Pacific plate is moving toward the northwest, past the North American plate (**FIGURE 7.23**). If this movement continues, the part of California west of the fault zone, including the Baja Peninsula of Mexico, will become an island off the west coast of the United States and Canada—with the potential to eventually reach Alaska. However, a more immediate concern is the earthquake activity triggered by movements along this fault system.

7.7 CONCEPT CHECKS

1. Sketch or describe how two plates move in relation to each other along a transform plate boundary.
2. Differentiate between transform faults and the two other types of plate boundaries.

Mobile Field Trip 7.23 Movement along the San Andreas Fault This aerial view shows the offset in the dry channel of Wallace Creek near Taft, California.



Michael Collier

7.8 HOW DO PLATES AND PLATE BOUNDARIES CHANGE?

Explain why plates such as the African and Antarctic plates are getting larger, while the Pacific plate is getting smaller.

Although the total surface area of Earth does not change, the size and shape of individual plates are constantly changing. For example, the African and Antarctic plates, which are mainly bounded by divergent boundaries—sites of seafloor production—are continually growing in size as new lithosphere is added to their margins. By contrast, the Pacific plate is being consumed into the mantle along its northern and western flanks faster that it is growing along the East Pacific Rise and thus is diminishing in size.

Another result of plate motion is that boundaries also migrate. For example, the position of the Peru–Chile trench, which is the result of the Nazca plate being bent downward as it descends beneath the South American plate, has changed over time (see Figure 7.12). Because of the westward drift of the South American plate relative to the Nazca plate, the position of the Peru–Chile trench has migrated in a westerly direction as well.

Plate boundaries can also be created or destroyed in response to changes in the forces acting on the lithosphere. Recall that the Red Sea is the site of a relatively new spreading center that came into existence less than 20 million years ago, when the Arabian Peninsula began to split from Africa. At other locations, plates carrying continental crust are presently moving toward one another. Eventually these continental fragments may collide and be sutured together. This could occur, for example, in the South Pacific, where Australia is moving northward toward southern Asia. If Australia continues its northward migration, the boundary separating it from Asia will disappear as these plates become one. The breakup of Pangaea is a classic example of how plate boundaries change through geologic time.

The Breakup of Pangaea

Wegener used evidence from fossils, rock types, and ancient climates to create a jigsaw-puzzle fit of the continents, thereby creating his supercontinent of Pangaea. In a similar manner, but employing modern tools not available to Wegener, geologists have re-created the steps in the breakup of this supercontinent, an event that began about 180 million years ago. From this work, the dates when individual crustal fragments separated from one another and their relative motions have been well established (**FIGURE 7.24**).

An important consequence of the breakup of Pangaea was the creation of a "new" ocean basin: the Atlantic. As you can see in Figure 7.24, splitting of the supercontinent did not occur simultaneously along the margins of the Atlantic. The first split developed between North America and Africa. Here, the continental crust was highly fractured, providing pathways for huge quantities of fluid lavas to reach the surface. Today, these lavas are represented by weathered igneous rocks found along the eastern seaboard of the United States—primarily buried beneath the sedimentary rocks that form the continental shelf. Radiometric dating of these

EYE ON EARTH

Baja California is separated from mainland Mexico by a long narrow sea called the Gulf of California (also known to local residents as the Sea of Cortez). The Gulf of California contains many islands that were created by volcanic activity.

QUESTION 1 *What type of plate boundary is responsible for opening the Gulf of California?*

QUESTION 2 *What major U.S. river originates in the Colorado Rockies and created a large delta at the northern end of the Gulf of California?*

QUESTION 3 *If the material carried by the river in Question 2 had not been deposited, the Gulf of California would extend northward to include the inland sea shown in this satellite image. What is the name of this inland sea?*

NASA

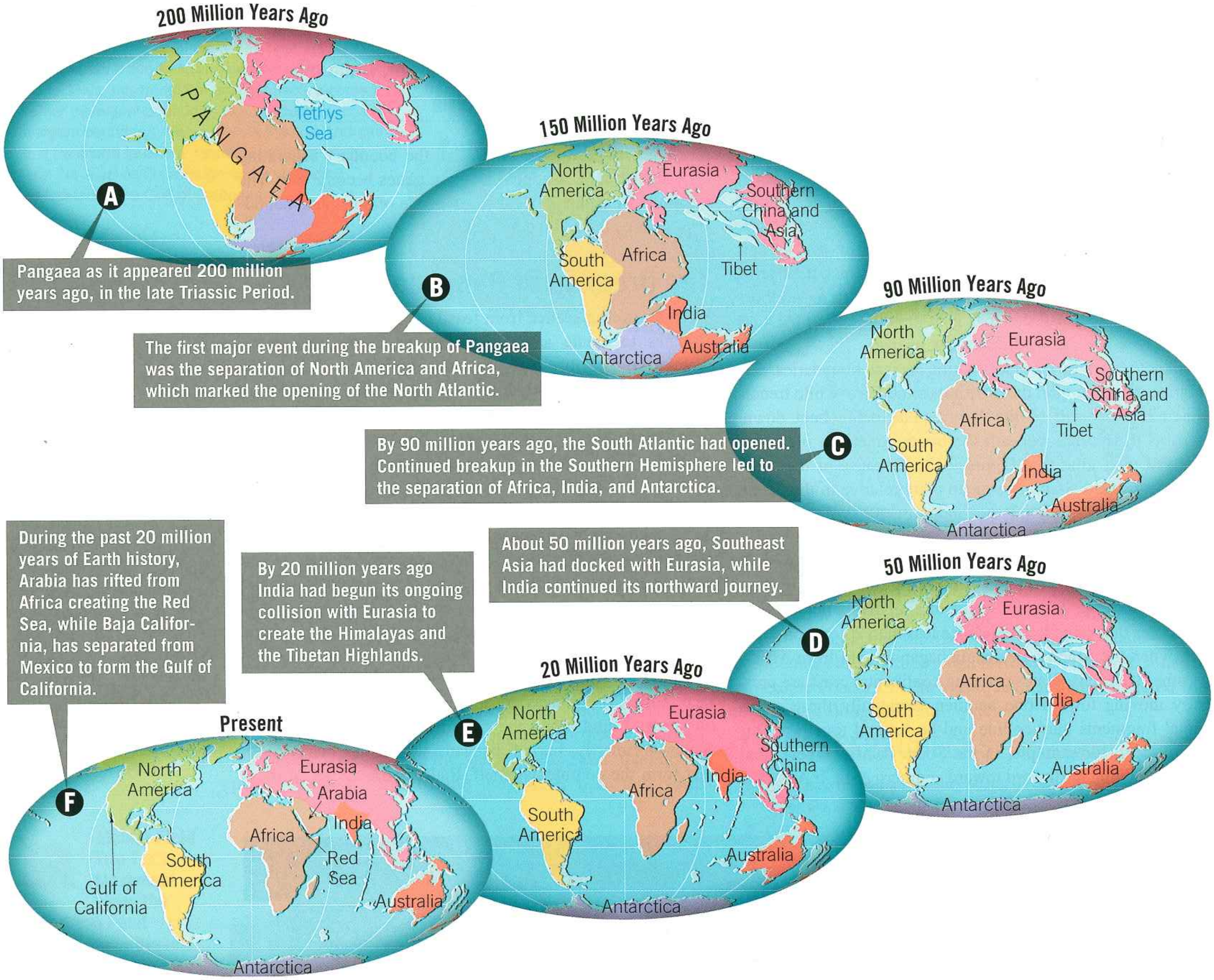


FIGURE 7.24 The Breakup of Pangaea

Pangaea as it appeared 200 million years ago, in the late Triassic Period.

The first major event during the breakup of Pangaea was the separation of North America and Africa, which marked the opening of the North Atlantic.

By 90 million years ago, the South Atlantic had opened. Continued breakup in the Southern Hemisphere led to the separation of Africa, India, and Antarctica.

About 50 million years ago, Southeast Asia had docked with Eurasia, while India continued its northward journey.

By 20 million years ago India had begun its ongoing collision with Eurasia to create the Himalayas and the Tibetan Highlands.

During the past 20 million years of Earth history, Arabia has rifted from Africa creating the Red Sea, while Baja California, has separated from Mexico to form the Gulf of California.

solidified lavas indicates that rifting began between 180 million and 165 million years ago. This time span represents the "birth date" for this section of the North Atlantic.

By 130 million years ago, the South Atlantic began to open near the tip of what is now South Africa. As this zone of rifting migrated northward, it gradually opened the South Atlantic (Figure 7.24B,C). Continued breakup of the southern landmass led to the separation of Africa and Antarctica and sent India on a northward journey. By the early Cenozoic, about 50 million years ago, Australia had separated from Antarctica, and the South Atlantic had emerged as a full-fledged ocean (**FIGURE 7.24D**).

A modern map (**FIGURE 7.24F**) shows that India eventually collided with Asia, an event that began about 50 million years ago and created the Himalayas as well as the Tibetan Highlands. About the same time, the separation of Greenland from Eurasia completed the breakup of the northern landmass. During the past 20 million years or so of Earth's history, Arabia rifted from Africa to form the Red Sea, and Baja California separated from Mexico to form the Gulf of California (**FIGURE 7.24E**). Meanwhile, the Panama Arc joined North America and South America to produce our globe's familiar modern appearance.

Plate Tectonics in the Future

Geologists have extrapolated present-day plate movements into the future. **FIGURE 7.25** illustrates where Earth's landmasses may be 50 million years from now if present plate movements persist during this time span.

In North America we see that the Baja Peninsula and the portion of southern California that lies west of the San

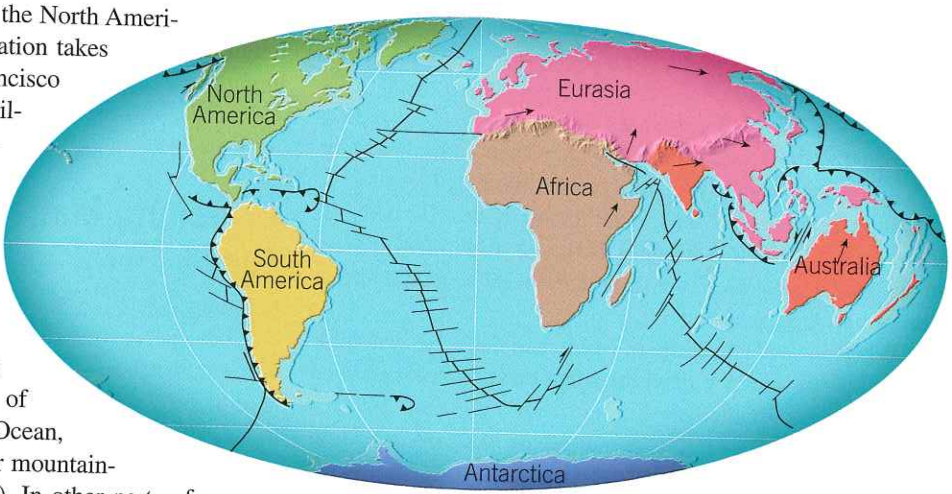


FIGURE 7.25 The World as it May Look 50 million Years from Now This reconstruction is highly idealized and based on the assumption that the processes that caused the breakup of Pangaea will continue to operate. (Modified after Robert S. Dietz, John C. Holden, C. Scotese, and others)

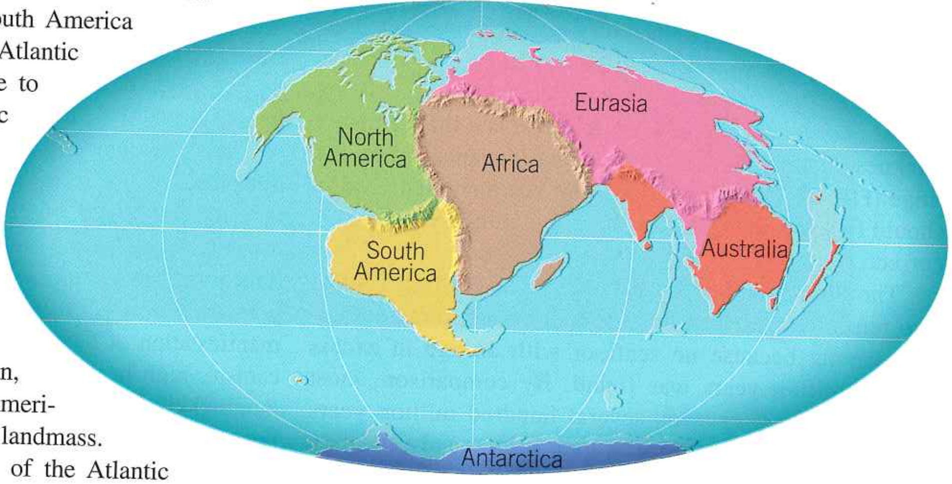


FIGURE 7.26 Earth as it May Appear 250 million Years from Now.

