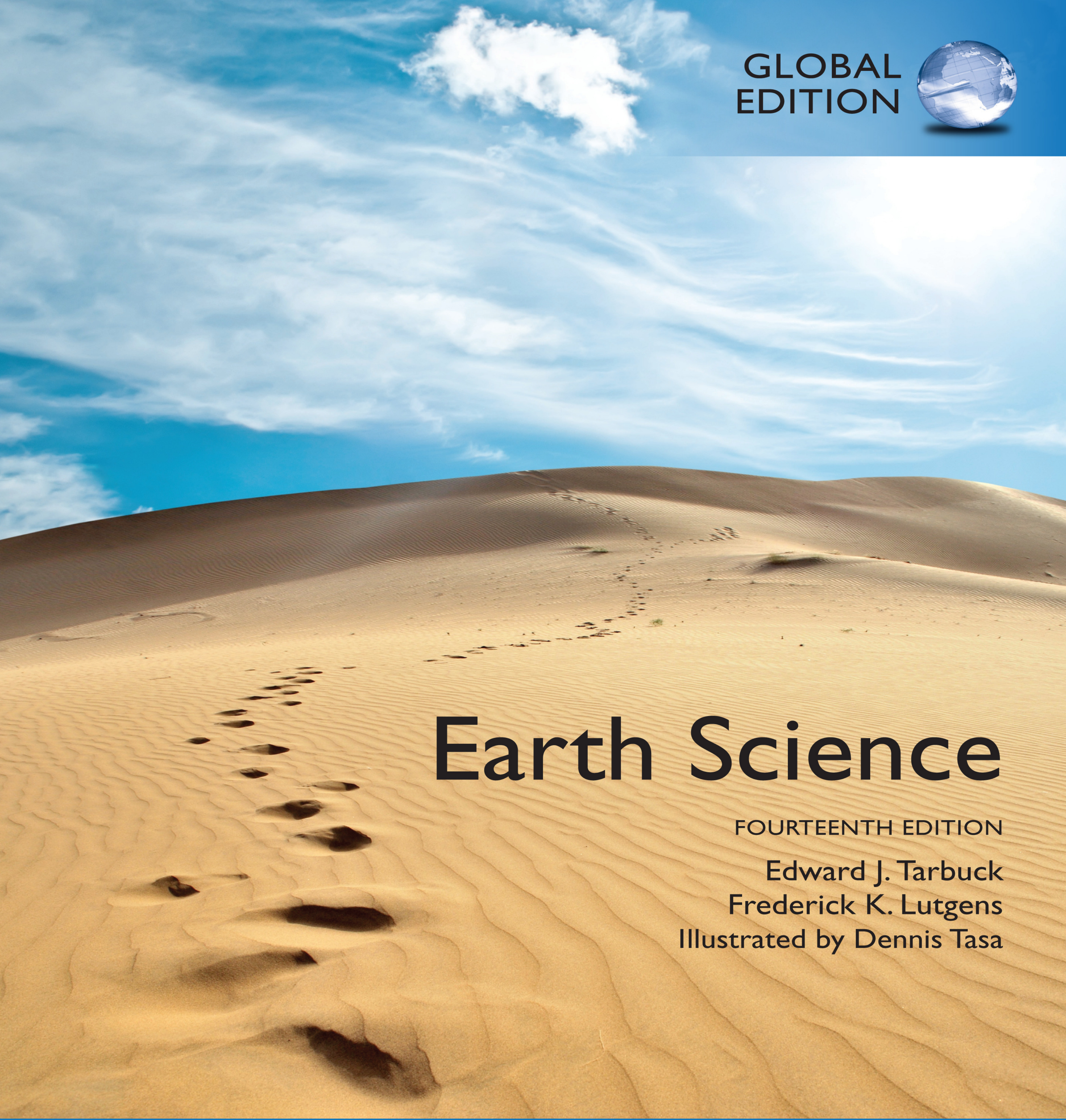

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In 1930 Wegener made his fourth and final trip to the Greenland Ice Sheet (**FIGURE 7.8**). Although the primary focus of this expedition was to study this great ice cap and its climate, Wegener continued to test his continental drift hypothesis. While 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

