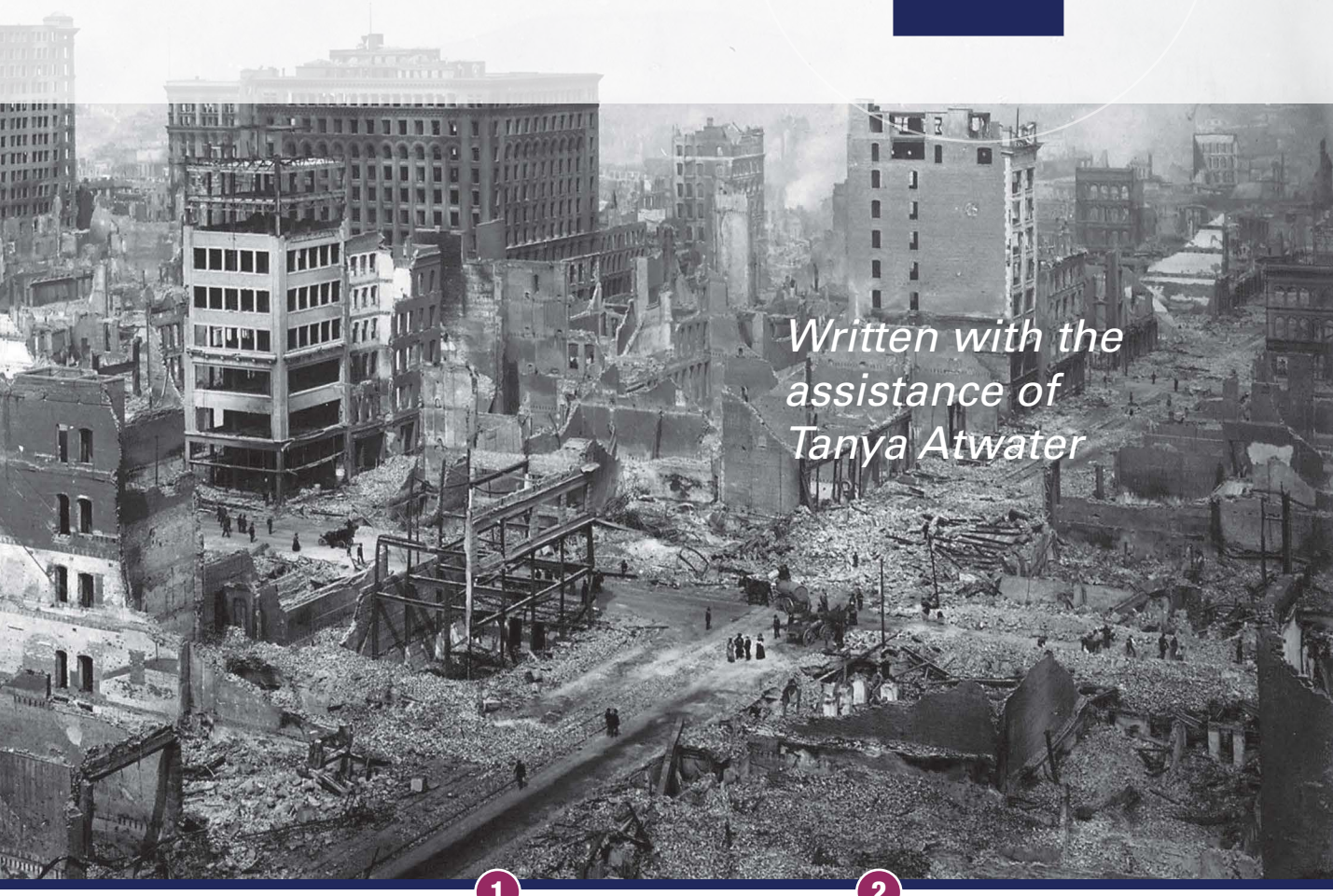
In about 20 million years the **cities** will be side by side

2



Written with the assistance of Tanya Atwater

APPLYING the 5 fundamental concepts Two Cities on a Plate Boundary

1

Science helps us predict hazards.

Like the way scientific investigation of the San Francisco earthquake led to an understanding of the earthquake hazard of the San Andreas fault, Plate Tectonic Theory, developed in the 1960s, provided a testable model from which scientists could understand the distribution and predict the occurrences of several destructive natural geologic hazards linked to plate tectonics.

2

Knowing hazard risks can help people make decisions.

Although the internal structure of Earth and plate tectonics are not natural hazards in a strict sense, many of the most destructive natural hazards are directly and indirectly related, and therefore understanding these processes can help guide your decisions in how to minimize your risk from related natural hazards.

Internal Structure of Earth and Plate Tectonics

Two Cities on a Plate Boundary

California straddles the boundary between two tectonic plates. That boundary between the North American and Pacific plates is the notorious San Andreas fault (Figure 2.1). A *fault* is a fracture along which one plate has moved relative to the other, and the San Andreas fault is a huge zone of fracturing hundreds of kilometers long. Two major cities, Los Angeles to the south and San Francisco to the north, are located on opposite sides of this fault. In 1906, movement on the San Andreas fault caused a major earthquake that devastated San Francisco, destroying about 80 percent of the city and killing 3,000. At that time, earthquakes were not understood and most believed they resulted from underground explosions. However, scientific investigations of

< SAN FRANCISCO FOLLOWING THE 1906 EARTHQUAKE
Fires, set off by earthquake ruptured gas mains, raged across the city for days following the 1906 earthquake. More than 25,000 buildings were destroyed by the fires including those in the financial district, shown here. *(NARA National Archives and Records Administration, Photographer: Chadwick, H. D.)*

LEARNING Objectives

The surface of Earth would be much different—relatively smooth, with monotonous topography—if not for the active tectonic processes within Earth that produce earthquakes, volcanoes, mountain chains, continents, and ocean basins. In this chapter, we focus directly on the interior of Earth.

After reading this chapter, you should be able to:

LO:1 Describe the basic internal structure and processes of Earth.

LO:2 Summarize the various lines of evidence that support the theory of plate tectonics.

LO:3 Compare and contrast the different types of plate boundaries.

LO:4 Explain the mechanisms of plate tectonics.

LO:5 Outline how plate tectonics has changed the appearance of Earth's surface over time.

LO:6 Compare and contrast the two fundamental processes that drive plate tectonics.

LO:7 Link plate tectonic processes to natural hazards.

3

Linkages exist between natural hazards.

The movement of tectonic plates is directly linked to earthquakes and most volcanic activity. These hazards are in turn linked to tsunamis and mass wasting and, because plate tectonics is responsible for creating high topography, plate movement is indirectly linked to weather patterns and severe weather, flooding, erosion, and climate change.

4

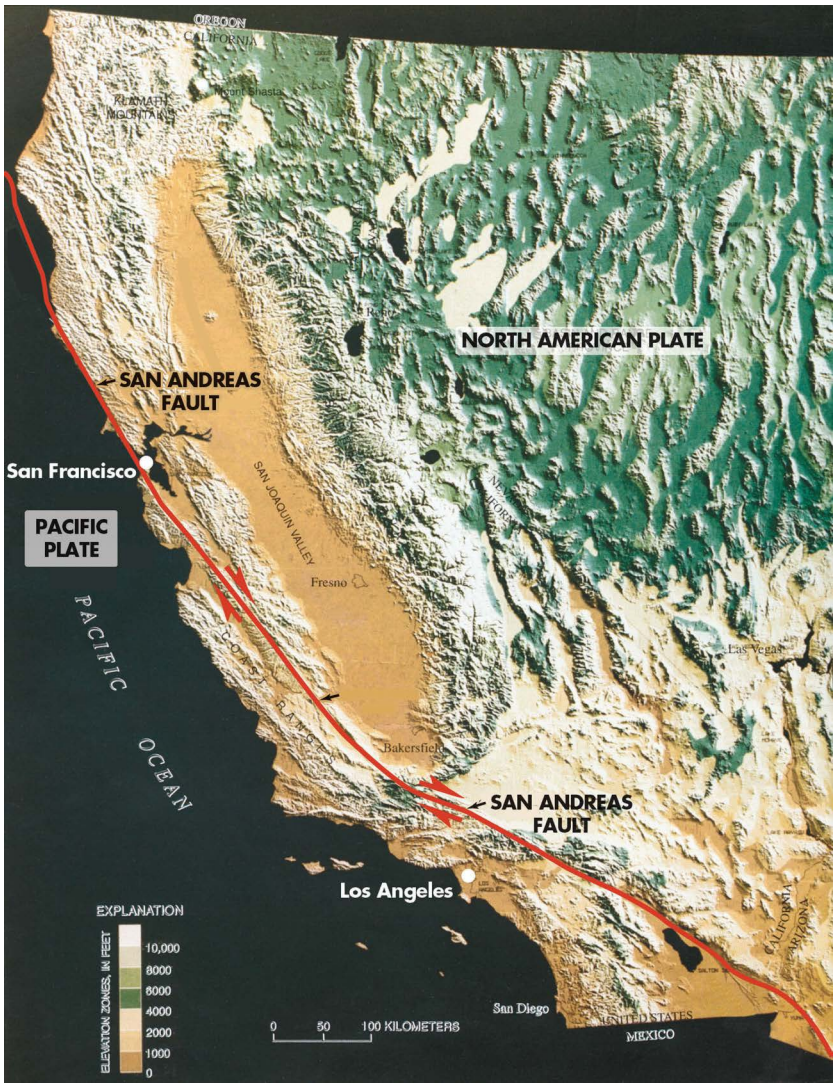
Humans can turn disastrous events into catastrophes.

In 1906, the combined population of San Francisco and Los Angeles was less than 1 million. Today, more than 17 million people live in these two cities at the boundary between the Pacific and North American plates. When the "Big One" does strike, population growth alone may be responsible for a catastrophe.

5

Consequences of hazards can be minimized.

As with California's strict building codes, which enable man-made structures to withstand ground shaking from earthquakes, in the following chapters you will learn that the consequences of other hazards associated with plate tectonics can be minimized.



< FIGURE 2.1 San Andreas Fault

False color topographic map of the western United States showing the location of the San Andreas fault in California. Red arrows show relative plate motions on either side of the fault. *(Based on R. E. Wallace/ National Earthquake Information Center. U.S.G.S.)*

the 1906 earthquake led to the identification of the San Andreas fault and a new understanding of the cause of earthquakes and consequent ground shaking.

Many of the moderate to large earthquakes in the Los Angeles area are on faults related to the San Andreas fault system. Most of the beautiful mountain topography in coastal California near both cities is a direct result of processes related to movement on the fault. However, this beautiful landscape comes at a high cost to society. Since 1906, earthquakes on the San Andreas fault system or on nearby faults, undoubtedly influenced by the plate boundary, have cost hundreds of lives and many billions of dollars in property damage. Constructing buildings, bridges, and other structures in California is more expensive than elsewhere because these must be designed to withstand ground shaking caused by earthquakes. Older structures must be *retrofitted*—changes made to their structure—to withstand the shaking, and many people purchase earthquake insurance in an attempt to protect themselves from "the Big One."

Los Angeles is on the Pacific plate and is slowly moving toward San Francisco, which is on the North American plate. In about 20 million years, the cities will be side by side. If people are present, they might be arguing over which is a suburb of the other. Of course, there will still be a plate boundary between the Pacific and North American plates 20 million years from now, because large plates have long geologic lives, on the order of 100 million years. However, the boundary may not be the San Andreas fault. The plate boundary will probably have moved eastward, and the topography of what is now California may be somewhat different. In fact, some earthquake activity, such as the large 1992 Landers earthquake east of the San Andreas fault, may mark the beginning of a shift in the plate boundary.