Andreas Fault will have slid past the North American plate. If this northward migration takes place, Los Angeles and San Francisco will pass each other in about 10 million years, and in about 60 million years the Baja Peninsula will begin to collide with the Aleutian islands.

If Africa continues on a northward path, it will continue to collide with Eurasia. The result will be the closing of the Mediterranean, the last remnant of a once vast ocean called Tethys Ocean, and the initiation of another major mountain-building episode (see Figure 7.25). In other parts of the world, Australia will be astride the equator and, along with New Guinea, will be on a collision course with Asia. Meanwhile, North and South America will begin to separate, while the Atlantic and Indian Oceans will continue to grow, at the expense of the Pacific Ocean.

A few geologists have even speculated on the nature of the globe 250 million years in the future. As shown in **FIGURE 7.26**, the next supercontinent may form as a result of subduction of the floor of the Atlantic Ocean, resulting in the collision of the Americas with the Eurasian–African landmass. Support for the possible closing of the Atlantic comes from a similar event when an ocean that predates the Atlantic closed during the formation of Pangaea. During the next 250 million years, Australia is also projected to collide with Southeast Asia. If this scenario is accurate, the dispersal of Pangaea will end when the continents reorganize into the next supercontinent.

Such projections, although interesting, must be viewed with considerable skepticism because many assumptions must be correct for these events to unfold as just described. Nevertheless, changes in the shapes and positions of continents that are equally profound will undoubtedly occur for many hundreds of millions of years to come. Only after much more of Earth's internal heat has been lost will the engine that drives plate motions cease.

7.8 CONCEPT CHECKS

1. What two plates are growing in size? Which plate is shrinking?
2. What new ocean basin was created by the breakup of Pangaea?
3. Briefly describe some major changes to the globe when we extrapolate present-day plate movements 50 million years into the future.

7.9 TESTING THE PLATE TECTONICS MODEL

List and explain the evidence used to support the plate tectonics theory.

Some of the evidence supporting continental drift has already been presented. With the development of the theory of plate tectonics, researchers began testing this new model of how Earth works. Although new supporting data were obtained, it has often been new interpretations of already existing data that have swayed the tide of opinion.

Evidence: Ocean Drilling

Some of the most convincing evidence for seafloor spreading came from the Deep Sea Drilling Project, which operated from 1968 until 1983. One of the early goals of the project was to gather samples of the ocean floor in order to establish its age. To accomplish this, the *Glomar Challenger*, a drilling ship capable of working in water thousands of meters deep, was built. Hundreds of holes were drilled through the layers of sediments that blanket the ocean crust, as well as into the basaltic rocks below. Rather than radiometrically date the crustal rocks, researchers used the fossil remains of microorganisms found in the sediments resting directly on the crust to date the seafloor at each site. Radiometric dates of the ocean crust itself are unreliable because of the alteration of basalt by seawater.

When the oldest sediment from each drill site was plotted against its distance from the ridge crest, the plot showed that the sediments increased in age with increasing distance from the ridge. This finding supported the seafloor-spreading hypothesis, which predicted that the youngest oceanic crust would be found at the ridge crest, the site of seafloor production, and the oldest oceanic crust would be located adjacent to the continents.

The thickness of ocean-floor sediments provided additional verification of seafloor spreading. Drill cores from the *Glomar Challenger* revealed that sediments are almost entirely absent on the ridge crest and that sediment thickness increases with increasing distance from the ridge (**FIGURE 7.27**). This pattern of sediment distribution should be expected if the seafloor-spreading hypothesis is correct.

The data collected by the Deep Sea Drilling Project also reinforced the idea that the ocean basins are geologically young because no seafloor with an age in excess of 180 million years was found. By comparison, most continental crust exceeds several hundred million years in age, and some has been located that exceeds 4 billion years in age.

In October 2003, the *JOIDES Resolution* became part of a new program, the Integrated Ocean Drilling Program (IODP). This new international effort uses multiple vessels for exploration, including the massive 210-meter-long (nearly 770-foot-long) *Chikyu* (meaning "planet Earth" in Japanese), which began operations in 2007 (see Figure 7.27). One of the goals of the IODP is to recover a complete section of the ocean crust, from top to bottom.

Evidence: Mantle Plumes and Hot Spots

Mapping volcanic islands and seamounts (submarine volcanoes) in the Pacific Ocean revealed several linear chains of volcanic structures. One of the most-studied chains consists of at least 129 volcanoes that extend from the Hawaiian islands to Midway Island and continue northwestward toward the Aleutian trench (**FIGURE 7.28**). Radiometric dating of this linear structure, called the *Hawaiian Island–Emperor Seamount chain*, showed that the volcanoes increase in age with increasing distance from the Big Island of Hawaii. The youngest volcanic island in the chain (Hawaii) rose from the ocean floor less than 1 million years ago, whereas Midway Island is 27 million years old, and Detroit Seamount, near the Aleutian trench, is about 80 million years old (see Figure 7.28).

Most researchers agree that a cylindrically shaped upwelling of hot rock, called a **mantle plume**, is located beneath the island of Hawaii. As the hot, rocky plume ascends through the mantle, the confining pressure drops, which triggers partial melting. (This process, called *decompression melting*, is discussed in Chapter 9.) The surface manifestation of this activity is a **hot spot**, an area of volcanism, high heat flow, and crustal uplifting that is a few hundred kilometers across. As the Pacific plate moved over a hot spot, a chain of volcanic structures known as a **hot-spot track** was built. As shown in Figure 7.28, the age of each volcano indicates how much time has elapsed since it was situated over the mantle plume.

A closer look at the five largest Hawaiian islands reveals a similar pattern of ages, from the volcanically active island of Hawaii to the inactive volcanoes that make up the oldest island, Kauai (see Figure 7.28). Five million years ago, when Kauai was positioned over the hot spot, it was the *only* modern Hawaiian island in existence. Visible evidence of the age of Kauai can be seen by examining its extinct volcanoes, which have been eroded into jagged peaks and vast canyons. By contrast, the relatively young island of Hawaii exhibits

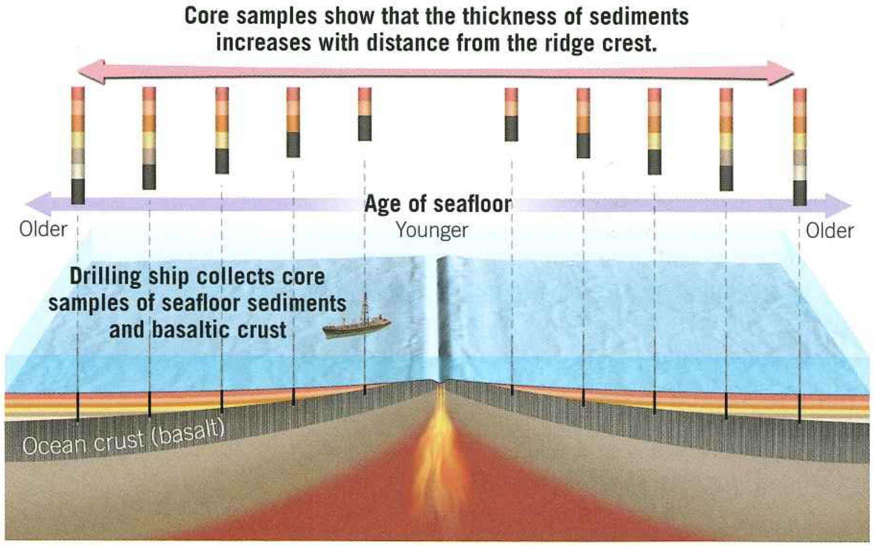
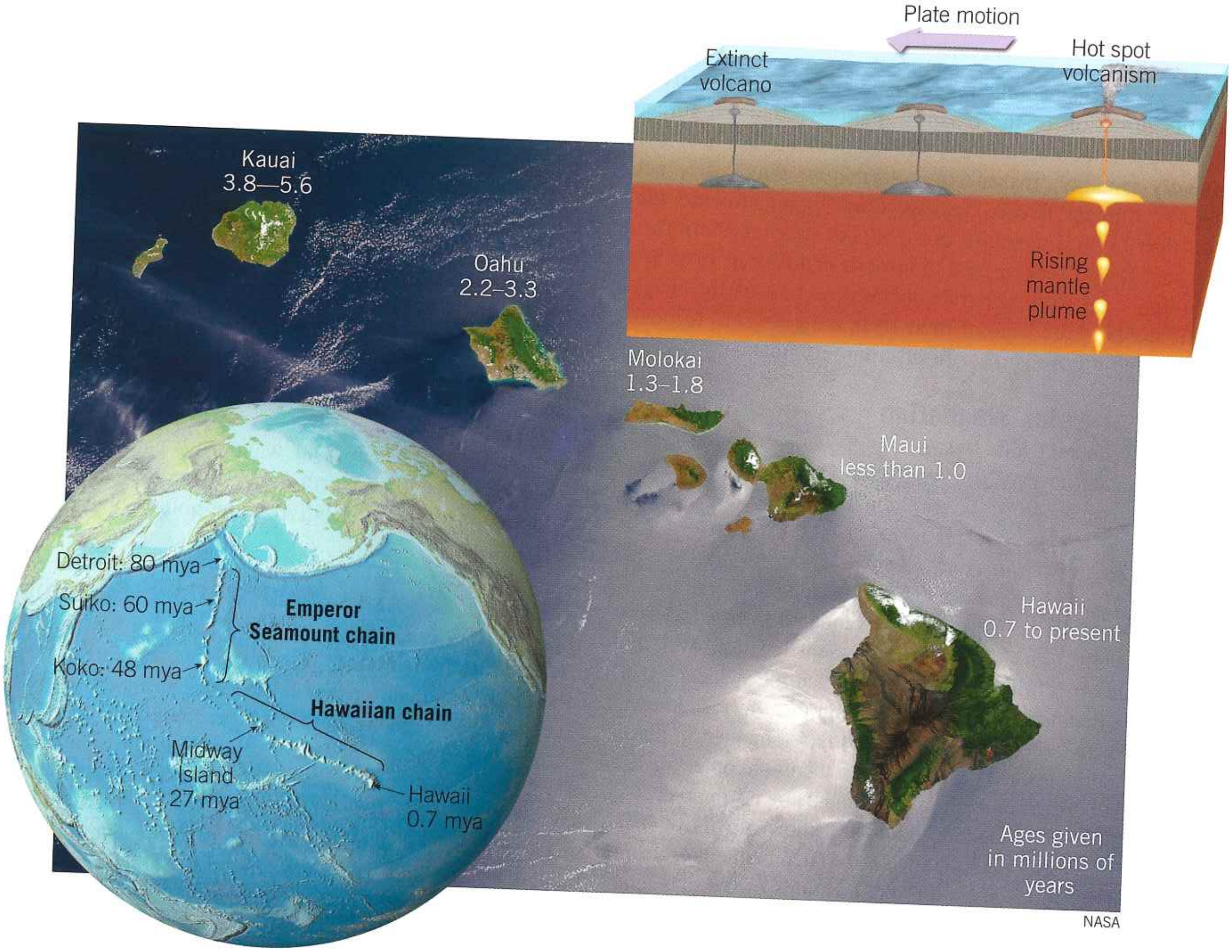