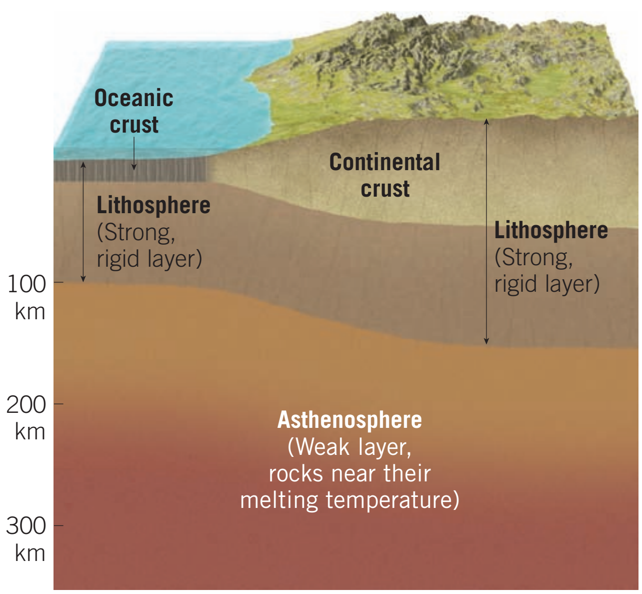
1. What two aspects of Wegener's continental drift hypothesis were objectionable to most Earth scientists?

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.

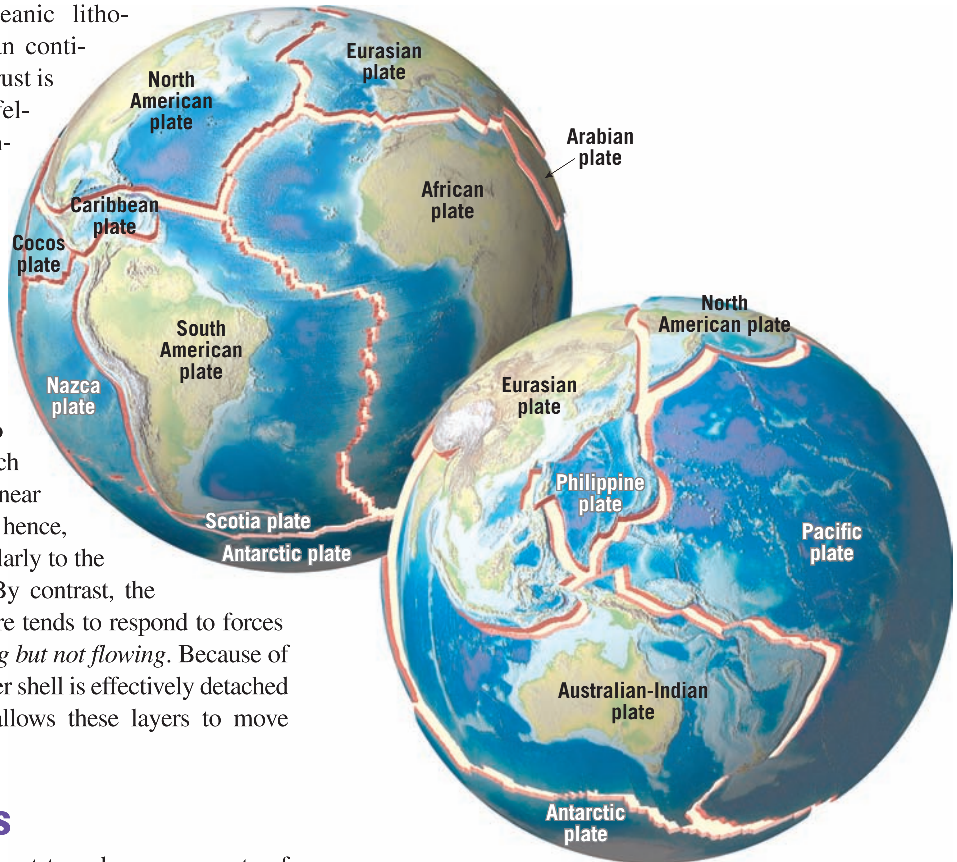


FIGURE 7.11 Earth's Major Lithospheric Plates

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.