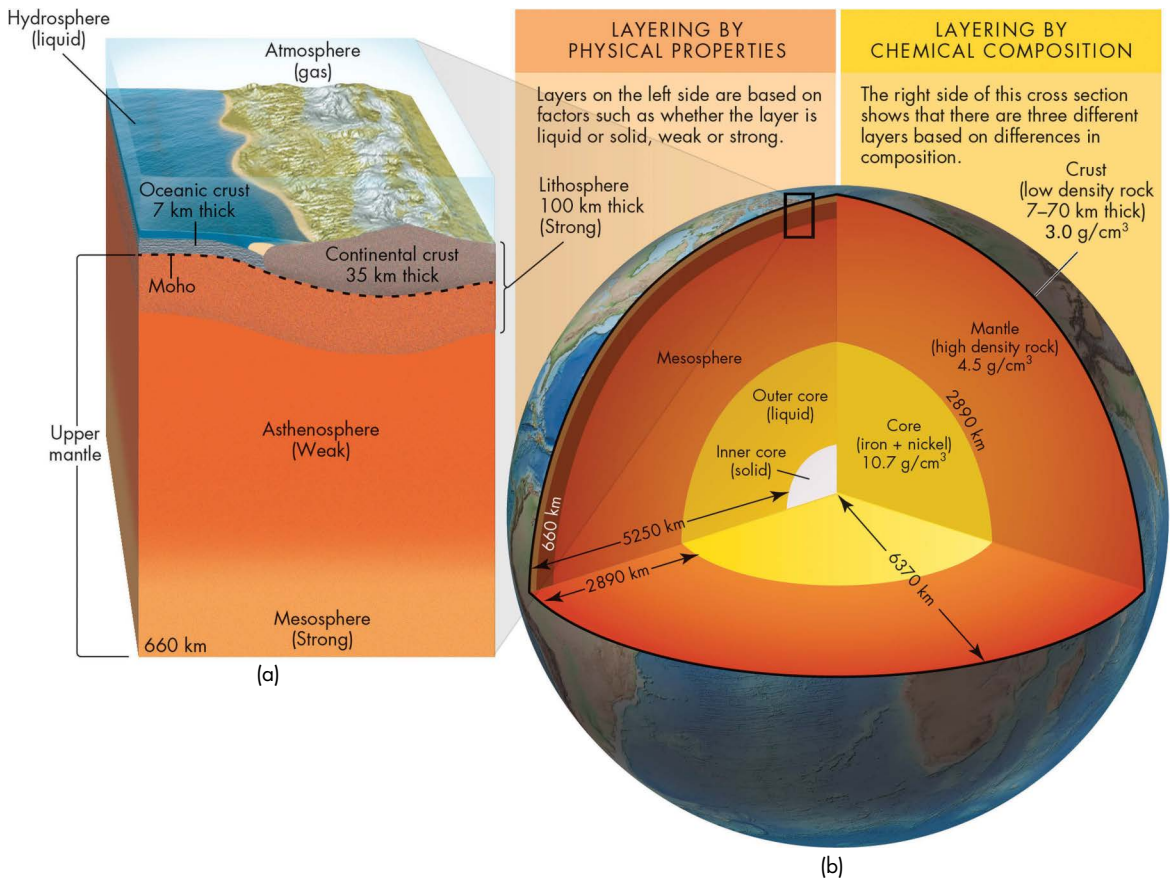
The Five Fundamental Concepts introduced in Chapter 1 are applied here to our discussion of damaging earthquakes on the San Andreas fault, which result from the movement of tectonic plates (see Applying the Fundamental Concepts, above). Each of the following chapters will similarly begin with an example of applying the fundamental concepts to an

introductory case study, and at the end of each chapter the case study will be revisited in detail and you will have an opportunity to apply the five fundamental concepts yourself.

2.1 Internal Structure of Earth

Earth is a complex dynamic planet with a layered internal structure that in some ways resembles a chocolate-covered cherry. That is, Earth has a rigid outer shell, a solid center, and a thick layer of gooey material between the two that moves around as a result of dynamic internal processes. These internal processes have incredibly important impacts on the surface of Earth. They are responsible for the largest landforms: continents and ocean basins. The configuration of the continents and ocean basins in part controls the oceans' currents and the distribution of heat carried by seawater in a global system that affects climate, weather, and the distribution of plant and animal life on Earth. Finally, Earth's internal processes are also responsible for regional landforms including mountain chains, chains of active volcanoes, and large areas of elevated topography, such as the Tibetan Plateau and the Rocky Mountains. The high topography that includes mountains and plateaus significantly affects both global circulation patterns of air in the lower atmosphere (weather) and longer-term climate patterns, thereby directly influencing all life on Earth. Thus, our understanding of the internal processes of Earth is much more than simply academic interest. These processes are at the heart of producing the multitude of environments shared by all living things on Earth.

Earth Layers Earth has a radius of about 6370 km (~3960 mi.). The internal layers of Earth are shown and described in Figure 2.2. We can consider the internal structure of Earth in two fundamental ways:



▲ FIGURE 2.2 Earth and Its Interior
(a) Idealized diagram showing the internal structure of Earth and its layers extending from the center to the surface. (b) Notice that the lithosphere is a strong layer that includes the entire crust and part of the upper mantle. The asthenosphere, located entirely within the mantle, is a weak layer.

1. By composition and density (heavy or light).
2. By physical properties (e.g., solid or liquid, weak or strong).

Our discussion will explore the two ways of looking at the interior of our planet. Some of the basic components of Earth's structure[1] are:

- A solid **inner core** more than 1200 km (~750 mi.) thick, roughly the size of the moon but with a temperature about as high as the temperature of the surface of the sun.[2] The inner core is believed to be primarily metallic, composed mostly of iron (about 90 percent by weight), with minor amounts of elements such as sulfur, oxygen, and nickel.
- A liquid **outer core** with a thickness of just over 2200 km (~1370 mi.) and a composition similar to that of the inner core. The average density of the inner and outer core is approximately 10.7 grams per cubic centimeter (~0.39 pound per cubic inch). The maximum near the center of Earth is about 13 g/cm^3 (~0.47 lb/in.^{3}). By comparison, the density of water is 1 g/cm^3 (~0.04 lb/in.^{3}) and the average density of Earth is approximately 5.5 g/cm^3 (~0.2 lb/in.^{3}).
- The **mantle**, nearly 2900 km (~1800 mi.) thick, surrounds the outer core and is composed mostly of solid iron- and magnesium-rich silicate rocks. The average density of the mantle is approximately 4.5 g/cm^3 (~0.16 lb/in.^{3}), which is less than half that of the underlying core.
- The **crust**, with variable thickness, is the outer rock layer of Earth. The boundary between the mantle and crust is known as the Mohorovičić discontinuity (also called the **Moho**). The Moho separates the lighter rocks of the crust, which have an average density of approximately 3.0 g/cm^3 (~0.10 lb/in.^{3}), from the more dense rocks of the mantle below.

Continents and Ocean Basins Have Significantly Different Properties and History Within the uppermost portion of the mantle, near the surface of Earth, our terminology becomes more complicated. For example, the cool, strong outermost layer or sphere of Earth is also called the **lithosphere** (*lithos* means "rock"). It is much stronger and more rigid than the material underlying it, the **asthenosphere** (*asthenos* means "without strength"), which is a hot and slowly flowing layer of relatively weak rock (Figure 2.2). The lithosphere averages about 100 km (~62 mi.) in thickness, ranging from a few kilometers (~1 to 2 mi.) thick beneath the crests of mid-ocean ridges to about 120 km (~75 mi.) beneath ocean basins and 20 to 400 km (~13 to 250 mi.) beneath the continents. The crust is embedded in the top of the lithosphere. Crustal rocks are less dense than the mantle rocks below, and oceanic crust is slightly denser than continental crust. Oceanic crust is also thinner: The ocean floor has a uniform crustal thickness of about 6 to 7 km (~3.7 to 4.4 mi.), whereas the crustal thickness of continents averages about 35 km (~22 mi.) and may be up to 70 km (~44 mi.) thick beneath mountainous regions. Thus, the average crustal thickness is less than 1 percent of the total radius of Earth and can be compared to the thin skin of a tangerine. Yet it is this layer that is of particular interest to us because we live at the surface of the continental crust.

In addition to differences in density and thickness, continental and oceanic crusts have very different geologic histories. Oceanic crust of the present ocean basins is less than approximately 200 million years old, whereas continental crust may be several billion years old. Three thousand kilometers (~1865 mi.) below us, at the core–mantle boundary, processes may be occurring that significantly affect our planet at the surface. Scientists speculate that gigantic cycles of convection occur within Earth's mantle, rising from as deep as the core–mantle boundary up to the surface and then falling

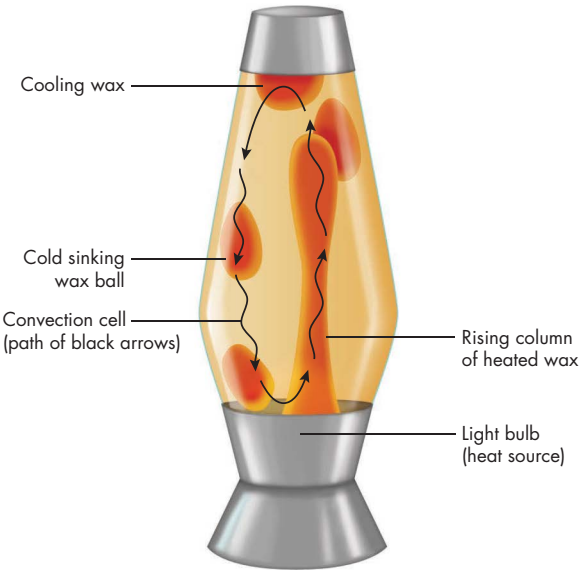


FIGURE 2.3 Convection
Annotated photograph of a lava lamp illustrating the concept of convection. Heating at the base of the lamp causes the wax to rise buoyantly due to a decrease in density. Away from the heat source, the wax cools and becomes more dense, sinking back to the bottom and completing the convection cell.

back again. The concept of **convection** is illustrated by using a lava lamp (Figure 2.3). In the base of the lamp is a light bulb that provides heat to the so-called lava in the lamp, which is actually a type of wax. Heating causes the wax at the bottom of the lamp to expand, which lowers its density. Once the density of the wax is less than that of the fluid in the lamp, it will rise toward the top. As it rises and moves away from the heat source, the wax cools, begins to contract, and its density increases. Once its density is greater than that of the fluid it will sink towards the bottom, where it will be heated again and the process is repeated. This temperature-driven circulation is known as a *convection cell*.

Although it is a bit more difficult to comprehend convection cells operating in solid rock, it has been suggested that convection cells operate within Earth's mantle. Mantle convection is fueled by Earth's internal heat, which results from the original heat of formation of the planet, heat generated by crystallization of the core, and heat supplied by radioactive decay of elements (such as uranium) scattered throughout the mantle. A complete convection cycle in the mantle may take as long as 500 million years.[1] The simplest way to understand mantle convection is to understand plate tectonics, which can be thought of as the surface manifestation of this process.

2.1 CHECK your understanding

1. What are the major differences between the inner and outer cores of Earth?
2. In what ways are the major properties of the lithosphere different from those of the asthenosphere?

2.2 Plate Tectonics

The term *tectonics* refers to the large-scale geologic processes that deform Earth's lithosphere, producing landforms such as ocean basins, continents, and mountains. Tectonic processes are driven by forces within Earth. These processes are part of the tectonic system, an important subsystem of the Earth system.

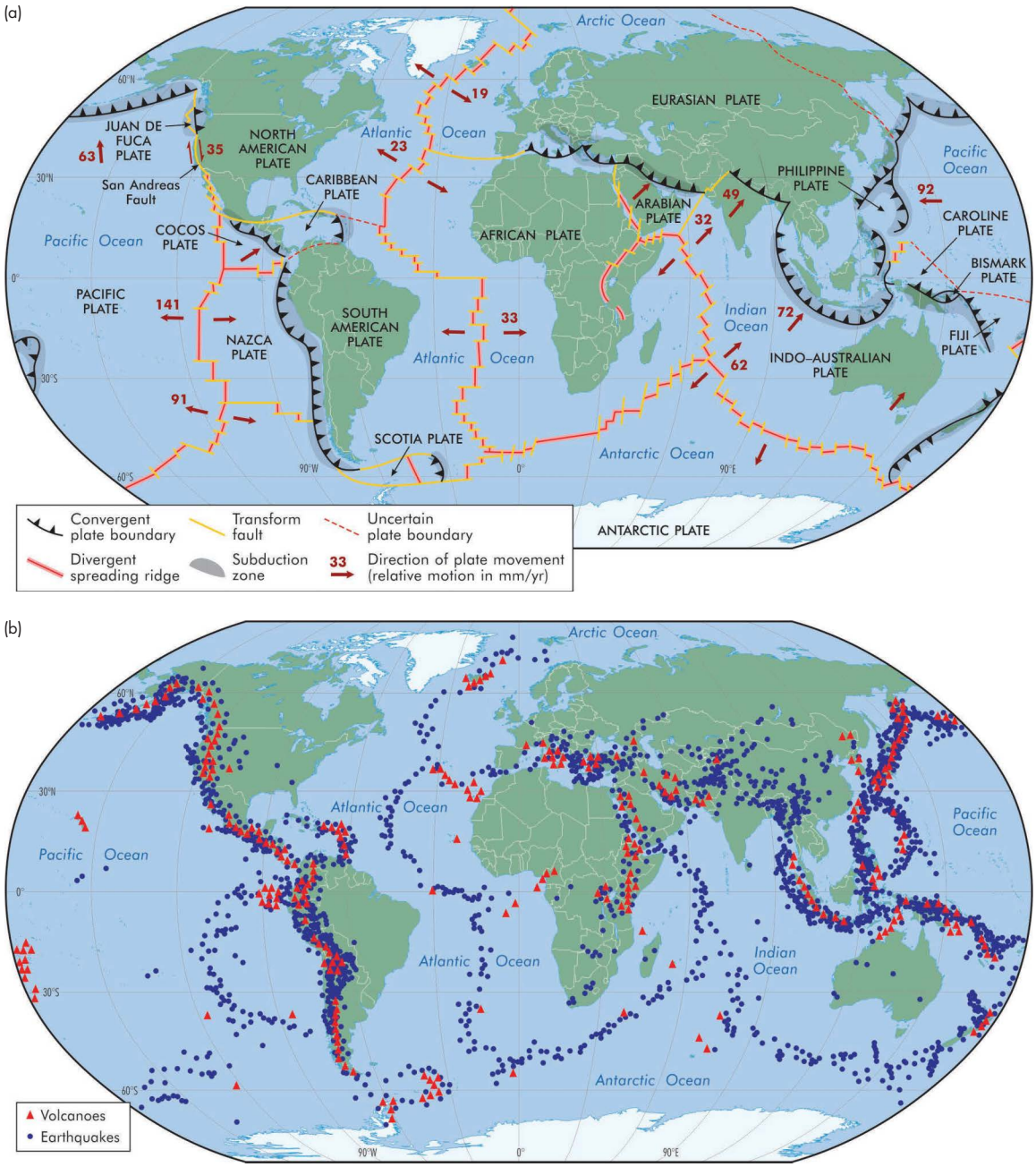
MOVEMENT OF THE TECTONIC PLATES

The lithosphere is broken into large pieces called *lithospheric plates* or *tectonic plates*[3] that are in motion due to the weak character of the underlying asthenosphere, which is able to flow. The world map in Figure 2.4a shows the locations and names of the major tectonic plates; the red arrows indicate the relative movement of each plate with respect to any adjacent plate. Processes associated with the creation, movement, and destruction of these plates are collectively known as **plate tectonics**. Plate tectonics is responsible for several of the most devastating natural hazards discussed in this book, including earthquakes and volcanoes.