FIGURE 7.27 Deep-sea Drilling Data collected through deep-sea drilling have shown that the ocean floor is indeed youngest at the ridge axis.

***Chikyu* is a state-of-the-art drilling ship designed to drill up to 7,000 meters (more than 4 miles) below the seafloor.**


AP Photo/Itsuo Inouye



NASA

FIGURE 7.28 Hot Spots and Hot-Spot Tracks Radiometric dating of the Hawaiian islands shows that volcanic activity increases in age moving away from the Big Island of Hawaii.

many fresh lava flows, and one of its five major volcanoes, Kilauea, remains active today.

Evidence: Paleomagnetism

Anyone who has used a compass to find direction knows that Earth's magnetic field has north and south magnetic poles. Today these magnetic poles roughly align with the geographic poles. (The geographic poles are located where Earth's rotational axis intersects the surface.) Earth's magnetic field is similar to that produced by a simple bar magnet. Invisible lines of force pass through the planet and extend from one magnetic pole to the other (**FIGURE 7.29**). A compass needle, itself a small magnet free to rotate on an axis, becomes aligned with the magnetic lines of force and points to the magnetic poles.

Earth's magnetic field is less obvious than the pull of gravity because humans cannot feel it. Movement of a compass needle, however, confirms its presence. In addition, some naturally occurring minerals are magnetic and are influenced by Earth's magnetic field. One of the most common is the iron-rich mineral *magnetite*, which is abundant in lava flows of basaltic composition.* Basaltic lavas erupt at the surface at temperatures greater than 1000°C (1800°F), exceeding a threshold temperature for magnetism known as the **Curie point** (about 585°C [1085° F]). Consequently, the magnetite grains in molten lava are nonmagnetic. However, as the lava cools, these

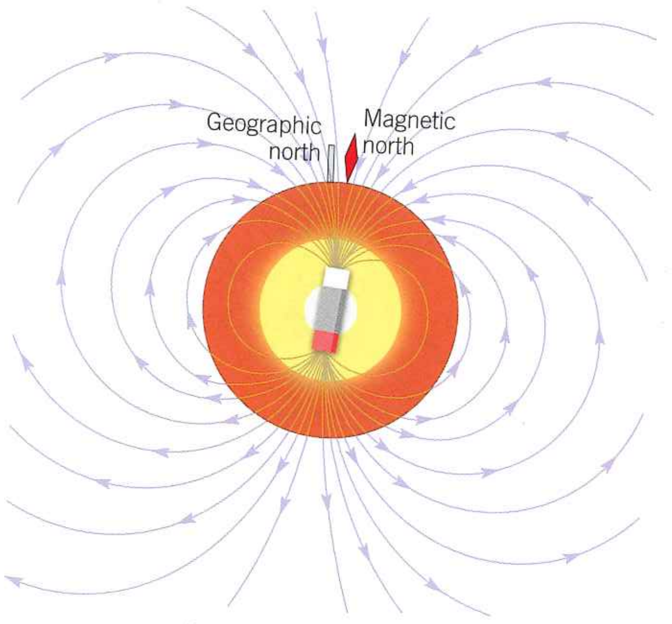


FIGURE 7.29 Earth's Magnetic Field Earth's magnetic field consists of lines of force much like those a giant bar magnet would produce if placed at the center of Earth.

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*Some sediments and sedimentary rocks also contain enough iron-bearing mineral grains to acquire a measurable amount of magnetization.

iron-rich grains become magnetized and align themselves in the direction of the existing magnetic lines of force. Once the minerals solidify, the magnetism they possess usually remains "frozen" in this position. Thus, they act like a compass needle because they "point" toward the position of the magnetic poles at the time of their formation. Rocks that formed thousands or millions of years ago and contain a "record" of the direction of the magnetic poles at the time of their formation are said to possess **paleomagnetism**, or **fossil magnetism**.

Apparent Polar Wandering

A study of paleomagnetism in ancient lava flows throughout Europe led to an interesting discovery. The magnetic alignment of iron-rich minerals in lava flows of different ages indicated that the position of the paleomagnetic poles had changed through time. A plot of the location of the magnetic north pole, as measured from Europe, revealed that during the past 500 million years, the pole had gradually wandered from a location near Hawaii northeastward to its present location over the Arctic Ocean (**FIGURE 7.30**). This was strong evidence that either the magnetic north pole had migrated, an idea known as *polar wandering*, or that the poles had remained in place and the continents had drifted beneath them—in other words, Europe had drifted in relation to the magnetic north pole.

Although the magnetic poles are known to move in a somewhat erratic path, studies of paleomagnetism from numerous locations show that the positions of the magnetic poles, averaged over thousands of years, correspond closely to the positions of the geographic poles. Therefore, a more acceptable explanation for the apparent polar wandering paths was provided by Wegener's hypothesis: If the magnetic poles remain stationary, their *apparent movement* is produced by continental drift.

Further evidence for continental drift came a few years later, when a polar-wandering path was constructed for North America (see Figure 7.30A). For the first 300 million years or so, the paths for North America and Europe were found to be similar in direction—but separated by about 5000 kilometers (3000 miles). Then, during the middle of the Mesozoic era (180 million years ago), they began to converge on the present North Pole. The explanation for these curves is that North America and Europe were joined until the Mesozoic, when the Atlantic began to open. From this time forward, these continents continuously moved apart. When North America and Europe are moved back to their pre-drift positions, as shown in Figure 7.30B, these apparent wandering paths coincide. This is evidence that North America and Europe were once joined and moved relative to the poles as part of the same continent.

Magnetic Reversals and Seafloor Spreading

Another discovery came when geophysicists learned that over periods of hundreds of thousands of years, Earth's magnetic field periodically reverses polarity. During a **magnetic reversal**, the magnetic north pole becomes the magnetic south pole and vice versa. Lava solidifying during a period of reverse polarity will be magnetized with the polarity opposite that of volcanic rocks being formed today. When rocks exhibit the same magnetism as the present magnetic field, they are said to possess **normal polarity**, whereas rocks exhibiting the opposite magnetism are said to have **reverse polarity**.

Once the concept of magnetic reversals was confirmed, researchers set out to establish a time scale for these occurrences. The task was to measure the magnetic polarity of hundreds of lava flows and use radiometric dating techniques

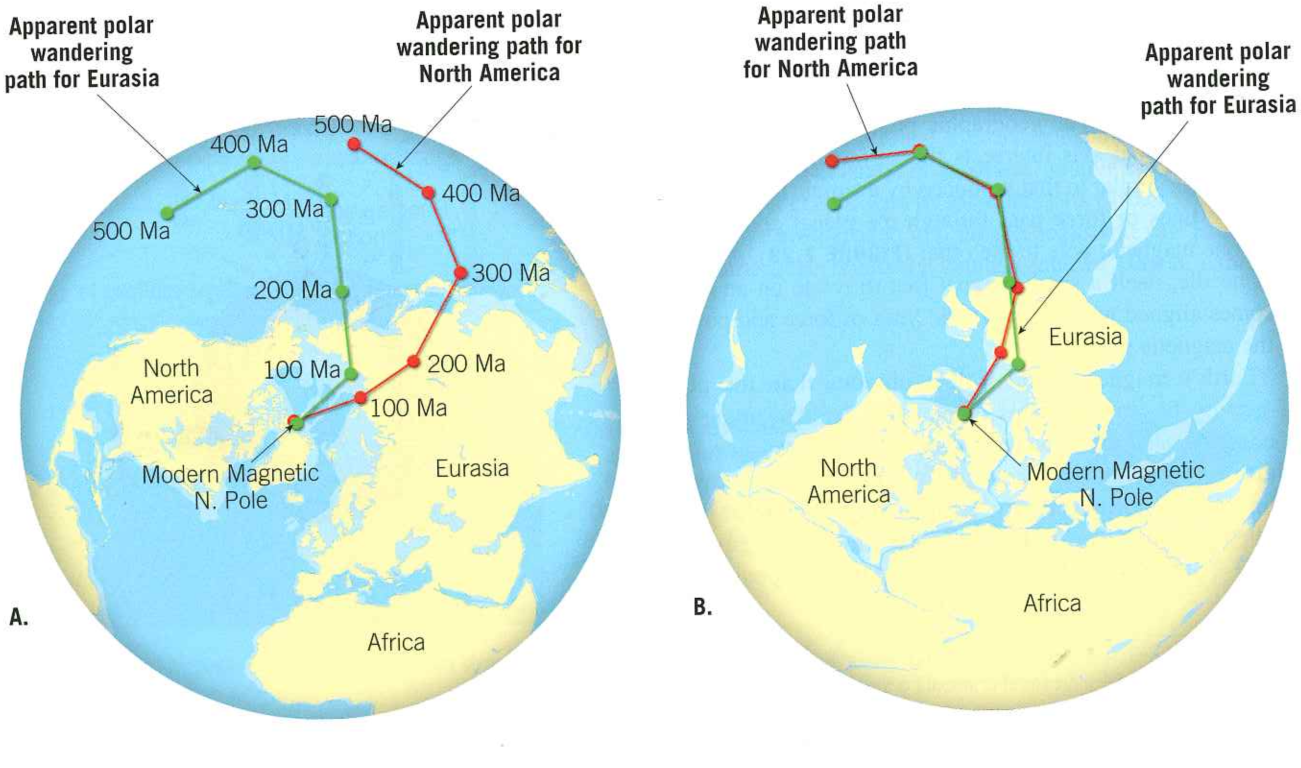
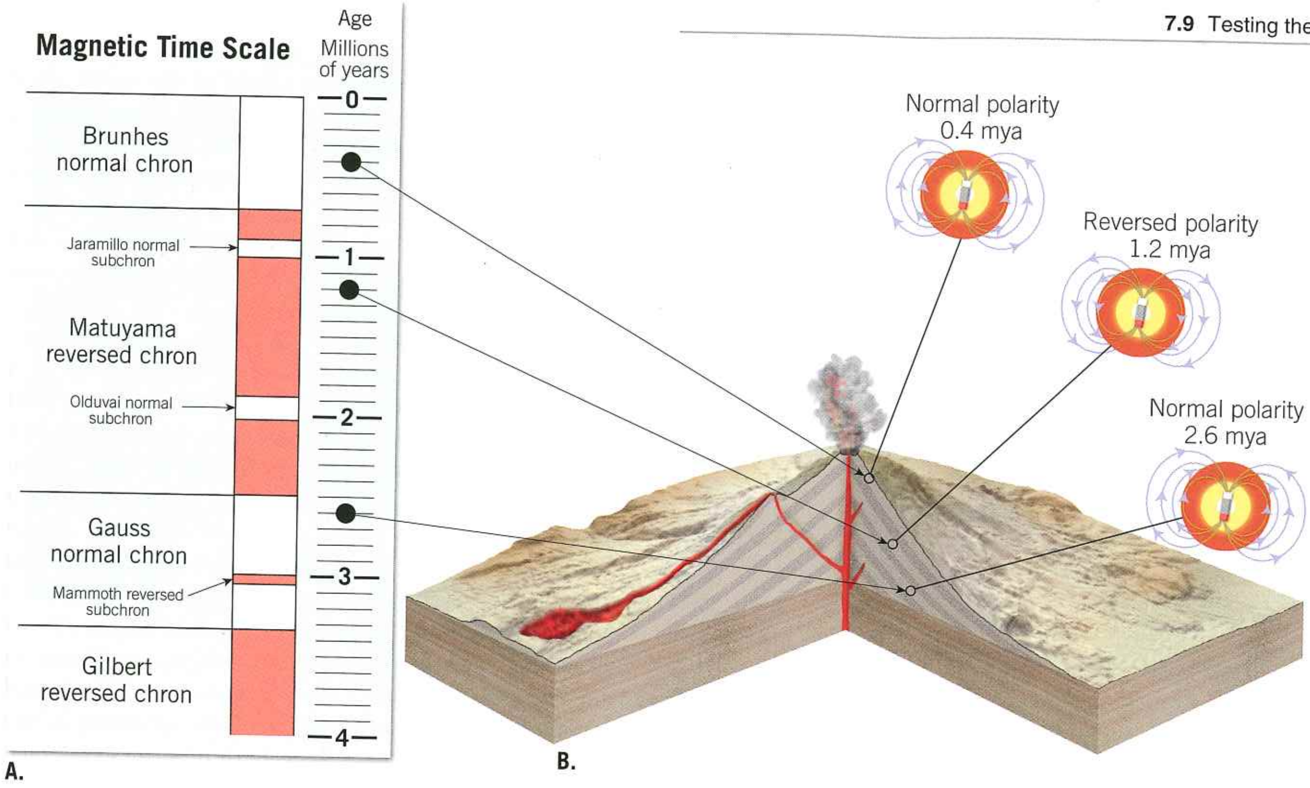