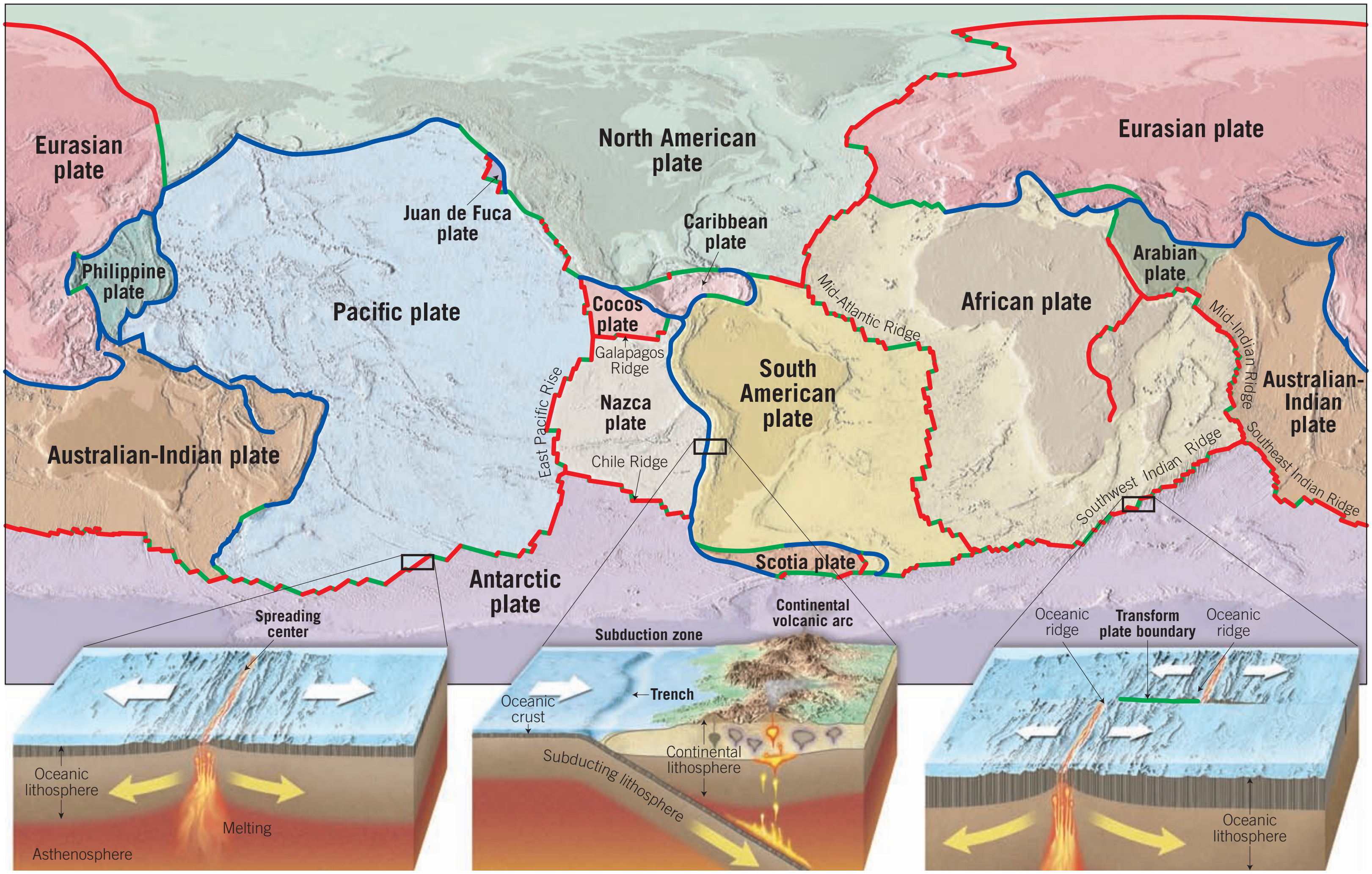
Intermediate-sized plates include the *Caribbean*, *Nazca*, *Philippine*, *Arabian*, *Cocos*, *Scotia*, and *Juan de Fuca plates.* These plates, with the exception of the Arabian plate, are composed mostly of oceanic lithosphere. In addition, several smaller plates (*microplates*) have been identified 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**).



A. Divergent plate boundary
B. Convergent plate boundary
C. Transform plate boundary

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.