It is important to notice that all of the major plates include both a part of a continent and a part of an ocean basin (Figure 2.4a). Even the Pacific plate, which is mostly composed of oceanic lithosphere, includes a small piece of the North American continent, as discussed earlier (see Figure 2.1). Some plates are very large and some are relatively small, although they are all significant on a regional scale. For example, the Juan de Fuca plate off the Pacific Northwest coast of the United States (Figure 2.4a), which is relatively small, is responsible for many of the earthquakes in northern California and all of the volcanoes in Oregon and Washington. Because there is relative movement between the edges of adjacent lithospheric plates, plate boundaries are geologically active areas. Specifically, most earthquakes are associated with plate boundaries, and the edges of plates can easily be identified by plotting the distribution of global seismicity on a world map (Figure 2.4b). Over geologic time, plates are formed and destroyed, cycling materials from the interior of Earth to the surface and back again at these boundaries. The continuous recycling of tectonic plates is collectively called the *tectonic cycle*.

Plate Tectonic Theory As the rigid lithospheric plates move over the asthenosphere, they carry the continents embedded within them.[4] The idea that continents move is not new; it was first suggested by German scientist Alfred Wegener in 1915. His primary evidence for **continental drift** was based on the congruity of the shape of continents, and the similarity in the fossils found in South America and Africa, which are now separated by the Atlantic Ocean (see Section 2.4). Although Wegener's hypothesis was correct, it was not taken seriously because he could not explain the mechanism by which the continents drifted around Earth's surface. The explanation came to light in the late 1960s, when **seafloor spreading** was discovered. In seafloor regions called **mid-ocean ridges** or **spreading centers**, tectonic plates move away, or diverge from one another. Divergence causes the plates to grow because hot rock from Earth's interior rises to fill the void space and then cools, adding new oceanic lithosphere to the plate edge (Figure 2.5). While oceanic lithosphere is created along some plate boundaries (spreading centers), it is destroyed at others, where cool, dense lithosphere sinks into the

asthenosphere at **subduction zones** (Figure 2.5). Thus, continents do not move *through* oceanic crust; rather, they are *carried along with it* as the crust moves either away from spreading centers or toward subduction zones. Because the rate of production of new lithosphere at spreading centers is balanced by consumption at subduction zones, the size of Earth remains constant, neither growing nor shrinking.



▲ FIGURE 2.4 Earth's Plates

(a) Map showing the major tectonic plates, plate boundaries, and direction of relative plate movement. (b) Map showing location of volcanoes and earthquakes. Notice the strong correlation between the locations of earthquakes and volcanoes on this map and the locations of plate boundaries in (a). *(Based on Christopherson, R.,* Geosystems, *2nd ed. Englewood Cliffs, NJ, 1994; Macmillan and Hamblin, W. K.,* Earth's Dynamic Systems, *6th ed. New York: Macmillan, 1992)*

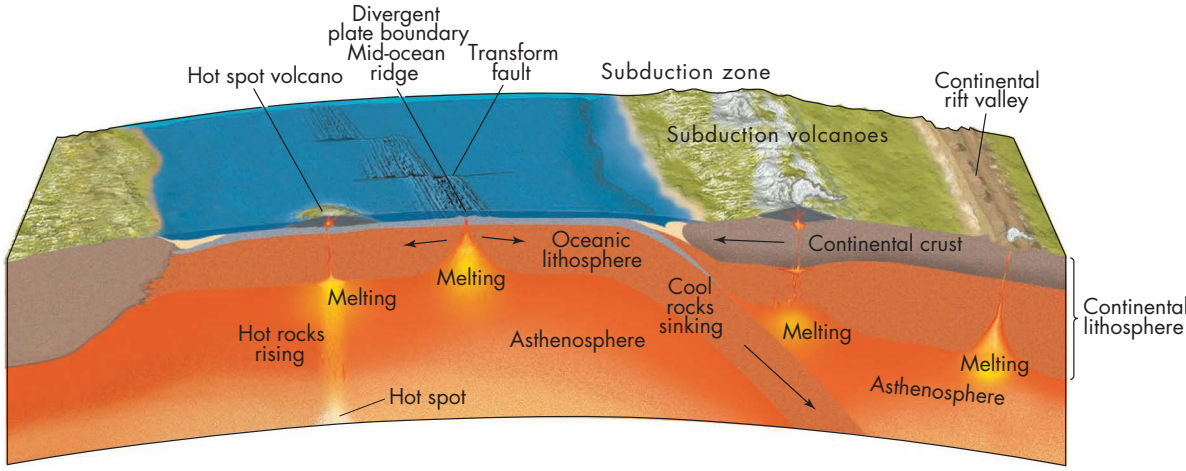


FIGURE 2.5 Model of Plate Tectonics

Block diagram illustrating important plate tectonic features. New oceanic lithosphere is being produced at the mid-ocean ridge (divergent plate boundary). Elsewhere, oceanic lithosphere returns to the interior of Earth at a subduction zone (convergent plate boundary).

Sinking Plates Generate Volcanoes and Earthquakes The concept of a lithospheric plate sinking into the upper mantle at a subduction zone is shown in detail in Figure 2.6. Interaction between the cold down-going, or subducting, oceanic crust and the hot asthenosphere causes rocks at a depth of about 150 km (~90 mi.) to begin melting, generating large volumes of molten rock called *magma* (see Chapter 5). The less dense magma rises to the surface through the overriding plate, producing a chain of volcanoes along the subduction zone, These volcanic chains, like the one that rings the Pacific Basin, are known as a *volcanic arc*. The path of the descending plate (or *slab*, as it sometimes is called) into the upper mantle is clearly marked by earthquakes. As the oceanic plate subducts, earthquakes are produced both between it and the overriding plate and within the interior of the subducting plate. Earthquakes occur because the sinking lithospheric plate is relatively cooler and stronger than the surrounding asthenosphere; this difference causes rocks to break and seismic energy to be released (see Chapter 3).[5]

Descending plates may enter a subduction zone at very shallow or nearly vertical angles. Scientists can determine this angle by plotting the locations of shallow, intermediate, and deep earthquakes that occur in the down-going slab (Figure 2.6). These inclined planes of earthquakes are called **Wadati–Benioff zones**. The

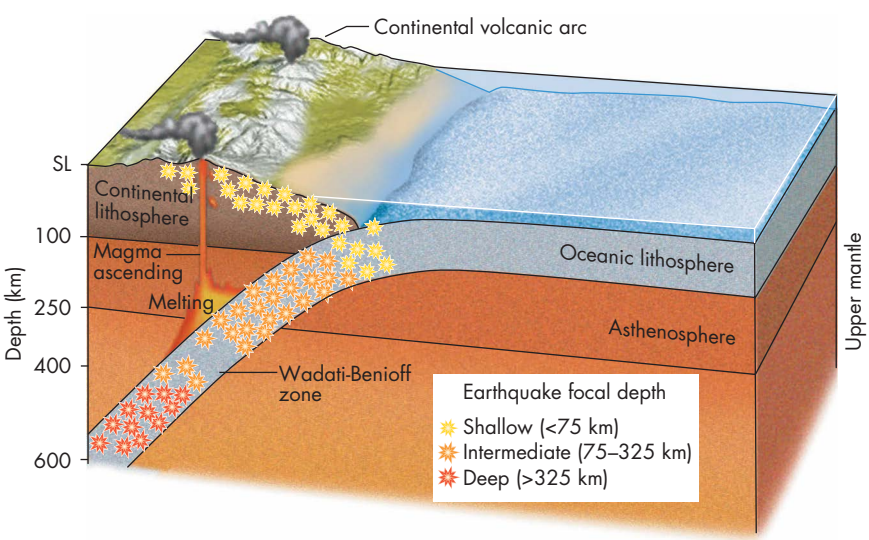


FIGURE 2.6 Subduction Zone

Idealized diagram illustrating the linkage between subduction zone processes and the occurrence of volcanoes and earthquakes. Interaction between the subducting oceanic lithosphere causes melting and volcanism on Earth's surface. Destructive earthquakes are common at subduction zones and occur over a broad range of depths. The inclined array of earthquake foci from shallow to deep that delineates the descending lithospheric plate is known as the Wadati–Benioff zone (named after the two scientists who discovered it).

very existence of Wadati–Benioff zones is strong evidence that subduction of rigid "breakable" lithosphere is occurring.[5]

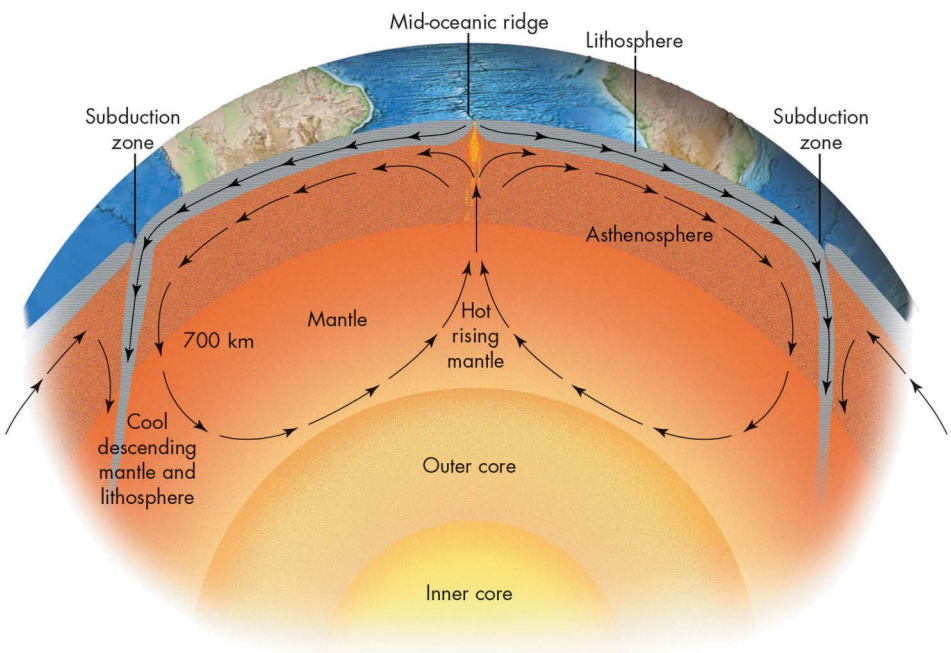
Plate Tectonics Is a Unifying Theory The theory of plate tectonics is to geology what Darwin's origin of species is to biology: a unifying concept that explains an enormous variety of phenomena. Biologists now have an understanding of evolutionary change; geologists understand how Earth works: the direction of plate movement, distribution of earthquakes and volcanoes, similarities among fossils on different continents, and changes in Earth's magnetism. In geology, we are still seeking the exact mechanism that drives plate tectonics, but we think it is most likely convection within Earth's mantle (see Section 2.1).

Figure 2.7 illustrates hypothetical convection cells that may drive plate tectonics, where hot molten rocks from deep in Earth's mantle buoyantly rise toward the base of the lithosphere. Divergence of the plates along mid-ocean ridges causes some magma to leak out onto the seafloor and hot rocks below the surface to cool, adding new oceanic lithosphere to the edge of the plates. Over the next 10–200 million years this newly formed oceanic lithosphere will be eventually conveyed away from its source of heat at the divergent plate boundary and will cool. Once the ocean lithosphere has cooled enough so that its density is similar to that of the underlying asthenosphere, it will be able to sink back down into the mantle at a subduction zone, completing the convection cell (Figure 2.7).

TYPES OF PLATE BOUNDARIES

There are three basic types of plate boundaries—divergent, convergent, and transform—which are defined by the relative movement of the plates on either side of the boundary (see Figure 2.4a and Table 2.1). These boundaries are not narrow cracks, as shown on maps and diagrams,[5] but are zones that range from a few to hundreds of kilometers across. Plate boundary zones are narrower in oceanic crust and broader in continental crust.