FIGURE 7.30 Apparent Polar Wandering Paths
A. The more westerly path determined from North American data is thought to have been caused by the westward drift of North America by about 24 degrees from Eurasia. **B.** The positions of the wandering paths when the landmasses are reassembled in their pre-drift locations.



SmartFigure 7.31 Time Scale of Magnetic Reversals **A.** Time scale of Earth's magnetic reversals for the past 4 million years. **B.** This time scale was developed by establishing the magnetic polarity for lava flows of known age. (Data from Allen Cox and G. B. Dalrymple)

to establish the age of each flow. **FIGURE 7.31** shows the **magnetic time scale** established using this technique for the past few million years. The major divisions of the magnetic time scale are called *chrons* and last roughly 1 million years. As more measurements became available, researchers realized that several short-lived reversals (less than 200,000 years long) often occurred during a single chron.

Meanwhile, oceanographers had begun to do magnetic surveys of the ocean floor in conjunction with their efforts to construct detailed maps of seafloor topography. These magnetic surveys were accomplished by towing very sensitive instruments, called **magnetometers**, behind research vessels (**FIGURE 7.32A**). The goal of these geophysical surveys was to map variations in the strength of Earth's magnetic field

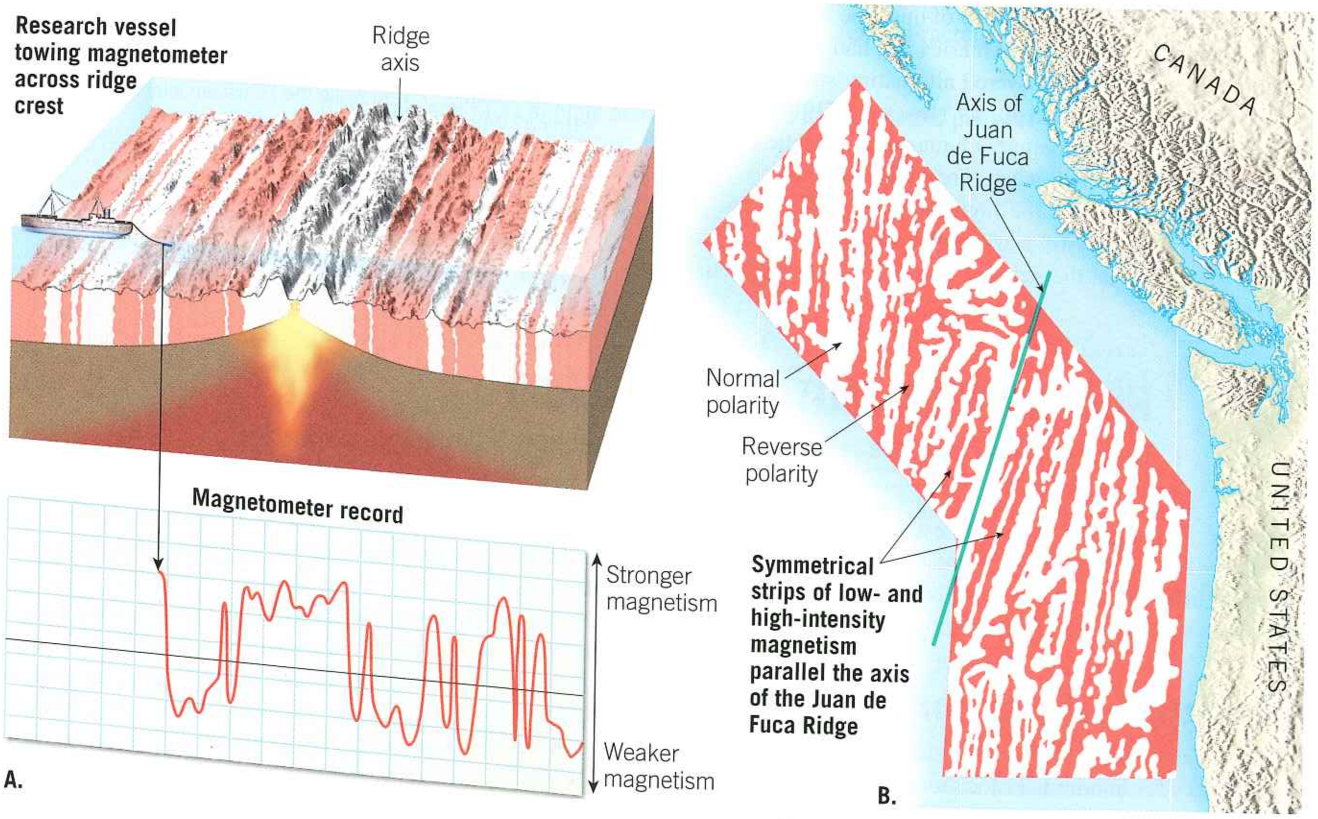
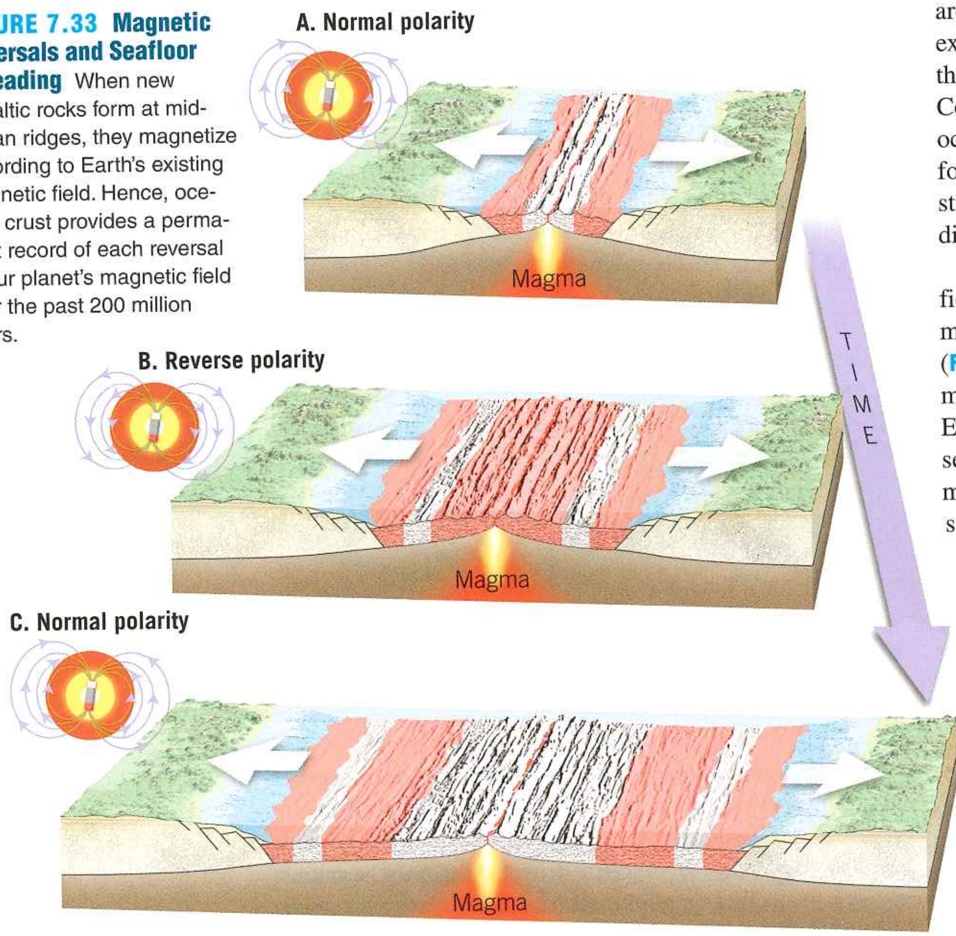


FIGURE 7.32 Ocean Floor as a Magnetic Recorder **A.** Magnetic intensities are recorded when a magnetometer is towed across a segment of the ocean floor. **B.** Notice the symmetrical strips of low- and high-intensity magnetism that parallel the axis of the Juan de Fuca Ridge. Vine and Matthews suggested that the strips of high-intensity magnetism occur where normally magnetized oceanic rocks enhanced the existing magnetic field. Conversely, the low-intensity strips are regions where the crust is polarized in the reverse direction, which weakens the existing magnetic field.