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.

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

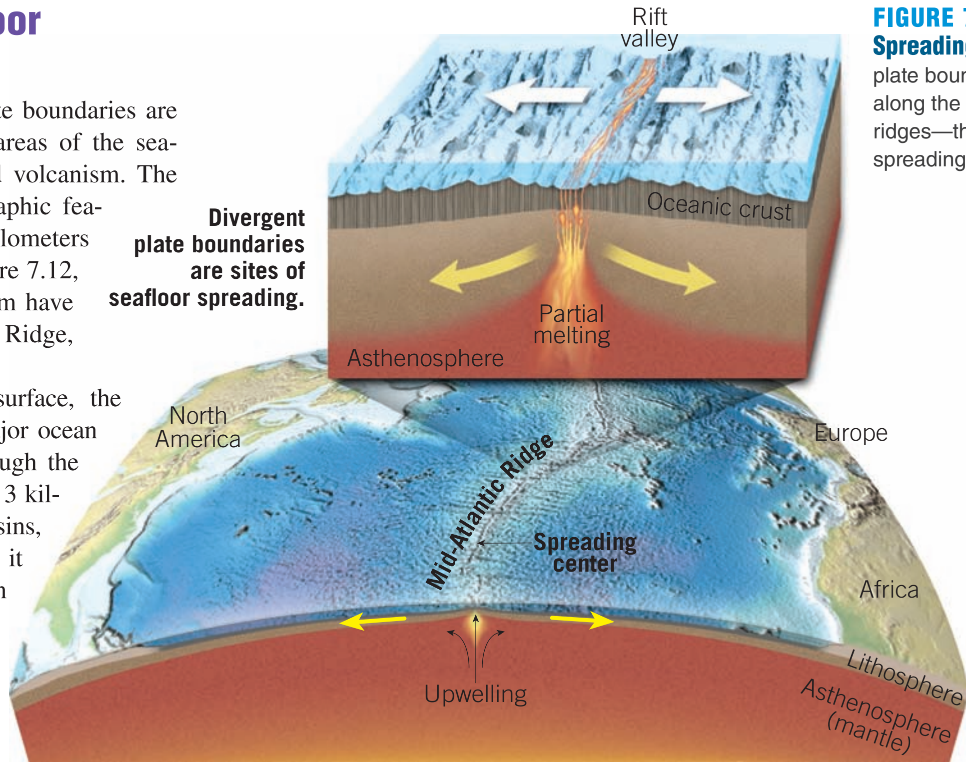
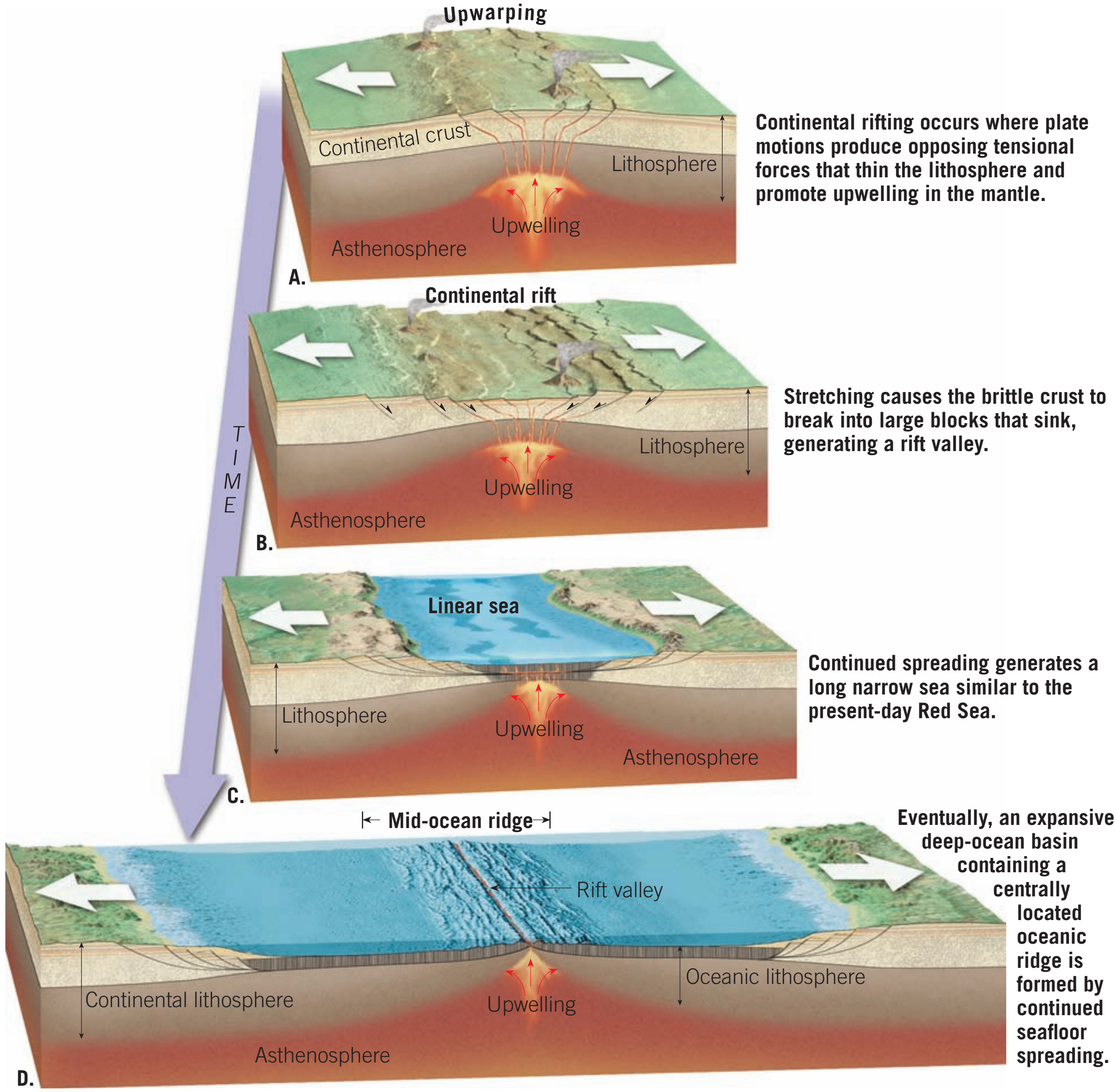