Divergent boundaries occur where neighboring parts of plates are moving away from each other and new lithosphere is being produced. Typically this process, called seafloor spreading, occurs at mid-ocean ridges. Mid-ocean ridges form when hot material from the mantle rises up to form a broad ridge, typically with a central rift valley. It is called a *rift valley*, or *rift*, because the plates are diverging, pulling the lithosphere apart and splitting, or rifting, it. The system of mid-ocean ridges along divergent plate boundaries forms linear submarine mountain chains that are found in virtually every ocean basin on Earth (Figure 2.8). Although the peaks of the mountain chain are as high as 2500 meters (~8200 ft.) above the surrounding seafloor, this range is completely concealed below sea level, except on the island of Iceland (see Chapter 5). The mid-ocean ridge mountain chain may not contain the tallest mountains, but with a length of 65,000 km (~40,400 mi.) this submarine range is 10 times longer than any mountain range on land. Although much less common, divergent plate boundaries and rift valleys can develop above sea



< FIGURE 2.7 Plate Movement
Model of plate movement and mantle convection. The outer layer (or lithosphere) is approximately 100 km (~62 mi.) thick and is stronger and more rigid than the underlying asthenosphere, which is a hot and slowly flowing layer of relatively low-strength rock. The mid-ocean ridge is a spreading center where plates pull apart, drawing up hot, buoyant material into the gap. Conveyed away from the ridge, the plates cool and become dense and are able to descend back into the mantle at subduction zones, completing the convection system. *(From Grand, S. P., "Mantle Shear Structure Beneath the Americas and Surrounding Oceans,"* Journal of Geophysical Research *99: 11591–621, 1994. Based on Hamblin, W. K.,* Earth's Dynamic Systems, *6th ed. New York: Macmillan, 1992.)*

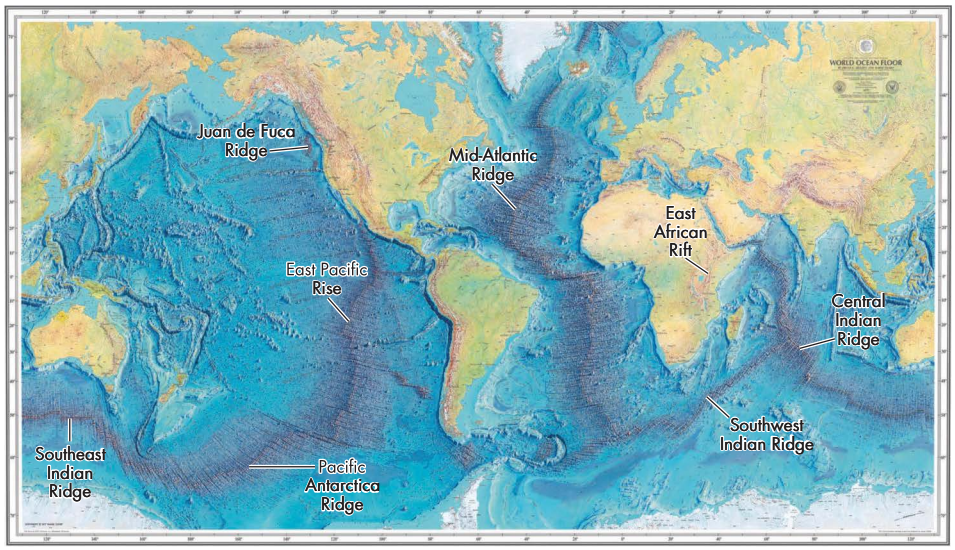
TABLE 2.1 Types of Plate Boundaries: Dynamics, Results, and Examples

Plate Boundary	Plates Involved	Dynamics	Results	Examples	Natural Hazards
Divergent	Usually ocean	Spreading. The two plates move away from each other and molten rock rises up to fill the gap.	Mid-ocean ridge forms and new oceanic lithosphere is created and added to each plate.	Mid-Atlantic Ridge, which defines the African and North American plate boundary (Figure 2.8).	Light to moderate earthquakes and nonexplosive volcanic eruptions
Convergent (subduction)	Ocean–continent	Oceanic plate sinks beneath continental plate.	A volcanic continental arc and deep trench are formed. Earthquakes and volcanic activity are found here.	Andes Mountains, a continental volcanic chain formed at the Nazca and South American plate boundary (Figure 2.4a).	Great earthquakes; explosive volcanic eruptions; tsunamis, flooding, mass wasting, and subsidence
Convergent (subduction)	Ocean–ocean	Older, denser, oceanic plate sinks beneath younger, less dense oceanic plate.	A volcanic island arc and deep trench is formed. Earthquakes and volcanic activity are found here.	Caribbean Islands, an ocean island arc formed at the boundary between the Caribbean and South American plates (Figure 2.4a).	Great earthquakes; explosive volcanic eruptions; tsunamis, flooding, mass wasting, and subsidence
Convergent (collision)	Continent–continent	Neither plate is dense enough to sink into the asthenosphere; compression results.	A large, high mountain chain is formed, and earthquakes are common.	Himalayan Mountains, the result of collision and shortening between the Indo-Australian and Eurasian plates (Figure 2.4a).	Major earthquakes, flooding, and mass wasting
Transform	Ocean–ocean or continent–continent	The plates slide past one another.	Earthquakes are common and may result in some topographic changes.	San Andreas fault, which defines the boundary between the North American and Pacific plates (Figure 2.11).	Strong to major earthquakes

level on continents, such as the Great Rift Valley in east Africa (see Figure 2.4a and Figure 2.8).

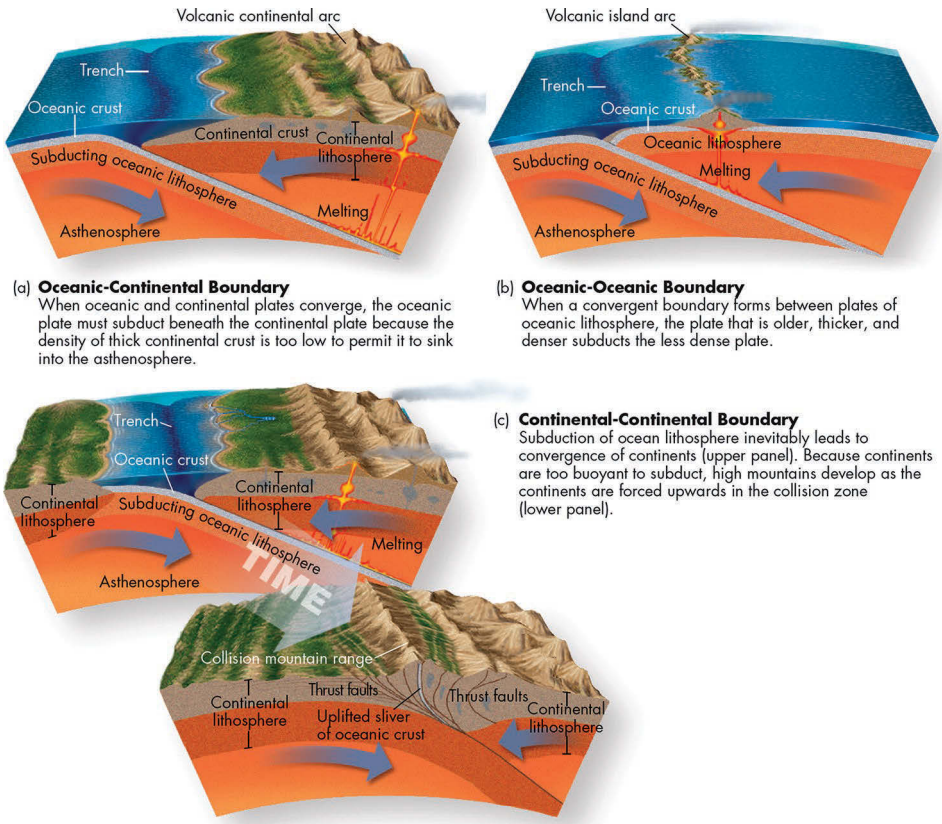
Convergent boundaries occur where plates move toward each other. If one of the converging plates is oceanic and the other is continental, an oceanic–continental plate collision results. The higher-density oceanic plate descends, or subducts, into the mantle beneath the leading edge of the continental plate, producing a subduction zone (Figure 2.9a). The convergence or collision of a continent with an ocean plate can result in compression. *Compression* is a type of stress, or force per unit area. When an oceanic-continental plate collision occurs, compression is exerted on the lithosphere, resulting in shortening of the surface of Earth, like pushing a tablecloth to produce folds. Shortening can cause folding, as in the tablecloth example, and faulting, or displacement of rocks along fractures to thicken the lithosphere. This process of deformation produces major mountain chains and volcanoes such as the Andes in South America and the Cascade Mountains in the U.S. Pacific Northwest.

If two oceanic lithospheric plates collide (oceanic-to-oceanic plate collision), one plate subducts beneath the other, and a subduction zone and arc-shaped chain of volcanoes known as an *island arc* are formed (Figure 2.9b) as, for example, the Aleutian Islands of the North Pacific. A **submarine trench**, a relatively narrow (usually several thousand km long and several km deep) depression on the ocean floor, is often formed as the result of the convergence of two colliding plates with subduction of one. The trench is located seaward of a subduction zone associated with an oceanic–continental plate or on the side of the downgoing plate in an oceanic–oceanic plate collision (see Figure 2.9a and b). Submarine trenches are sites of some of the deepest oceanic waters on Earth. For example, the Marianas Trench at the center edge of the Philippine plate has a depth of 11 km (~7 mi.), which is deep enough for Mount Everest to fit into. Other major trenches include the Aleutian Trench south of Alaska and the Peru-Chile Trench west of South America.



▲ FIGURE 2.8 Mid-Ocean Ridge System

Topographic map of the world's ocean basin emphasizing the tectonic significance of mid-ocean ridge divergent plate boundaries. Note that the ridges are not continuous but are composed of thousands of individual spreading centers connected by transform faults that are perpendicular to the ridges. (World Ocean Floor Panorama *by Bruce C. Hezeen and Marie Tharp. Copyright by Marie Tharp 1977/2003. Reproduced by permission of Marie Tharp Maps, LLC 8 Edward Street, Sparkill, New York 10976.)*



(a) **Oceanic-Continental Boundary**
When oceanic and continental plates converge, the oceanic plate must subduct beneath the continental plate because the density of thick continental crust is too low to permit it to sink into the asthenosphere.

(b) **Oceanic-Oceanic Boundary**
When a convergent boundary forms between plates of oceanic lithosphere, the plate that is older, thicker, and denser subducts the less dense plate.

(c) **Continental-Continental Boundary**
Subduction of ocean lithosphere inevitably leads to convergence of continents (upper panel). Because continents are too buoyant to subduct, high mountains develop as the continents are forced upwards in the collision zone (lower panel).

◀ FIGURE 2.9 Convergent Plate Boundaries

Idealized diagram illustrating characteristics of three types of convergent plate boundaries.



FIGURE 2.10 Mountains in Italy
Mountain peaks (the Dolomites) in northern Italy are part of the Alpine mountain system formed from the collision between Africa and Europe. *(Edward A. Keller)*

If the leading edges of both plates contain relatively light, buoyant continental crust, subduction into the mantle of one of the plates is difficult. In this case, a continent–continent plate collision occurs, in which the edges of the plates collide, causing shortening and lithospheric thickening due to folding and faulting (Figure 2.9c). Where the two plates join is known as a *suture zone*. Continent–continent collision has produced some of the highest mountain systems on Earth, such as the Alpine and Himalayan mountain belts (Figure 2.10). Many older mountain belts were formed in a similar way; for example, the Appalachians in the eastern United States which formed during an ancient continent–continent plate collision 250 to 350 million years ago.

Transform boundaries, or transform faults, occur where the edges of two plates slide past each other, like the San Andreas fault in California shown in Figure 2.11. If you examine Figure 2.8, you will see that a mid-ocean ridge is not a single, continuous rift but a series of rifts that are offset from one another along connecting transform faults. Although the most common locations for transform plate boundaries are within oceanic crust, some occur within continents. A well-known continental transform boundary is the San Andreas fault in California, where the rim of the Pacific plate is sliding horizontally past the rim of the North American plate (see Figure 2.1 and Figure 2.11).

Locations where three plates border one another are known as **triple junctions**. Figure 2.11 shows several such junctions: Two examples are the meeting point of the Juan de Fuca, North American, and Pacific plates on the West Coast of North America (this is known as the Mendocino triple junction) and the junction of the spreading ridges associated with the Pacific, Cocos, and Nazca plates west of South America.