A. Normal polarity

B. Reverse polarity

C. Normal polarity

FIGURE 7.33 Magnetic Reversals and Seafloor Spreading When new basaltic rocks form at mid-ocean ridges, they magnetize according to Earth's existing magnetic field. Hence, oceanic crust provides a permanent record of each reversal of our planet's magnetic field over the past 200 million years.

that arise from differences in the magnetic properties of the underlying crustal rocks.

The first comprehensive study of this type was carried out off the Pacific coast of North America and had an unexpected outcome. Researchers discovered alternating stripes of high- and low-intensity magnetism, as shown in **FIGURE 7.32B**. This relatively simple pattern of magnetic variation defied explanation until 1963, when Fred Vine and D. H. Matthews demonstrated that the high- and low-intensity stripes supported the concept of seafloor spreading. Vine and Matthews suggested that the stripes of high-intensity magnetism are regions where the paleomagnetism of the ocean crust exhibits normal polarity (see Figure 7.30A). Consequently, these rocks *enhance* (reinforce) Earth's magnetic field. Conversely, the low-intensity stripes are regions where the ocean crust is polarized in the reverse direction and therefore *weaken* the existing magnetic field. But how do parallel stripes of normally and reversely magnetized rock become distributed across the ocean floor?

Vine and Matthews reasoned that as magma solidifies along narrow rifts at the crest of an oceanic ridge, it is magnetized with the polarity of the existing magnetic field (**FIGURE 7.33**). Because of seafloor spreading, this strip of magnetized crust would gradually increase in width. When Earth's magnetic field reverses polarity, any newly formed seafloor having the opposite polarity would form in the middle of the old strip. Gradually, the two halves of the old strip would be carried in opposite directions, away from the ridge crest. Subsequent reversals would build a pattern of normal and reverse magnetic stripes, as shown in Figure 7.33. Because new rock is added in equal amounts to both trailing edges of the spreading ocean floor, we should expect the pattern of stripes (size and polarity) found on one side of an oceanic ridge to be a mirror image of those on the other side. In fact, a survey across the Mid-Atlantic Ridge just south of Iceland reveals a pattern of magnetic stripes exhibiting a remarkable degree of symmetry in relation to the ridge axis.

7.9 CONCEPT CHECKS

1. What is the age of the oldest sediments recovered using deep-ocean drilling? How do the ages of these sediments compare to the ages of the oldest continental rocks?
2. Assuming that hot spots remain fixed, in what direction was the Pacific plate moving while the Hawaiian islands were forming? When Suiko Seamount was forming?
3. How do sediment cores from the ocean floor support the concept of seafloor spreading?
4. Describe how Fred Vine and D. H. Matthews related the seafloor-spreading hypothesis to magnetic reversals.

7.10 HOW IS PLATE MOTION MEASURED

Describe two methods researchers use to measure relative plate motion.

A number of methods are used to establish the direction and rate of plate motion. Some of these techniques not only confirm that lithospheric plates move but allow us to trace those movements back in geologic time.

Geologic Evidence for Plate Motion

Using ocean-drilling ships, researchers have obtained radiometric dates for hundreds of locations on the ocean floor. By knowing the age of a sample and its distance from the ridge axis where it was generated, an average rate of plate motion can be calculated.

Scientists have used these data, combined with paleomagnetism stored in hardened lavas on the ocean floor, to create maps that show the age of the ocean floor. The map in **FIGURE 7.34** shows that the reddish-orange colored bands range in age from the present to about 30 million years ago. The width of the bands indicates how much crust formed

Age of Oceanic Lithosphere

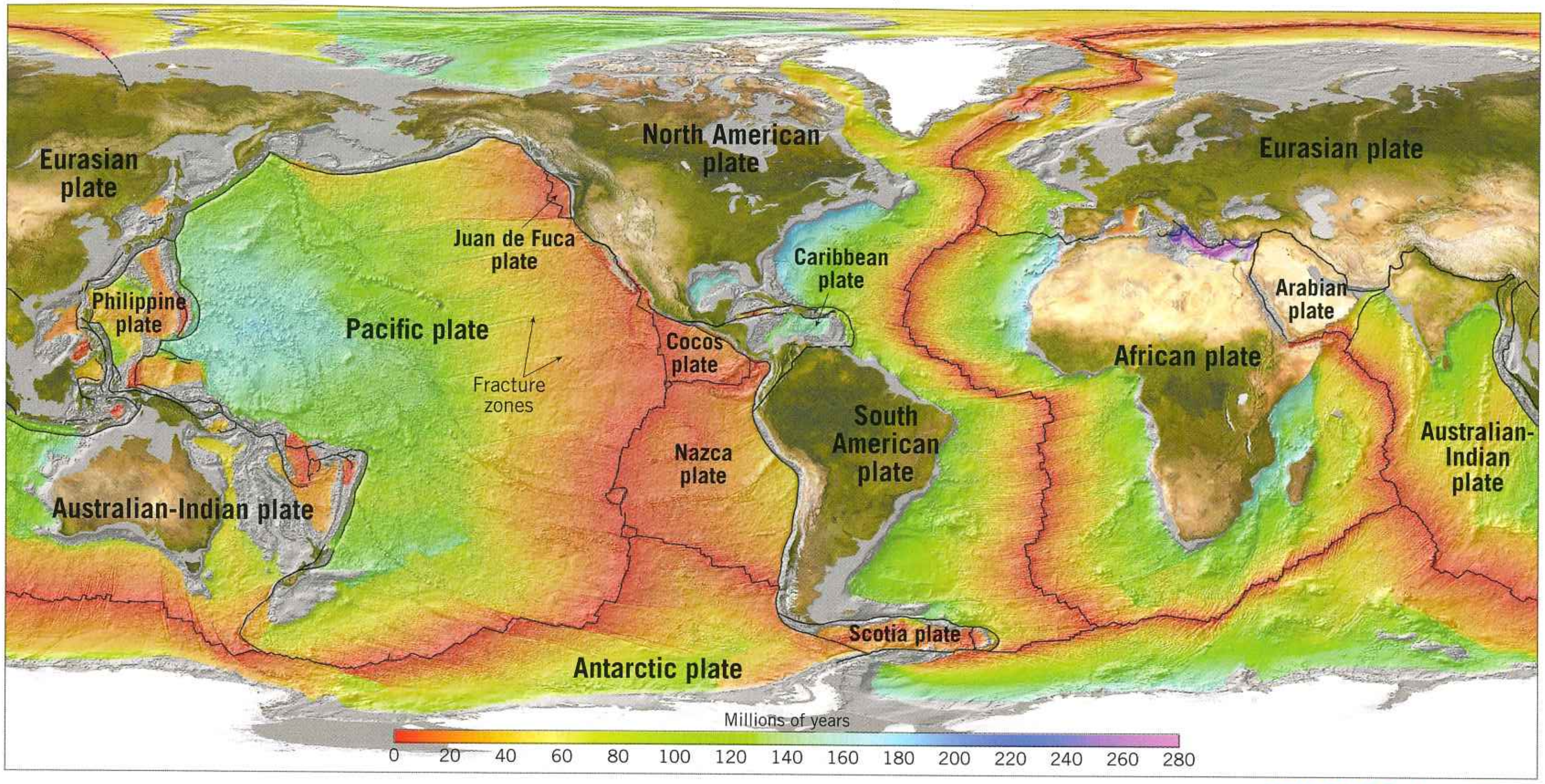


FIGURE 7.34 Age of the Ocean Floor

during that time period. For example, the reddish-orange band along the East Pacific Rise is more than three times wider than the same-color band along the Mid-Atlantic Ridge. Therefore, the rate of seafloor spreading has been approximately three times faster in the Pacific basin than in the Atlantic.

Maps of this type also provide clues to the current direction of plate movement. Notice the offsets in the ridges; these are transform faults that connect the spreading centers. Recall that transform faults are aligned parallel to the direction of spreading. Therefore, when measured carefully, transform faults yield the direction of plate movement.

One way geologists can establish the direction of plate motion in the past is by examining the long fracture zones that extend for hundreds or even thousands of kilometers from ridge crests. Fracture zones are inactive extensions

Directions and rates of plate motions measured in centimeters per year

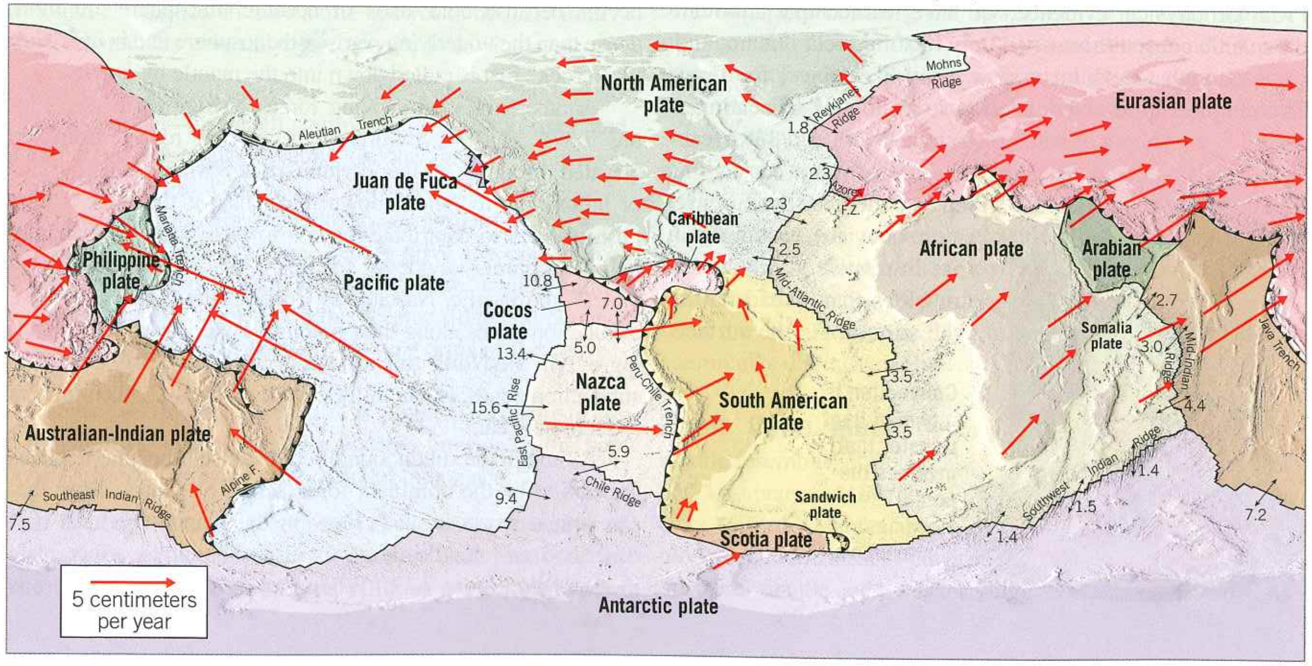


FIGURE 7.35 Rates of Plate Motion The red arrows show plate motion at selected locations based on GPS data. The small black arrows and labels show seafloor spreading velocities based mainly on paleomagnetic data. (Seafloor data from DeMets and others; GPS data from Jet Propulsion Laboratory)

of transform faults and therefore preserve a record of past directions of plate motion. Unfortunately, most of the ocean floor is less than 180 million years old, so to look deeper into the past, researchers must rely on paleomagnetic evidence provided by continental rocks.