FIGURE 7.13 Seafloor Spreading Most divergent plate boundaries are situated along the crests of oceanic ridges—the sites of seafloor spreading.

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)

SmartFigure 7.15
Continental Rifting
Formation of a new ocean basin.



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

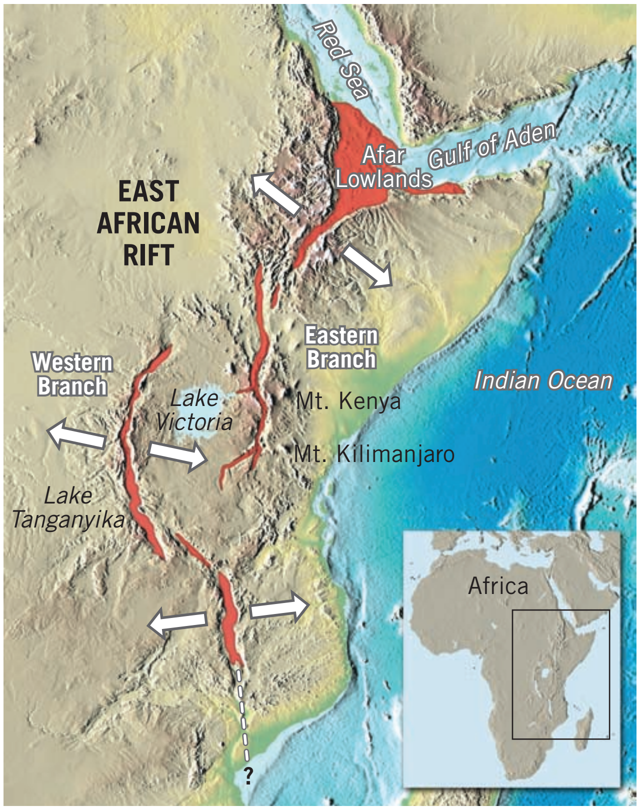


FIGURE 7.16 East African Rift Valley

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).

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 oceanic 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