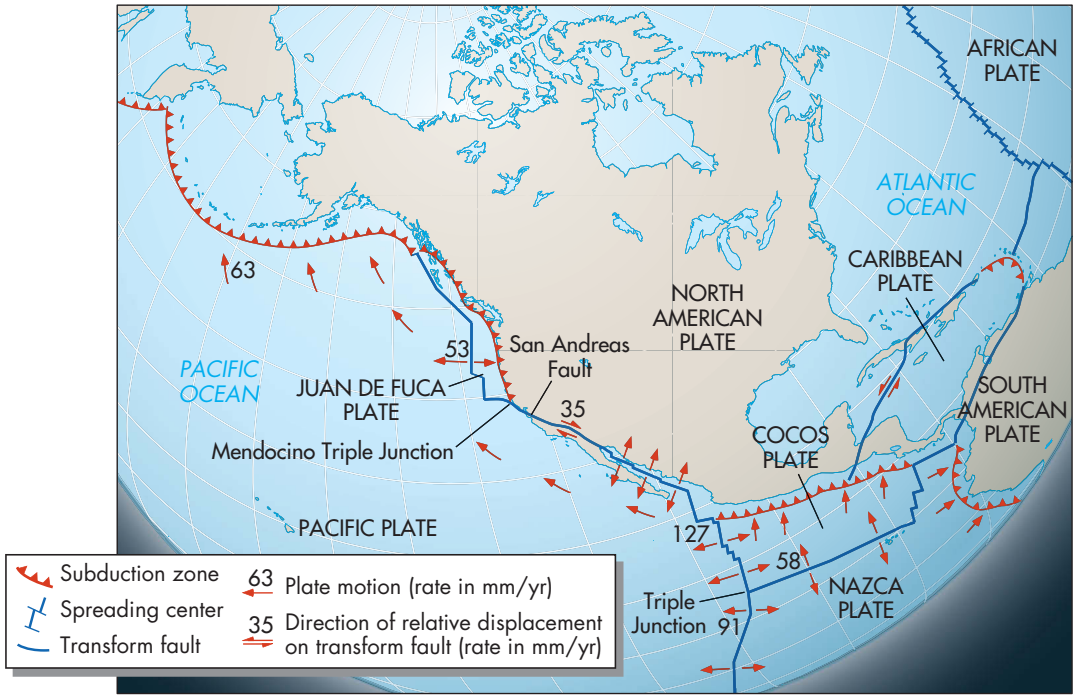
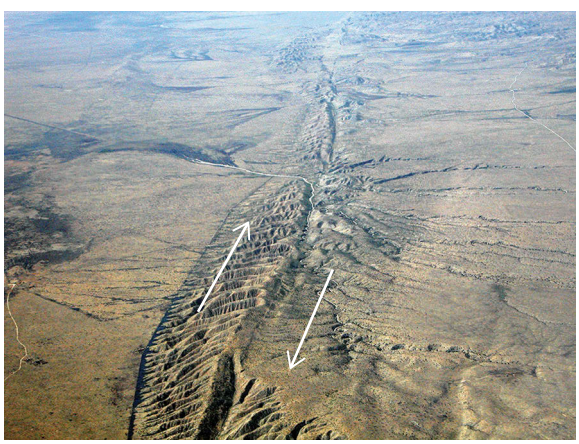


FIGURE 2.11 North American Plate Boundary
Detail of boundary between the North American plate and Pacific plate. *(Based on information by Tanya Atwater)*

RATES OF PLATE MOTION

Plate Motion Is a Fast Geologic Process The directions in which plates move are shown on Figure 2.4a. In general, plates move a few centimeters per year, about as fast as some people's hair and fingernails grow. The Pacific plate moves past the North American plate along the San Andreas fault about 3.5 cm (~1.4 in.) per year, so that features such as rock units or streams are gradually displaced over time where they cross the fault (Figure 2.12). During the past 5 million years, there has been about 175 km (~110 mi.) of displacement, a distance equivalent to driving two hours at 55 mph (~90 kph) on a highway along the San Andreas fault. Although the central portions of the plates move along at a steady slow rate, plates interact at their boundaries, where collision or subduction or both occur, and movement may not be smooth or steady. The plates often get stuck together. The movement is analogous to sliding one rough wood board over another. Movement occurs when the splinters of the boards break off and the boards move quickly by each other. When rough edges along the plate move quickly, an earthquake is produced (see Chapter 3). Along the San Andreas fault, which is a transform plate boundary, the displacement is horizontal and can amount to several meters during a great earthquake. During an earthquake in 1857 on the San Andreas fault, a horse corral across the fault was reportedly changed from a circle to an "S" shape. Fortunately, such an event generally occurs at any given location only once every 100 years or so. Over long time periods, rapid displacement from periodic earthquakes and more continuous slow "creeping" displacements add together to produce the average rate of several centimeters of movement per year along the San Andreas fault.



▲ FIGURE 2.12 The San Andreas Fault
The fault is visible as a linear depression with low hills on either side that run from the bottom to the top of the photograph. Note the prominent stream that is diverted toward the north (top of image) along the fault. *(Doc Searle/Flickr CCBYSA 2.0)*

2.2 CHECK your understanding

1. Why was the continental drift hypothesis not taken seriously?
2. What enables the tectonic plates to move?
3. What are the three major types of plate boundaries?
4. How is a subduction zone different from a collision zone?

2.3 A Detailed Look at Seafloor Spreading

When Alfred Wegener proposed the idea of continental drift in 1915, he had no solid evidence of a mechanism that could move continents. The global extent of mid-ocean ridges was discovered in the 1950s, and in 1962 geologist Harry H. Hess published a paper suggesting that continental drift was the result of the process of seafloor spreading along those ridges. New oceanic lithosphere is produced at the mid-ocean ridge spreading centers as shown in Figure 2.5 (divergent plate boundary). The lithospheric plate then moves laterally, carrying along the embedded continents in the tops of moving plates. These ideas produced a new major paradigm that greatly changed our ideas about how Earth works.[5,6,7]

The validity of seafloor spreading was established from three sources: (1) identification and mapping of oceanic ridges, (2) dating of volcanic rocks on the floor of the ocean, and (3) understanding and mapping of the paleomagnetic history of ocean basins.

PALEOMAGNETISM

We introduce and discuss Earth's magnetic field and paleomagnetic history in some detail in order to understand how seafloor spreading and plate tectonics were discovered. Earth has had a magnetic field for at least the past 3 billion years[2] (Figure 2.13). The field can be represented by a dipole magnetic field with lines of magnetic force extending from the South Pole to the North Pole. A dipole magnetic field is one that has equal and opposite charges at either end. As described in Section 2.1, convection occurs in the iron-rich, fluid, hot outer core of Earth because of compositional changes and heat at the inner–outer core boundary. As more buoyant material in the outer core rises, it starts

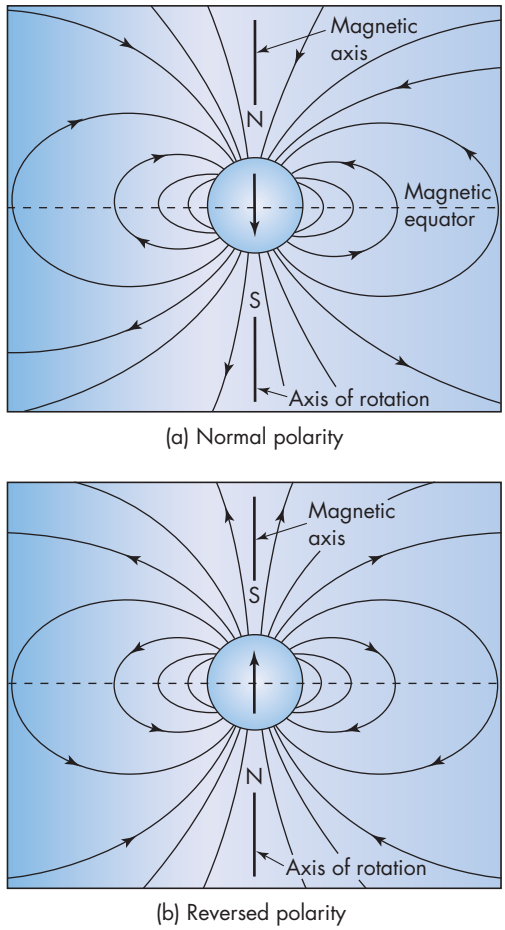


FIGURE 2.13 Magnetic Reversal
Idealized diagram showing the magnetic field of Earth under (a) normal polarity and (b) reversed polarity. *(From Kennett, J., Marine Geology. Englewood Cliffs, NJ: Prentice Hall, © 1982. Reprinted and electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.)*

the convection. The convection in the outer core, along with the rotation of Earth that causes rotation of the outer core, initiates a flow of electric current in the core. This flow of current within the core produces and sustains Earth's magnetic field.[2,7]

Earth's magnetic field is sufficient to permanently magnetize some surface rocks. For example, volcanic rock that erupts and cools at mid-ocean ridges becomes magnetized at the time it passes through a critical temperature. At that critical temperature, known as the *Curie point*, iron-bearing minerals (such as magnetite) in the volcanic rock orient themselves parallel to the magnetic field. This is a permanent magnetization known as *thermoremnant magnetization*.[7] The term **paleomagnetism** refers to the study of the magnetism of rocks at the time their magnetic signature formed. It is used to determine the magnetic history of Earth.

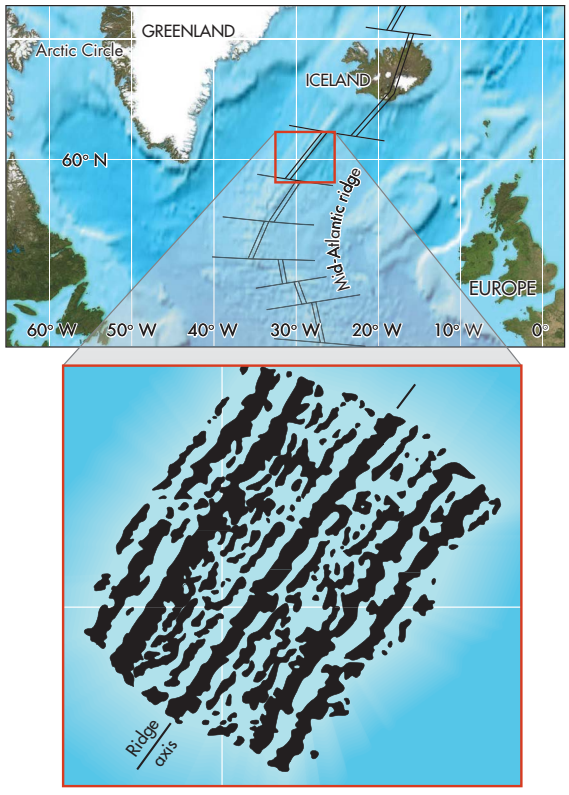
The magnetic field, based on the size and conductivity of Earth's core, must be continuously generated or it would decay away in about 20,000 years. It would decay because the temperature of the core is too high to sustain permanent magnetization.[2]

Earth's Magnetic Field Periodically Reverses

Before the discovery of plate tectonics, geologists working on land had already discovered that some volcanic rocks were magnetized in a direction opposite to the present-day field, suggesting that the polarity of Earth's magnetic field was reversed at the time the volcanic rocks erupted onto the seafloor and cooled (Figure 2.13b). The rocks were examined for whether their magnetic field was normal, as it is today, or reversed relative to that of today, for certain time intervals of Earth's history. A chronology for the last few million years was constructed on the basis of the dating of the "reversed" rocks. You can verify the current magnetic field of Earth by using a compass; at this point in Earth's history, the needle points to the north magnetic pole. During a period of reversed polarity, the needle would point south! The cause of **magnetic reversals** is not well known, but it is related to changes in the convective movement of the liquid material in the outer core and processes occurring in the inner core. Reversals in Earth's magnetic field are random, occurring on average every few hundred thousand years. The change in polarity of Earth's magnetic field takes a few thousand years to occur, which in geologic terms is a very short time.

What Produces Magnetic Stripes?

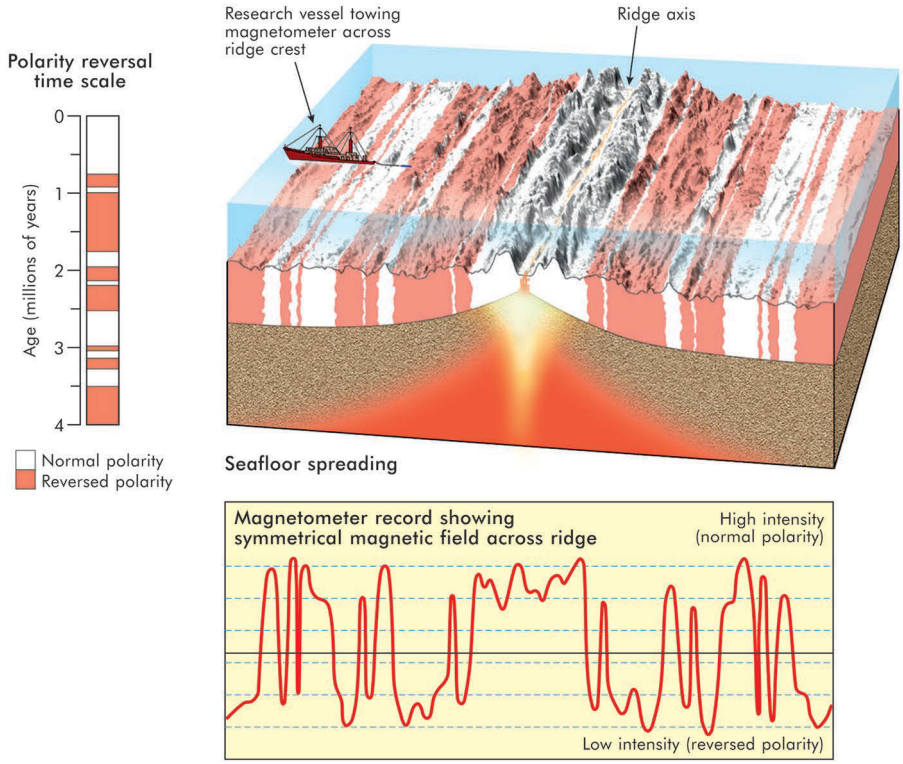
To further explore the Earth's magnetic field, geologists towed magnetometers, instruments that measure magnetic properties of rocks, from ships and completed magnetic surveys. The paleomagnetic record of the ocean floor is easy to read because of the fortuitous occurrence of the volcanic rock basalt (see Chapter 5) that is produced at spreading centers and forms the floors of the ocean basins of Earth. The rock is fine-grained and contains sufficient iron-bearing minerals to produce a good magnetic record. The marine geologists' discoveries were not expected. The rocks on the floor of the ocean were found to have irregularities in the magnetic field. These irregular magnetic patterns were called anomalies or perturbations of Earth's magnetic field caused by local fields of magnetized rocks on the seafloor. The anomalies can be represented as stripes on maps. When mapped, the stripes form quasi-linear patterns parallel to oceanic ridges. The marine geologists found that their sequences of stripe width patterns matched the sequences established by land geologists for polarity



< FIGURE 2.14 Magnetic Anomalies on the Seafloor
Map showing a magnetic survey southwest of Iceland along the Mid-Atlantic Ridge. Positive magnetic anomalies are black (normal), and negative magnetic anomalies are white (reversed). Note that the pattern is symmetrical on the two sides of the mid-ocean ridge. *(Based on Heirtzler, J. R., Le Pichon, X., and Baron, J. G., "Magnetic Anomalies Over the Reykjanes Ridge,"* Deep-Sea Research *13: 427–43, 1966. Reprinted by permission of Elsevier Sciences, Ltd.)*

reversals in land volcanic rocks. Magnetic survey data for an area southwest of Iceland are shown on Figure 2.14. The black stripes represent normally magnetized rocks and the intervening white stripes represent reversed magnetized rocks.[8] Notice that the stripes are not evenly spaced but form patterns that are symmetrical on opposite sides of the Mid-Atlantic Ridge.