Measuring Plate Motion from Space

You are likely familiar with the Global Positioning System (GPS), which is part of the navigation system used to locate one's position in order to provide directions to some other location. The GPS employs satellites that send radio signals that are intercepted by GPS receivers located at Earth's surface. The exact position of a site is determined by simultaneously establishing the distance from the receiver to four or more satellites. Researchers use specifically designed equipment to locate the position of a point on Earth to within a few millimeters (about the diameter of a small pea). To establish plate motions, GPS data are collected at numerous sites repeatedly over a number of years.

Data obtained from these and other techniques are shown in **FIGURE 7.35**. Calculations show that Hawaii is moving in a northwesterly direction and approaching Japan at 8.3 centimeters per year. A location in Maryland is retreating from a location in England at a speed of 1.7 centimeters per year—a value that is close to the 2.0-centimeters-per-year spreading rate established from paleomagnetic evidence obtained for the North Atlantic. Techniques involving GPS devices have also been useful in establishing small-scale crustal movements such as those that occur along faults in regions known to be tectonically active (for example, the San Andreas Fault).

7.10 CONCEPT CHECKS

1. What do transform faults that connect spreading centers indicate about plate motion?
2 Refer to Figure 7.35 and determine which three plates appear to exhibit the highest rates of motion.

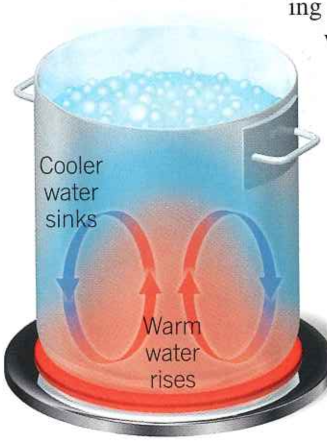
7.11 WHAT DRIVES PLATE MOTIONS?

Summarize what is meant by plate–mantle convection and explain two of the primary driving forces of plate motion.

Researchers are in general agreement that some type of convection—where hot mantle rocks rise and cold, dense oceanic lithosphere sinks—is the ultimate driver of plate tectonics. Many of the details of this convective flow, however, remain topics of debate in the scientific community.

Forces That Drive Plate Motion

From geophysical evidence, we have learned that although the mantle consists almost entirely of solid rock, it is hot and weak enough to exhibit a slow, fluid-like convective flow. The simplest type of **convection** is analogous to heating a pot of water on a stove (**FIGURE 7.36**). Heating the base of a pot causes the water to become less dense (more buoyant), causing it to rise in relatively thin sheets or blobs that spread out at the surface. As the surface layer cools, its density increases, and the cooler water sinks back to the bottom of the pot, where it is reheated until it achieves enough buoyancy to rise again. Mantle convection is similar to, but considerably more complex than, the model just described.



Convection is a type of heat transfer that involves the actual movement of a substance.

FIGURE 7.36 Convection in a Cooking Pot As a stove warms the water in the bottom of a cooking pot, the heated water expands, becomes less dense (more buoyant), and rises. Simultaneously, the cooler, denser water near the top sinks.

There is general agreement that subduction of cold, dense slabs of oceanic lithosphere is a major driving force of plate motion (**FIGURE 7.37**). This phenomenon, called **slab pull**, occurs because cold slabs of oceanic lithosphere are more dense than the underlying warm asthenosphere and hence "sink like a rock" that is pulled down into the mantle by gravity.

Another important driving force is **ridge push** (see Figure 7.37). This gravity-driven mechanism results from the elevated position of the oceanic ridge, which causes slabs of lithosphere to "slide" down the flanks of the ridge. Ridge push appears to contribute far less to plate motions than slab pull. The primary evidence for this is that the fastest-moving plates—the Pacific, Nazca, and Cocos plates—have extensive subduction zones along their margins. By contrast, the spreading rate in the North Atlantic basin, which is nearly devoid of subduction zones, is one of the lowest, at about 2.5 centimeters (1 inch) per year.

Although the subduction of cold, dense lithospheric plates appears to be the dominant force acting on plates, other factors are at work as well. Flow in the mantle, perhaps best described as "mantle drag," is also thought to affect plate motion (see Figure 7.37). When flow in the asthenosphere is

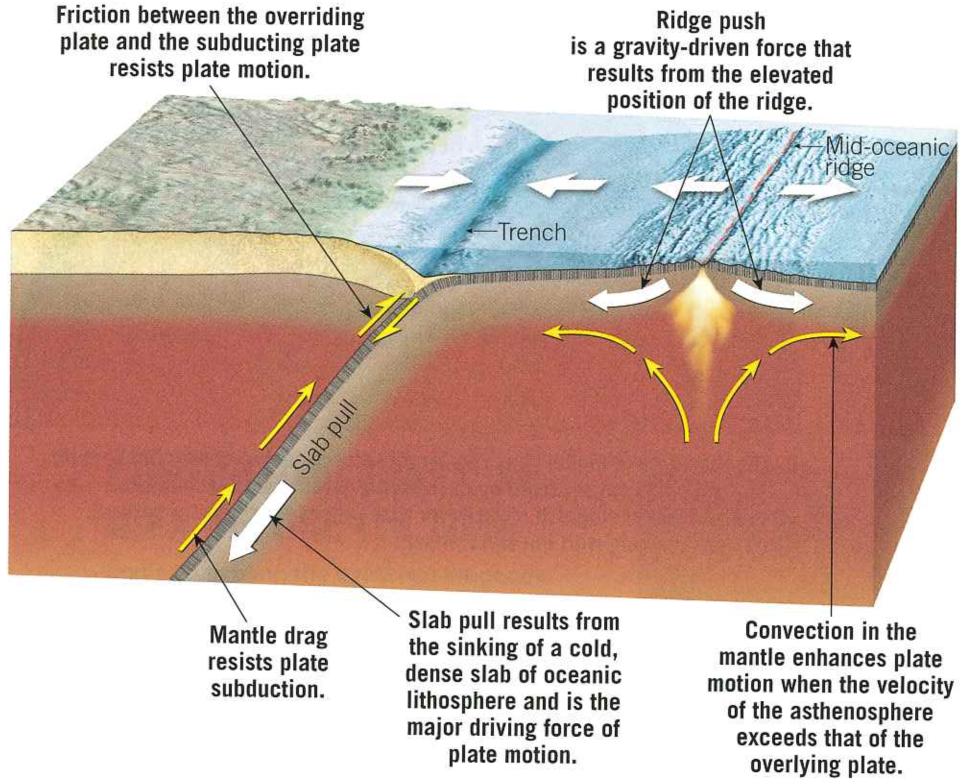


FIGURE 7.37 Forces That Act on Plates

moving at a velocity that exceeds that of the plate, mantle drag enhances plate motion. However, if the asthenosphere is moving more slowly than the plate, or if it is moving in the opposite direction, this force tends to resist plate motion. Another type of resistance to plate motion occurs along some subduction zones, where friction between the overriding plate and the descending slab generates significant earthquake activity.

Models of Plate–Mantle Convection

Although convection in the mantle has yet to be fully understood, researchers generally agree on the following:

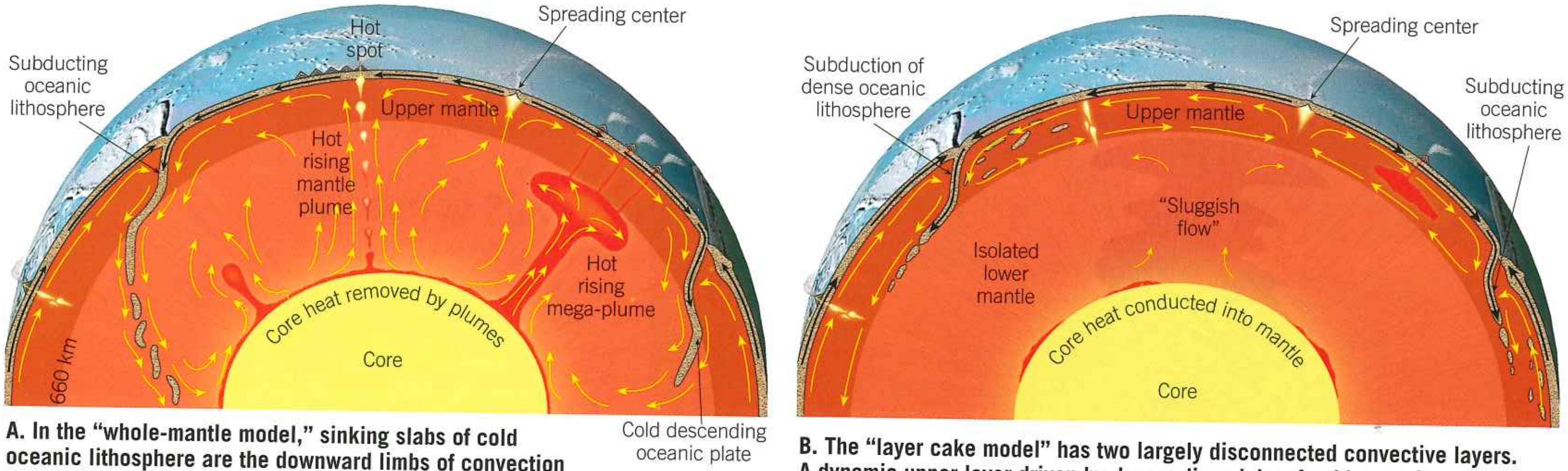
- Convective flow in the rocky 2900-kilometer- (1800-mile-) thick mantle—in which warm, buoyant rock rises and cooler, denser material sinks—is the underlying driving force for plate movement.
- Mantle convection and plate tectonics are part of the same system. Subducting oceanic plates drive the cold downward-moving portion of convective flow, while shallow upwelling of hot rock along the oceanic ridge and buoyant mantle plumes are the upward-flowing arms of the convective mechanism.
- Convective flow in the mantle is a major mechanism for transporting heat away from Earth's interior to the surface, where it is eventually radiated into space.

What is not known with certainty is the exact structure of this convective flow. Several models have been proposed for plate–mantle convection, and we will look at two of them.

Whole-Mantle Convection Most researchers favor some type of *whole-mantle convection* model, also called the *plume model*, in which cold oceanic lithosphere sinks to great depths and stirs the entire mantle (**FIGURE 7.38A**). The whole-mantle model suggests that the ultimate burial ground for subducting slabs is the core–mantle boundary. This downward flow is balanced by buoyantly rising mantle plumes that transport hot material toward the surface (see Figure 7.38A).

Two kinds of plumes have been proposed—narrow tube-like plumes and giant upwellings. The long, narrow plumes that extend from the core–mantle boundary are thought to produce hot-spot volcanism of the type associated with the Hawaiian islands, Iceland, and Yellowstone. Areas of large mega-plumes, as shown in Figure 7.38A, are thought to occur beneath the Pacific basin and southern Africa. The latter structure is thought to account for the fact that southern Africa has an elevation that is much higher than would be predicted for a stable continental landmass. Heat for both types of plumes is thought to arise mainly from the core, while the deep mantle provides a source for chemically distinct magmas.