Why Is the Seafloor No More Than 200 Million Years Old? The discovery of patterns of magnetic stripes at various locations in ocean basins allowed geologists to infer numerical dates for the volcanic rocks. Merging the magnetic anomalies with the numerical ages of the rocks produced the record of seafloor spreading. The spreading of the ocean floor, beginning at a mid-ocean ridge, could explain the magnetic stripe patterns.[9] Figure 2.15 is an idealized diagram showing how seafloor spreading may produce the patterns of magnetic anomalies (stripes). The pattern shown



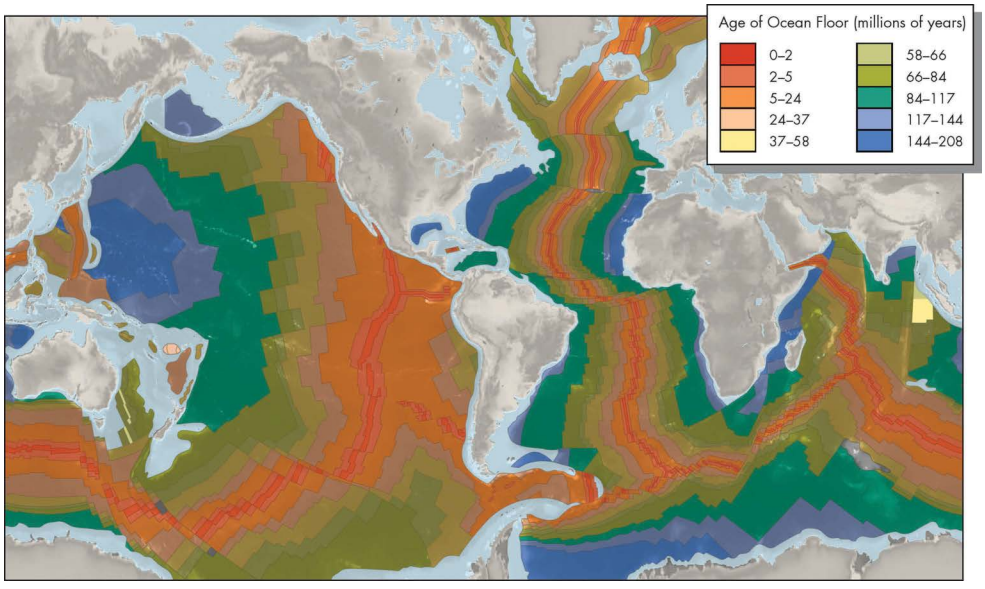
< FIGURE 2.15 Magnetic Reversals and Seafloor Spreading
Idealized diagram showing a mid-ocean ridge and rising magma in response to seafloor spreading. As the volcanic rocks cool, they become magnetized. The white stripes represent normal magnetization; the red stripes are reversed magnetization. The record shown here was formed over a period of several million years. Magnetic anomalies (stripes) are a mirror image of each other on opposite sides of the mid-ocean ridge. Thus, the symmetrical bands of the normal and reversed magnetized rocks are produced by the combined effects of the reversals and seafloor spreading.

is for the past several million years, which includes several periods of normal and reversed magnetization of the volcanic rocks. White stripes represent normally magnetized rocks, and red stripes are rocks with a reversed magnetic signature. Notice that the most recent magnetic reversal occurred approximately 0.7 million years ago. The basic idea illustrated by the figure is that rising magma at the oceanic ridge is extruded, or pushed out onto the surface, through volcanic activity, and the cooling rocks become normally magnetized. When the field is reversed, the cooling rocks preserve a reverse magnetic signature (Figure 2.15). Notice that the patterns of magnetic anomalies in rocks on both sides of the ridge are mirror images of one another. The only way such a pattern might result is through the process of seafloor spreading. Thus, the pattern of magnetic reversals found on rocks of the ocean floor is strong evidence that the process of seafloor spreading is happening.

Mapping of magnetic anomalies, when combined with age-dating of the magnetic reversals in land rocks, creates a database that suggests exciting inferences; Figure 2.16 shows the age of the ocean floor as determined from this database. The pattern, showing that the youngest volcanic rocks are found along active mid-ocean ridges, is consistent with the theory of seafloor spreading. As distance from these ridges increases, the age of the ocean floor also increases, to a maximum of about 200 million years, during the early Jurassic period. Thus, it appears that the present ocean floors of the world are no older than 200 million years. In contrast, rocks on continents are often much older than Jurassic, going back about 4 billion years, almost 20 times older than the ocean floors! We conclude that the thick continental crust, by virtue of its buoyancy, is more stable at Earth's surface than are rocks of the crust of the ocean basins. Continents form by the processes of accretion of sediments, addition of volcanic materials, and collisions of tectonic plates carrying continental landmasses. We will continue this discussion when we consider the movement of continents during the past 200 million years. However, it is important to recognize that it is the pattern of magnetic stripes that allows us to reconstruct how the plates and the continents embedded in them have moved throughout history.

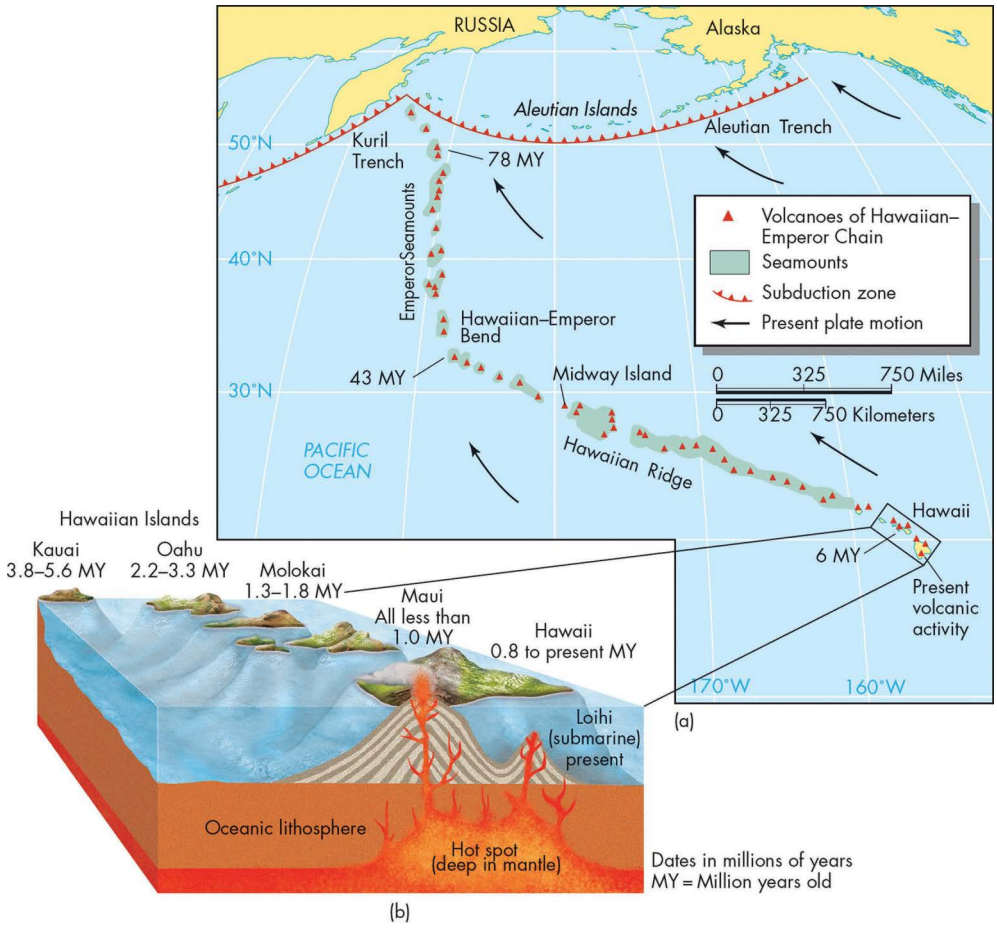
HOT SPOTS

There are a number of places on Earth called **hot spots**, characterized by volcanic centers resulting from hot materials produced deep in the mantle, perhaps near the core–mantle boundary (see Figure 2.5). The partially molten materials are hot and buoyant enough to move up through the mantle and the overlying, moving tectonic plates.[5,7] An example of a continental hot spot is the volcanic region of Yellowstone National Park. Hot spots are



▲ FIGURE 2.16 Age of the Ocean Floor

Age of the seafloor is determined from magnetic anomalies and other methods. The youngest ocean floor (red) is located along oceanic ridge systems, and older rocks are generally farther away from the ridges. The oldest ocean floor rocks are approximately 180 million years old. *(Based on Scotese, C. R., Gahagan, L. M., and Larson, R. L., "Plate Tectonic Reconstruction of the Cretaceous and Cenozoic Ocean Basins,"* Tectonophysics *155: 27–48, 1988. Reprinted by permission of Elsevier Sciences, Ltd.)*



▲ FIGURE 2.17 Hawaiian Hot Spot

(a) Map showing the Hawaiian–Emperor Chain of volcanic islands and seamounts. Actually, Midway Island and the Hawaiian Islands are the only volcanoes of the chain that protrude from the ocean's surface to form islands. *(Based on Claque, D. A., Dalrymple, G. B., and Moberly, R., "Petrography and K-Ar ages of Dredged Volcanic Rocks from the Western Hawaiian Ridge and Southern Emperor Seamount Chain,"* Geological Society of America Bulletin *86: 991–98, 1975)* (b) Sketch map showing the Hawaiian Islands, which range in age from present volcanic activity to about 6 million years old on the island of Kauai. Notice that most of the mass of the volcanoes forming the Hawaiian Islands lies below the ocean surface. *(From Thurman, Oceanography, 5th ed. Columbus, OH: Merrill, Plate 2. Reprinted and Electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.)*

also found in both the Atlantic and Pacific Oceans. If the hot spot is anchored in the slow-moving deep mantle, then as the oceanic plate moves over a hot spot, a linear chain of volcanoes is produced. Perhaps the best example of this type of hot spot is the line of volcanoes forming the Hawaiian–Emperor Chain in the Pacific Ocean (Figure 2.17a). Along this chain, volcanic eruptions range in age from present-day activity on the big island of Hawaii (in the southeast) to more than 78 million years ago near the northern end of the Emperor Chain. With the exception of the Hawaiian Islands and some coral atolls (ringlike coral islands such as Midway Island), the chain primarily consists of submarine volcanoes known as *sea-mounts*. Seamounts are islands that were eroded by waves and submarine landslides and subsequently sank beneath the ocean surface. As seamounts move farther off the fixed hot spot due to plate movement, the volcanic rocks that make up the islands cool and the oceanic crust they are on becomes denser and sinks.

Seamounts constitute impressive submarine volcanic mountains. In the Hawaiian Chain, the youngest volcano is Mount Loihi, which is still a submarine volcano, presumably directly over a hot spot, as idealized in Figure 2.17b. The ages of the Hawaiian Islands increase to the northwest, with the oldest being Kauai, about 6 million years old. Notice in Figure 2.17a that the line of seamounts makes a sharp bend at the junction of the Hawaiian and Emperor Chains. The age of the volcanic

rocks at the bend is about 43 million years, and the bend is interpreted to represent a time when plate motions changed.[10] If we assume that the hot spots are fixed deep in the mantle, then the chains of volcanic islands and submarine volcanoes along the floor of the Pacific Ocean that get older farther away from the hot spot provide additional evidence to support the movement of the Pacific plate. In other words, the ages of the volcanic islands and submarine volcanoes could systematically change as they do only if the plate is moving over the hot spot.

2.3 CHECK your understanding

1. Describe the major process that are thought to produce Earth's magnetic field.
2. How have magnetic reversals and the study of paleomagnetism been important in understanding plate tectonics?
3. What are hot spots?

2.4 Pangaea and Present Continents

Movement of the lithospheric plates is responsible for the locations of mountain ranges' present shape and location of the continents. There is good evidence that the most recent global episode of continental drift, driven by seafloor spreading, started about 180 million years ago, with the breakup of a supercontinent called Pangaea (this name, meaning "all lands," was first proposed by Wegener). Pangaea (pronounced *pan-jee-ah*) was enormous, extending from pole to pole and over halfway around Earth near the equator (Figure 2.18a). Pangaea had two parts (Laurasia to the north and Gondwana to the south) and was constructed during earlier continental collisions. Figure 2.18a shows Pangaea as it was nearly 180 million years ago. Seafloor spreading over the past 200 million years separated Eurasia and North America from the

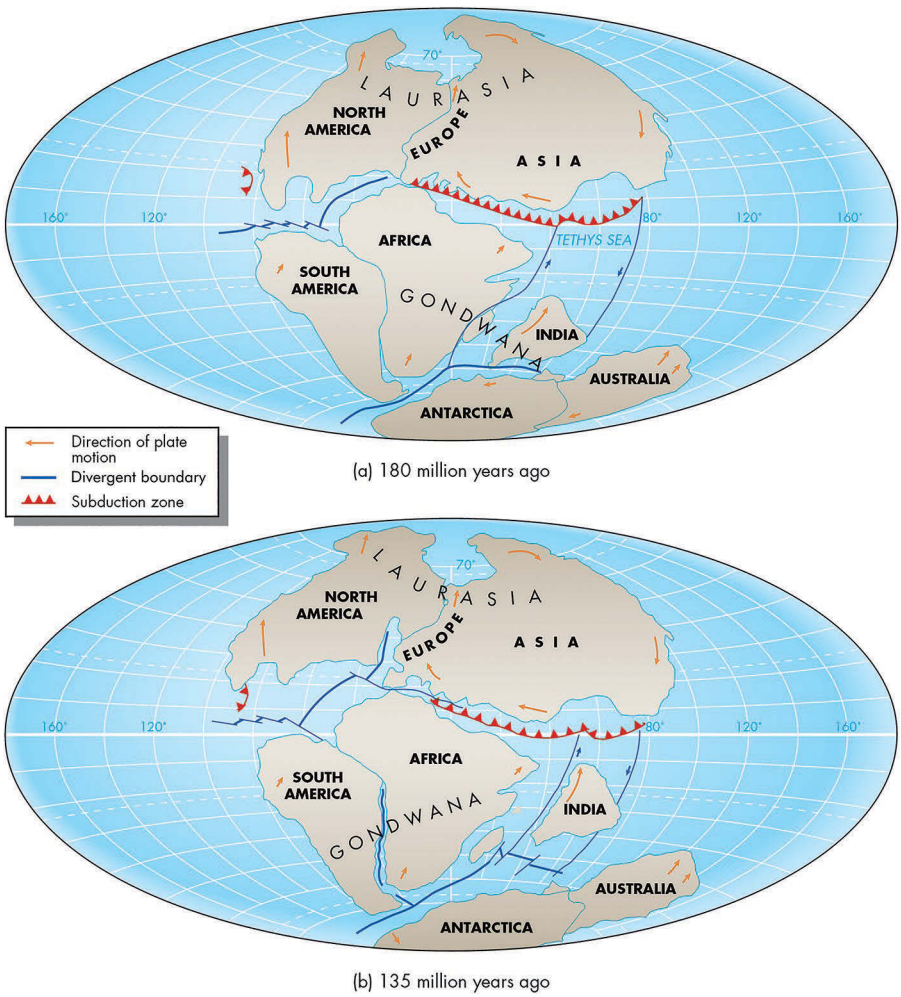
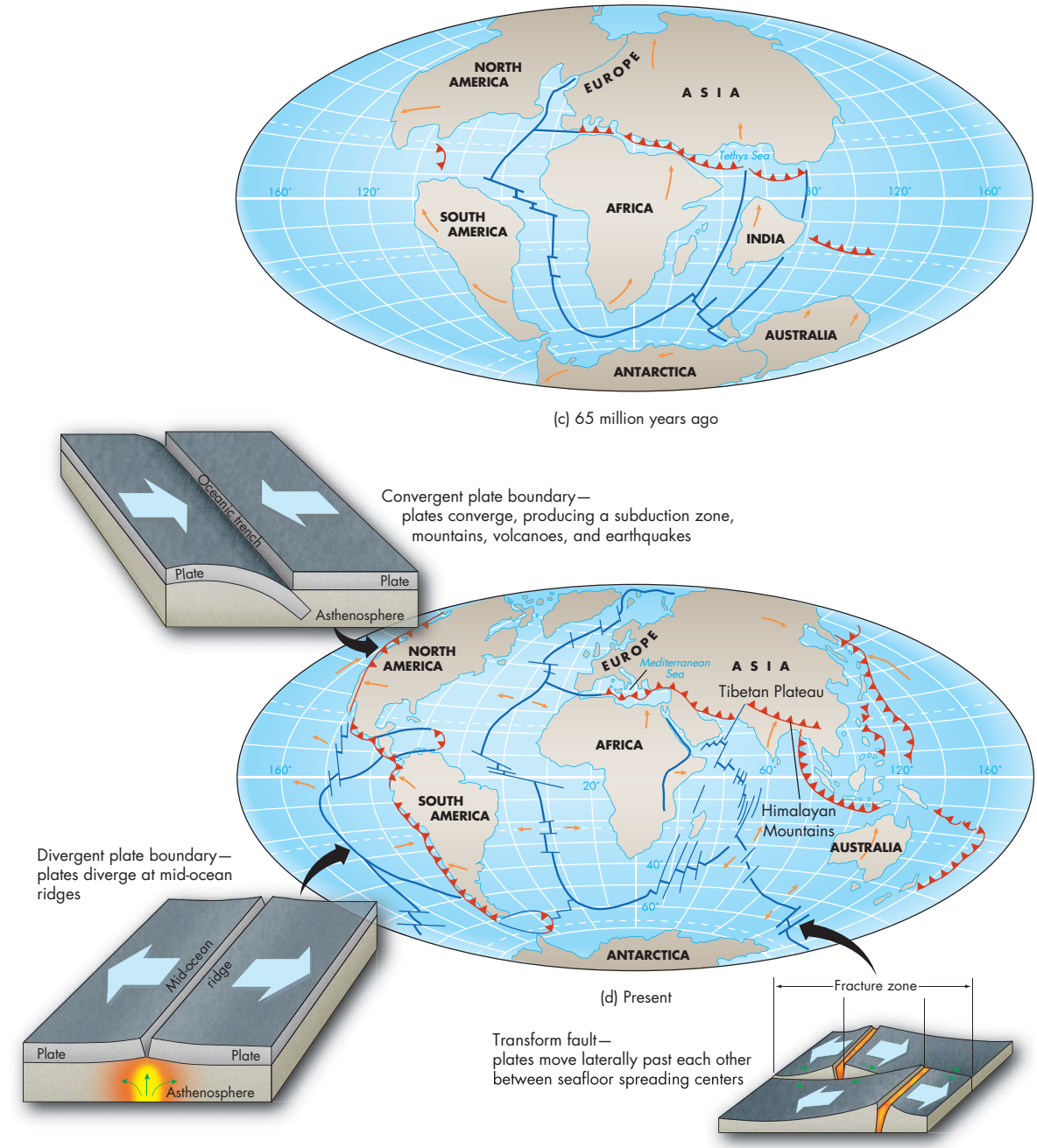


FIGURE 2.18 Two Hundred Million Years of Plate Tectonics

(a) The proposed positions of the continents at 180 million years ago, (b) 135 million years ago, (c) 65 million years ago, and (d) at present. Arrows show directions of plate motion. See text for further explanation of the closing of the Tethys Sea, the collision of India with China, and the formation of mountain ranges. *(Based on Dietz, R. S., and Holden, J. C. 1970. Reconstruction of Pangaea: Breakup and dispersion of continents, Permian to present.* Journal of Geophysical Research *75(26): 4939–56. Copyright by the American Geophysical Union. Reprinted with permission of Wiley Inc. Adaptation of block diagrams from Christopherson, R. W., Geosystems, 2nd ed. Englewood Cliffs, NJ: Macmillan/Prentice Hall, 1994. Reprinted and Electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.)*



▲ FIGURE 2.18 (*Continued*)

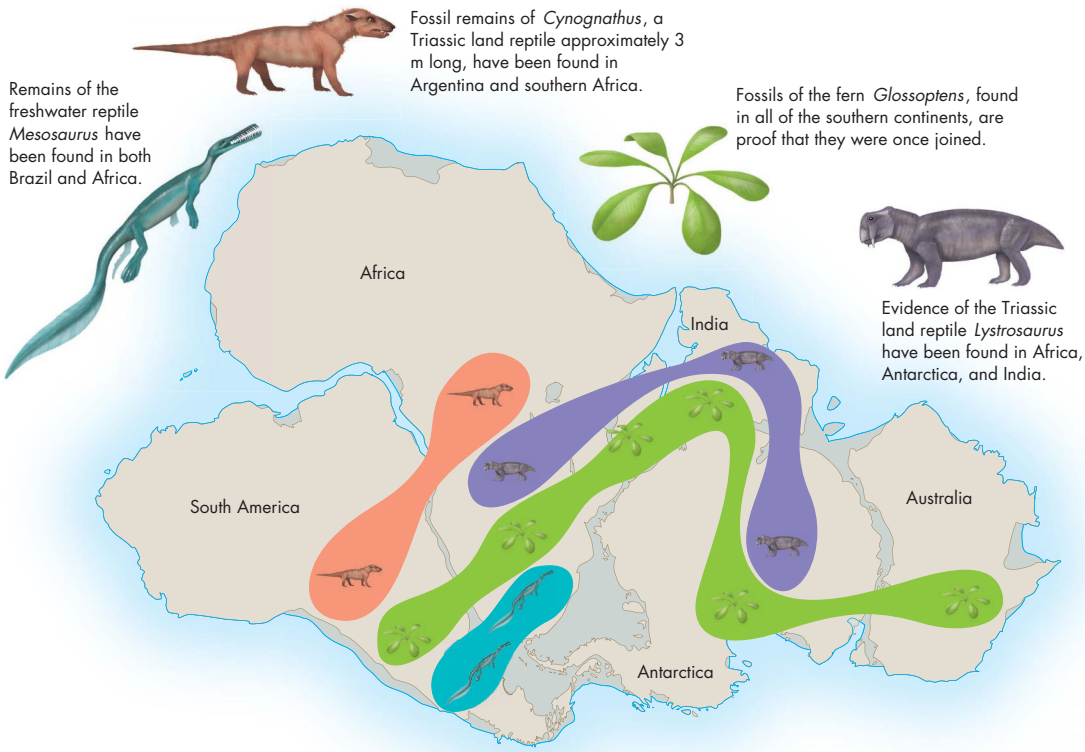
southern landmass, Eurasia from North America, and the southern continents (South America, Africa, India, Antarctica, and Australia) from one another (Figure 2.18b–d). The Tethys Sea, between Africa and Europe–Asia (Figure 2.18a–c), closed as part of the activity that produced the Alps in Europe. A small part of this once much larger sea remains today as the Mediterranean Sea. About 50 million years ago, India crashed into China in south Asia. That collision, which has caused India to forcefully intrude into China a distance comparable from New York to Miami, is still happening today, producing the Himalayan Mountains (the highest mountains above sea level in the world) and the Tibetan Plateau (see Figure 2.22).