Layer Cake Model Some researchers argue that the mantle resembles a "layer cake" divided at a depth of perhaps 660 kilometers (410 miles) but no deeper than 1000 kilometers (620 miles). As shown in **FIGURE 7.38B**, this layered model has two zones of convection—a thin, dynamic layer in the upper mantle and a thicker, sluggish one located below. As



A. In the "whole-mantle model," sinking slabs of cold oceanic lithosphere are the downward limbs of convection cells, while rising mantle plumes carry hot material from the core-mantle boundary toward the surface.

B. The "layer cake model" has two largely disconnected convective layers. A dynamic upper layer driven by descending slabs of cold oceanic lithosphere and a sluggish lower layer that carries heat upward without appreciably mixing with the layer above.

FIGURE 7.38 Models of Mantle Convection

with the whole-mantle model, the downward convective flow is driven by the subduction of cold, dense oceanic lithosphere. However, rather than reach the lower mantle, these subducting slabs penetrate to depths of no more than 1000 kilometers (620 miles). Notice in Figure 7.38B that the upper layer in the layer cake model is littered with recycled oceanic lithosphere of various ages. Melting of these fragments is thought to be the source of magma for some of the volcanism that occurs away from plate boundaries, as in the volcanoes of Hawaii.

In contrast to the active upper mantle, the lower mantle is sluggish and does not provide material to support volcanism at the surface. However, very slow convection within this layer likely carries heat upward, but very little mixing between these two layers is thought to occur.

The actual shape of the convective flow in the mantle is a matter of current scientific investigation and is highly debated by geologists. Perhaps a hypothesis that combines features from the layer cake model and the whole-mantle convection model will emerge.

McPHOTO/AGE Fotostock

7.11 CONCEPT CHECKS

1. Describe slab pull and ridge push. Which of these forces appears to contribute more to plate motion?
2. What role are mantle plumes thought to play in the convective flow in the mantle?
3. Briefly describe the two models proposed for mantle–plate convection.

EYE ON EARTH

In December 2011 a new volcanic island formed near the southern end of the Red Sea. People fishing in the area witnessed lava fountains reaching up to 30 meters (100 feet). This volcanic activity occurred off the west coast of Yemen, along the Red Sea Rift, among a collection of small islands in the Zubair Group. (NASA)

QUESTION 1 *What type of plate boundary produced this new volcanic island?*

QUESTION 2 *What two plates border the Red Sea Rift?*

QUESTION 3 *Are these two plates moving toward or away from each other?*

7 CONCEPTS IN REVIEW

Plate Tectonics: A Scientific Revolution Unfolds

7.1 FROM CONTINENTAL DRIFT TO PLATE TECTONICS

Discuss the view that most geologists held prior to the 1960s regarding the geographic positions of the ocean basins and continents.

- Fifty years ago, most geologists thought that ocean basins were very old and that continents were fixed in place. Those ideas were discarded with a scientific revolution that revitalized geology: the theory of plate tectonics. Supported by multiple kinds of evidence, plate tectonics is the foundation of modern Earth science.

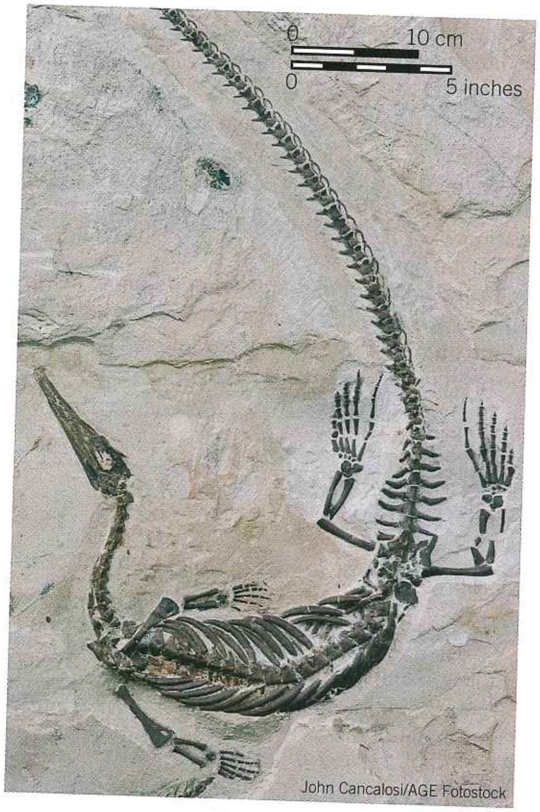
7.2 CONTINENTAL DRIFT: AN IDEA BEFORE ITS TIME

List and explain the evidence Wegener presented to support his continental drift hypothesis.

KEY TERMS continental drift, supercontinent, Pangaea

- German meteorologist Alfred Wegener formulated the idea of continental drift in 1917. He suggested that Earth's continents are not fixed in place but have moved slowly over geologic time.
- Wegener reconstructed a super-continent called Pangaea that existed about 200 million years ago, during the late Paleozoic and early Mesozoic.
- Wegener's evidence that Pangaea existed but later broke into pieces that drifted apart included (1) the shape of the continents, (2) continental fossil organisms that matched across oceans, (3) matching rock types and modern mountain belts, and (4) sedimentary rocks that recorded ancient climates, including glaciers on the southern portion of Pangaea.

Q Why did Wegener choose organisms such as *Glossopteris* and *Mesosaurus* as evidence for continental drift, as opposed to other fossil organisms such as sharks or jellyfish?



John Cancalosi/AGE Fotostock

7.3 THE GREAT DEBATE

Discuss the two main objections to the continental drift hypothesis.

- Wegener's hypothesis suffered from two flaws: It proposed tidal forces as the mechanism for the motion of continents, and it implied that the continents would have plowed their way through weaker oceanic crust, like a boat cutting through a thin layer of sea ice. Geologists rejected the idea of continental drift when Wegener proposed it, and it wasn't resurrected for another 50 years.

Q Today, we know that the early twentieth-century scientists who rejected the idea of continental drift were wrong. Were they therefore bad scientists? Why or why not?

7.4 THE THEORY OF PLATE TECTONICS

List the major differences between Earth's lithosphere and asthenosphere and explain the importance of each in the plate tectonics theory.

KEY TERMS ocean ridge system, theory of plate tectonics, lithosphere, asthenosphere, lithospheric plate (plate)

- Research conducted during World War II led to new insights that helped revive Wegener's hypothesis of continental drift. Exploration of the seafloor revealed previously unknown features, including an extremely long mid-ocean ridge system. Sampling of the oceanic crust revealed that it was quite young relative to the continents.
- The lithosphere is Earth's outermost rocky layer that is broken into plates. It is relatively stiff and deforms by breaking or bending. Beneath the lithosphere is the asthenosphere, a relatively weak layer that deforms by flowing. The lithosphere consists both of crust (either oceanic or continental) and underlying upper mantle.
- There are seven large plates, another seven intermediate-size plates, and numerous relatively small microplates. Plates meet along boundaries that may either be divergent (moving apart from each other), convergent (moving toward each other), or transform (moving laterally past each other).

7.5 DIVERGENT PLATE BOUNDARIES AND SEAFLOOR SPREADING

Sketch and describe the movement along a divergent plate boundary that results in the formation of new oceanic lithosphere.

KEY TERMS divergent plate boundary (spreading center), rift valley, seafloor spreading, continental rift

- Seafloor spreading leads to the generation of new oceanic lithosphere at mid-ocean ridge systems. As two plates move apart from one another, tensional forces open cracks in the plate, allowing magma to well up and generate new slivers of seafloor. This process generates new oceanic lithosphere at a rate of 2 to 15 centimeters (1 to 6 inches) each year.
- As it ages, oceanic lithosphere cools and becomes denser. As it is transported away from the mid-ocean ridge, it therefore subsides. At the same time, new material is added to its underside, causing the plate to grow thicker.
- Divergent boundaries are not limited to the seafloor. Continents can break apart, too, starting with a continental rift (as in modern-day eastern Africa) and eventually leading to a new ocean basin opening between the two sides of the rift.

7.6 CONVERGENT PLATE BOUNDARIES AND SUBDUCTION

Compare and contrast the three types of convergent plate boundaries and name a location where each type can be found.

KEY TERMS convergent plate boundary, subduction zone, deep-ocean trench, partial melting, continental volcanic arc, volcanic island arc (island arc)

- When plates move toward one another, oceanic lithosphere is subducted into the mantle, where it is recycled. Subduction manifests itself on the ocean floor as a deep linear trench. The subducting slab of oceanic lithosphere can descend at a variety of angles, from nearly horizontal to nearly vertical.
- Aided by the presence of water, the subducted oceanic lithosphere triggers melting in the mantle, which produces magma. The magma is less dense than the surrounding rock and will rise. It may cool at depth, thickening the crust, or it may make it all the way to Earth's surface, where it erupts as a volcano.
- A line of volcanoes that erupt through continental crust is termed a continental volcanic arc, while a line of volcanoes that erupt through an overriding plate of oceanic lithosphere is a volcanic island arc.
- Continental crust resists subduction due to its relatively low density, and so when an intervening ocean basin is completely destroyed through subduction, the continents on either side collide, generating a new mountain range.

Q Sketch a typical continental volcanic arc and label the key parts. Then repeat the drawing with an overriding plate made of oceanic lithosphere.

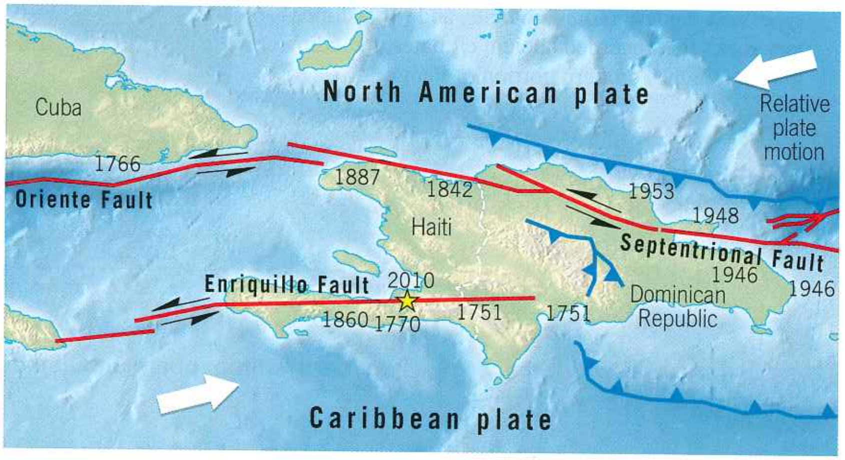
7.7 TRANSFORM PLATE BOUNDARIES

Describe the relative motion along a transform plate boundary and locate several examples on a plate boundary map.

KEY TERMS transform plate boundary (transform fault), fracture zone

- At a transform boundary, lithospheric plates slide horizontally past one another. No new lithosphere is generated, and no old lithosphere is consumed. Shallow earthquakes signal the movement of these slabs of rock as they grind past their neighbors.
- The San Andreas Fault in California is an example of a transform boundary in continental crust, while the fracture zones between segments of the Mid-Atlantic Ridge are examples of transform faults in oceanic crust.

Q On the accompanying tectonic map of the Caribbean, find the Enriquillo Fault. (The location of the 2010 Haiti earthquake is shown as a yellow star.) What type a fault is the Enriquillo Fault? Are there any other faults in the area that show the same type of motion?



7.8 HOW DO PLATES AND PLATE BOUNDARIES CHANGE?

Explain why plates such as the African and Antarctic plates are getting larger, while the Pacific plate is getting smaller.

- Although the total surface area of Earth does not change, the shape and size of individual plates are constantly changing as a result of subduction and seafloor spreading. Plate boundaries can also be created or destroyed in response to changes in the forces acting on the lithosphere.
- The breakup of Pangaea and the collision of India with Eurasia are two examples of how plates change through geologic time.

7.9 TESTING THE PLATE TECTONICS MODEL

List and explain the evidence used to support the plate tectonics theory.

KEY TERMS mantle plume, hot spot, hot-spot track, Curie point, paleomagnetism (fossil magnetism), magnetic reversal, normal polarity, reverse polarity, magnetic time scale, magnetometer

- Multiple lines of evidence have verified the plate tectonics model. For instance, the Deep Sea Drilling Project found that the age of the seafloor increases with distance from a mid-ocean ridge. The thickness of sediment atop this seafloor is also proportional to distance from the ridge: Older lithosphere has had more time to accumulate sediment.
- Overall, oceanic lithosphere is quite young, with none older than about 180 million years.
- A hot spot is an area of volcanic activity where a mantle plume reaches the surface. Volcanic rocks generated by hot-spot volcanism provide evidence of both the direction and rate of plate movement over time.
- Magnetic minerals such as magnetite align themselves with Earth's magnetic field as rock forms. These fossil magnets act as recorders of the ancient orientation of Earth's magnetic field. This is useful to geologists in two ways: (1) It allows a given stack of rock layers to be interpreted in terms of changing position relative to the magnetic poles through time, and (2) reversals in the orientation of the magnetic field are preserved as "stripes" of normal and reversed polarity in the oceanic crust. Magnetometers reveal this signature of seafloor spreading as a symmetrical pattern of magnetic stripes parallel to the axis of the mid-ocean ridge.

7.10 HOW IS PLATE MOTION MEASURED?

Describe two methods researchers use to measure relative plate motion.

- Data collected from the ocean floor have established the direction and rate of motion of lithospheric plates. Transform faults point in the direction the plate is moving. Sediments with diagnostic fossils and radiometric dates of igneous rocks both help to calibrate the rate of motion.
- GPS satellites can be used to accurately measure the motion of special receivers to within a few millimeters. These "real-time" data back up the inferences made from seafloor observations. Plates move at about the same rate your fingernails grow: an average of about 5 centimeters (2 inches) per year.

7.11 WHAT DRIVES PLATE MOTIONS?

Summarize what is meant by plate–mantle convection and explain two of the primary driving forces of plate motion.

KEY TERMS convection, slab pull, ridge push

- Some kind of convection (upward movement of less dense material and downward movement of more dense material) appears to drive the motion of plates.
- Slabs of oceanic lithosphere sink at subduction zones because a subducted slab is denser than the underlying asthenosphere. In this process, called slab pull, Earth's gravity tugs at the slab, drawing the rest of the plate toward the subduction zone. As lithosphere descends the mid-ocean ridge, it exerts a small additional force, the outward-directed ridge push. Frictional drag exerted on the underside of plates by flowing mantle is another force that acts on plates and influences their direction and rate of movement.
- The exact patterns of mantle convection are not fully understood. Convection may occur throughout the entire mantle, as suggested by the whole-mantle model. Or it may occur in two layers within the mantle—the active upper mantle and the sluggish lower mantle—as proposed in the layer cake model.

Q Compare and contrast mantle convection with the operation of a lava lamp.

Photo by Steve Bower/Shutterstock

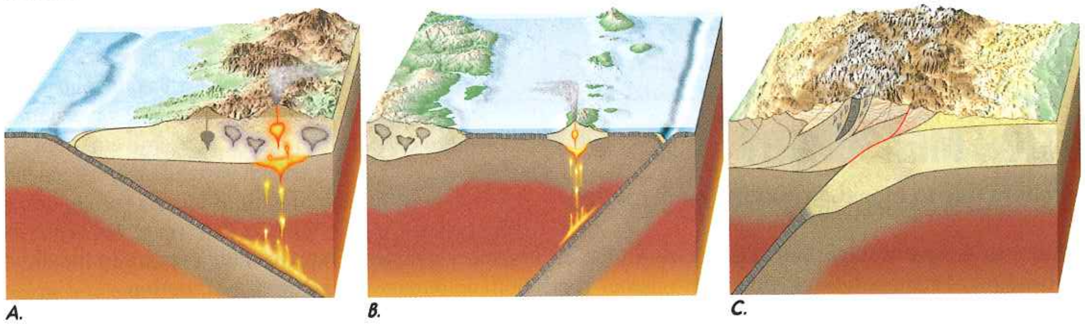
E IT SOME **THOUGHT**

fter referring to the section in the Introduction titled "The Nature of Scientific Inquiry," answer the following:

What observation led Alfred Wegener to develop his continental drift hypothesis?
Why did the majority of the scientific community reject the continental drift hypothesis?
Do you think Wegener followed the basic principles of scientific inquiry? Support your answer.

eferring to the accompanying diagrams that illustrate the three types of convergent plate boundaries, complete the llowing:

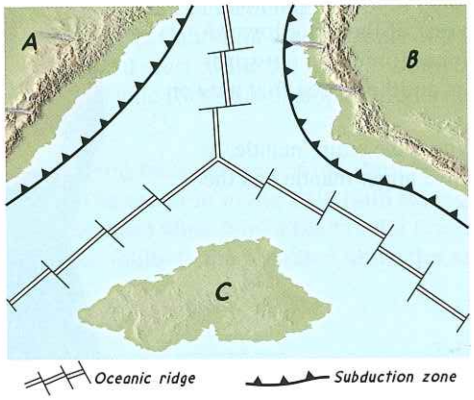
Identify each type of convergent boundary.
On what type of crust do volcanic island arcs develop?
Why are volcanoes largely absent where two continental blocks collide?
Describe two ways that oceanic–oceanic convergent boundaries are different from oceanic–continental boundaries. How are they similar?



ome predict that California will sink into the ocean. Is this idea consistent with the theory of plate tectonics? Explain.

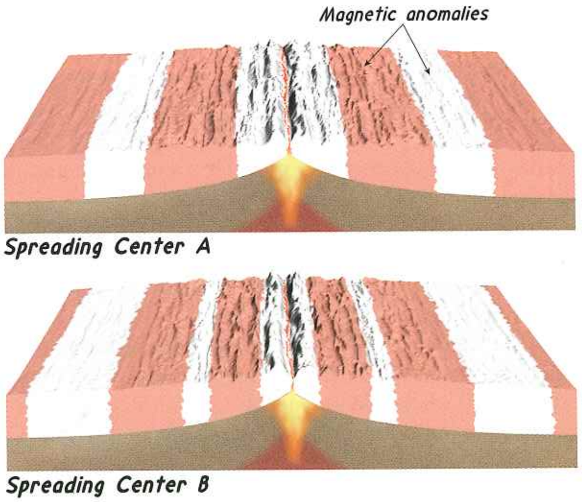
efer to the accompanying hypothetical plate map to answer the following questions:

How many portions of plates are shown?
Are continents A, B, and C moving toward or away from each other? How did you determine your answer?
Explain why active volcanoes are more likely to be found on continents A and B than on continent C.
Provide at least one scenario in which volcanic activity might be triggered on continent C.



olcanoes, such as the Hawaiian chain, that form over mantle plumes are ome of the largest shield volcanoes on Earth. However, several shield olcanoes on Mars are gigantic compared to those on Earth. What does his difference tell us about the role of plate motion in shaping the Marian surface?

6. Imagine that you are studying seafloor spreading along two different oceanic ridges. Using data from a magnetometer, you produced the two accompanying maps. From these maps, what can you determine about the relative rates of seafloor spreading along these two ridges? Explain.



7. Australian marsupials (kangaroos, koala bears, etc.) have direct fossil links to marsupial opossums found in the Americas. Yet the modern marsupials in Australia are markedly different from their American relatives. How does the breakup of Pangaea help to explain these differences (see Figure 7.24)?

8. Density is a key component in the behavior of Earth materials and is especially important in understanding key aspects of plate tectonics. Describe three different ways that density and/or density differences play a role in plate tectonics.

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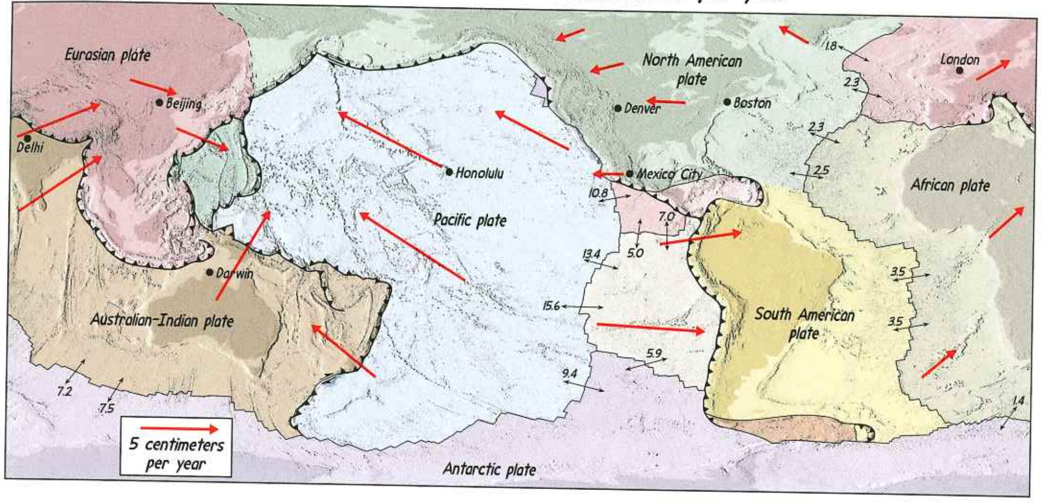
9. Refer to the accompanying map and the pairs of cities below to complete the following: (Boston, Denver), (London, Boston), (Honolulu, Beijing)

a. List the pair of cities that is moving apart as a result of plate motion.
b. List the pair of cities that is moving closer as a result of plate motion.
c. List the pair of cities that is presently not moving relative to each other.

Plate motion measured in centimeters per year



EXAMINING THE **EARTH SYSTEM**

1. As an integral subsystem of the Earth system, plate tectonics has played a major role in determining the events that have taken place on Earth since its formation about 4.6 billion years ago. Briefly comment on the general effect that the changing positions of the continents and the redistribution of land and water over Earth's surface have had on the atmosphere, hydrosphere, and biosphere through time. You may want to review plate tectonics by investigating the topic on the Internet using a search engine or visit the U.S. Geological Survey's (USGS's) This Dynamic Earth: The Story of Plate Tectonics Website, at **http://pubs.usgs.gov/gip/dynamic/dynamic.html.**

. Assume that plate tectonics did not cause the breakup of the supercontinent Pangaea. Use the accompanying map of Pangaea to describe how the climate (atmosphere), vegetation and animal life (biosphere), and geologic features (geosphere) would be different from the conditions that exist today in the areas currently occupied by the cities of Miami, Florida; Chicago, Illinois; New York, New York; and your college campus location.

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