Understanding Plate Tectonics Solves Long-Standing Geologic Problems Reconstruction of what the supercontinent Pangaea looked like before the most recent episode of continental drift has cleared up two interesting geologic problems:

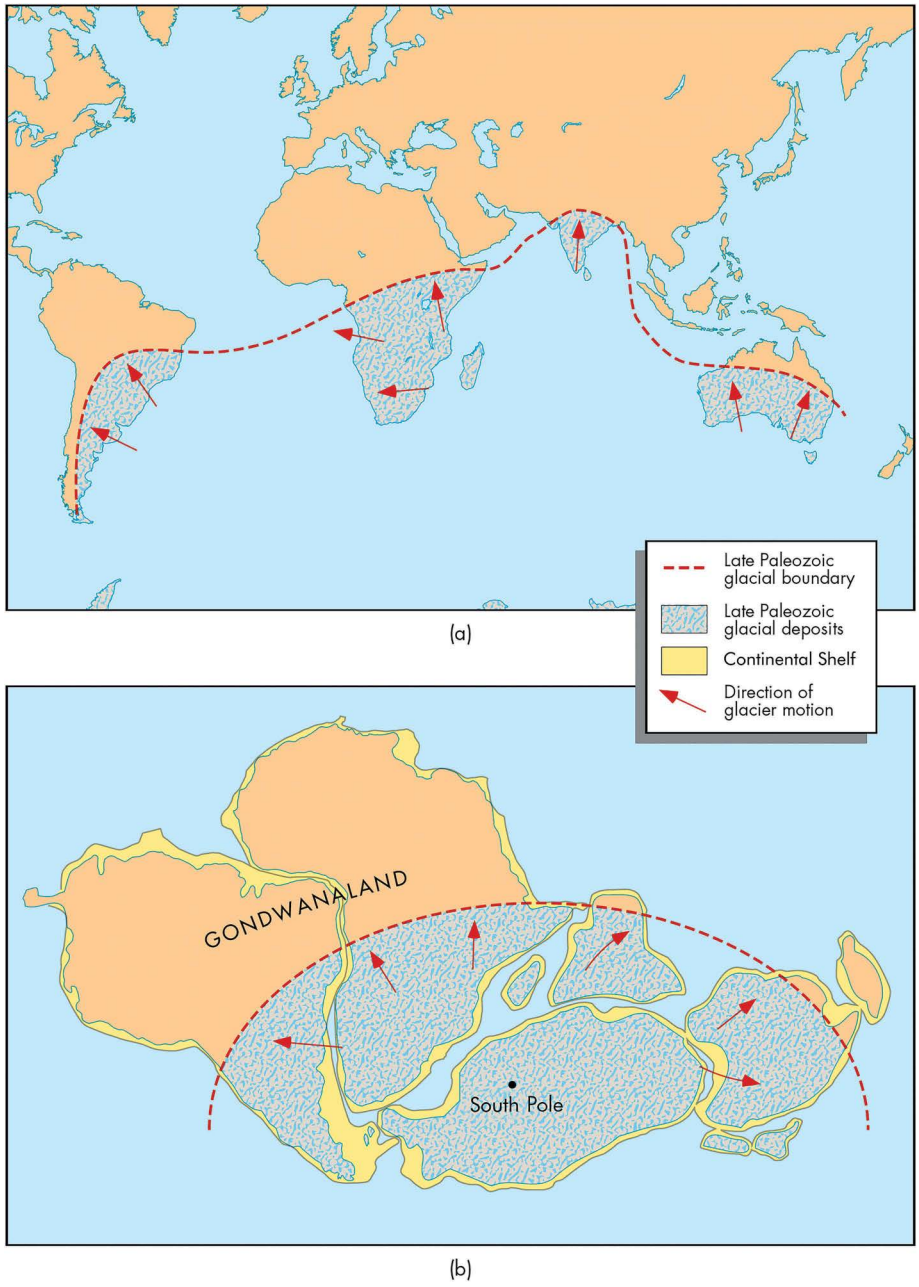
- Occurrence of the same fossil plants and animals on different continents would be difficult to explain if they had not been joined in the past (Figure 2.19).
- Evidence of ancient glaciation on several continents, with inferred directions of ice flow, makes sense only if the continents are placed back within Gondwanaland (southern Pangaea) near the South Pole as it was before splitting apart (Figure 2.20).

2.4 CHECK your understanding

1. What was Pangaea and when did it exist?
2. What geologic problems were solved when the existence of Pangaea was confirmed?



▲ FIGURE 2.19 Paleontological Evidence for Pangaea
This map shows some of the paleontological (fossil) evidence that supports continental drift. Scientists believe that these animals and plants could not have been found on all of these continents were they not once much closer together than they are today. Major ocean basins would have been physical barriers to their distribution. *(From Hamblin, W. K.,* Earth's Dynamic Systems, *6th ed. New York: Macmillan, 1992. Reprinted by permission of Macmillan.)*



< FIGURE 2.20 Glacial Evidence for Pangaea (a) Map showing the distribution of evidence for late Paleozoic glaciations. The arrows indicate the direction of ice movement. Notice that the arrows are all pointing away from ocean sources. Also these areas are close to the tropics today, where glaciation would have been unlikely in the past. These Paleozoic glacial deposits were formed when Pangaea was a supercontinent before fragmentation by continental drift. (b) The continents are restored (it is thought that continents drifted north away from the South Pole). Notice that the arrows now point outward as if moving away from a central area where glacial ice was accumulating. Thus, restoring the position of the continents produces a pattern of glacial deposits that makes much more sense. *(Based on Hamblin, W. K.,* Earth's Dynamic Systems, *6th ed. New York: Macmillan, 1992)*

2.5 How Plate Tectonics Works: Putting It Together

Driving Mechanisms That Move Plates Now that we have presented the concept that new oceanic lithosphere is produced at mid-ocean ridges because of seafloor spreading and that old, cooler plates sink into the mantle at subduction zones, let us evaluate the forces that cause the lithospheric plates to actually move and subduct. Figure 2.21 is an idealized diagram illustrating the two most likely driving forces: ridge push and slab pull.

The mid-ocean ridges or spreading centers stand at elevations of about 1 to 2.5 km (~3200 to 8200 ft.) above the ocean floor as linear, gently arched uplifts with widths greater than the distance from Florida to Canada (see Figure 2.8). *Ridge push* is a gravitational

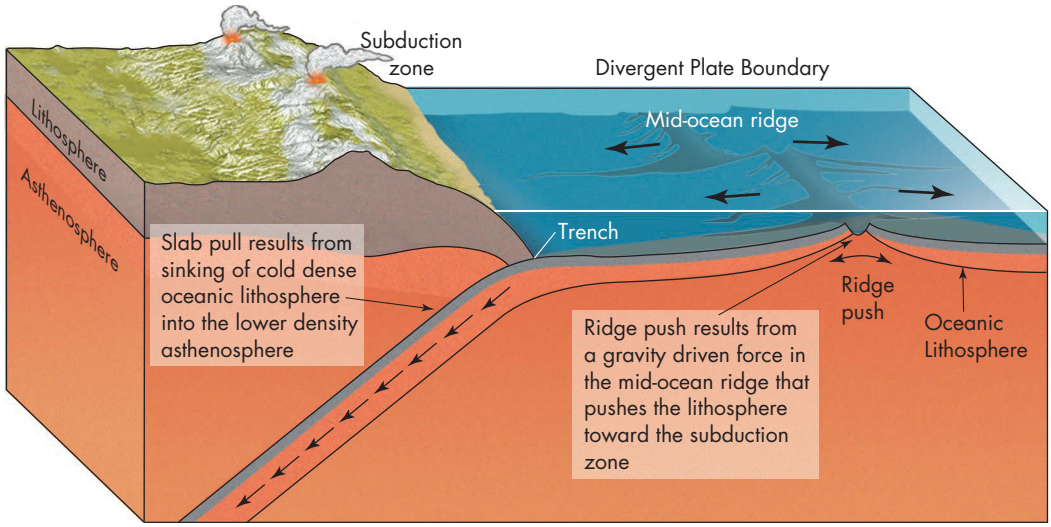


FIGURE 2.21 Push and Pull in Moving Plates

Idealized diagram showing concepts of ridge push and slab pull that facilitate the movement of lithospheric plates from spreading ridges to subduction zones. Both are gravity driven. The heavy lithosphere moves down the mid-ocean ridge slope and subducts down through the lighter, hotter mantle. *(Based on Cox, A., and Hart, R. B.,* Plate Tectonics. *Boston: Blackwell Scientific Publications, 1986)*

push, like a gigantic landslide, away from the ridge crest toward the subduction zone (the lithosphere slides on the asthenosphere). *Slab pull* results when the lithospheric plate moves farther from the ridge and cools, gradually becoming denser than the asthenosphere beneath it. At a subduction zone, the plate sinks through lighter, hotter mantle below the lithosphere, and the weight of this descending plate edge pulls on the entire plate, resulting in slab pull (Figure 2.21). Which of the two processes, ridge push or slab pull, is the more influential of the driving forces? Calculations of the expected gravitational effects suggest that ridge push is of relatively low importance compared with slab pull. In addition, it is observed that plates with large subducting slabs attached and pulling on them (e.g., the subduction zones surrounding the Pacific Basin) tend to move much more rapidly than those driven primarily by ridge push alone. Thus, slab pull may be more influential than ridge push in moving plates.

2.5 CHECK your understanding

1. What is the difference between ridge push and slab pull?
2. What evidence suggests that slab pull may be the dominant driver of plate tectonics?

2.6 Plate Tectonics and Hazards

The importance of the tectonic cycle to our lives cannot be overstated. Everything living on Earth is affected by plate tectonics. As the plates slowly move a few centimeters each year, so do the continents and ocean basins, producing zones of resources (oil, gas, and minerals), as well as earthquakes and volcanoes (see Figure 2.4b). The tectonic processes occurring at plate boundaries largely determine the types and properties of the rocks upon which we depend for our land, our mineral and rock resources, and the soils in which our food is grown.

The linkage of hazardous events to plate tectonics is obvious. When plate boundaries are mapped, the boundaries are located where volcanoes and earthquakes have occurred. Beyond this, several major conclusions may be drawn:

- At divergent plate boundaries, such as along the Mid-Atlantic Ridge, the dominant hazards are earthquakes and volcanic eruption. This is especially true where the boundary briefly comes on land in Iceland. There, volcanoes that underlie glacial ice are related to both volcanic hazards and flooding (see Applying the Fundamental Concepts in Chapter 5). Subglacial lakes may form as a result of heating from below; if these suddenly burst or if a volcanic eruption occurs, flooding will occur.

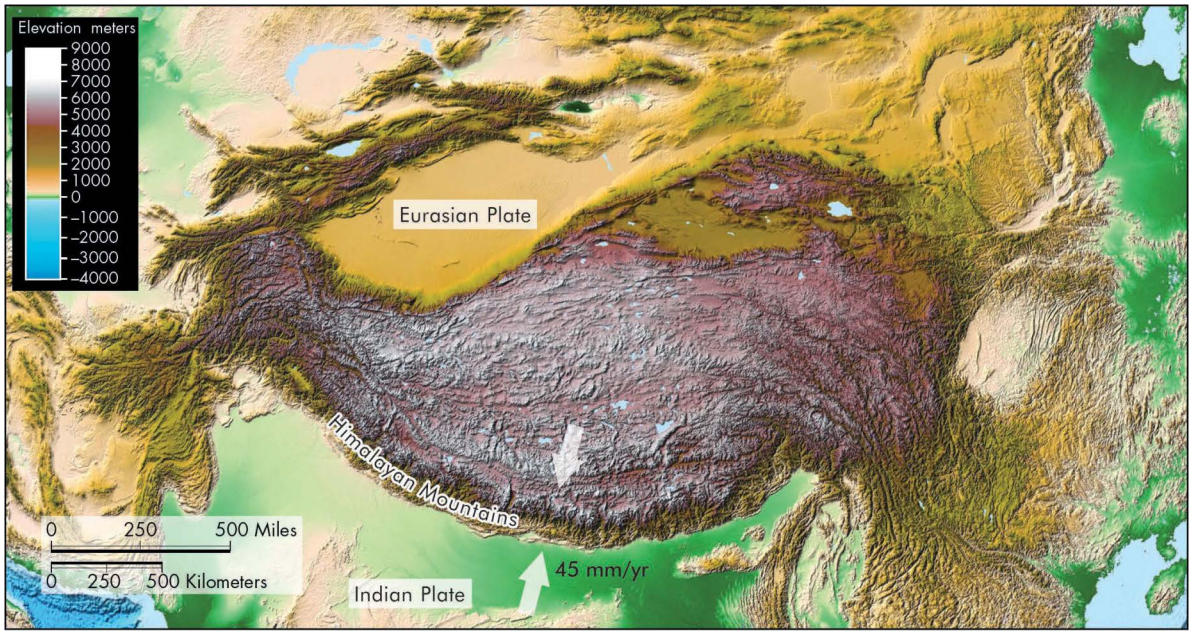


FIGURE 2.22 Continental Collision
False color topographic image showing continental collision between the Indian and Asian plates. Collision of the two plates has uplifted the Tibetan Plateau to an average of 5000 m (~16,400 ft.) and numerous peaks in the Himalayan Mountains to heights greater than 8000 m (~26,000 ft.).

- Along boundaries where one plate slides past another such as the San Andreas fault, the earthquake hazard is appreciable. There are a number of such boundaries around the world in places such as Southern California, Haiti, and New Zealand (see Figure 2.4a). Associated with these plate boundaries are often hilly or mountainous areas where rainfall may be higher and, thus, hazards such as landslides and flooding are also present.
- Convergent plate boundaries, where one plate dives beneath another or two collide, are areas particularly prone to natural hazards. Where subduction zone volcanism occurs, particularly explosive volcanoes are typical. Thus, we see the string of volcanoes in Alaska, the Pacific Northwest, New Zealand, Japan, and the western coast of South America. Where two continental landmasses collide and neither can be subducted, the highest topography in the world has been produced (Figure 2.22). Along with the earthquake hazard there is increasing precipitation and an abundance of high, steep slopes prone to landslides and flooding. Where India has collided with Asia for the past 50 million years, a high plateau (Tibetan Plateau) has formed and this high topography affects the occurrence of the summer monsoon as well as the global climate. Thus, plate tectonics can affect the occurrence of severe storms and related flooding and erosion. To a lesser extent, the same forces have produced the high plateau area of the Rocky Mountains that affects the regional climate and the monsoonal storms of the southwestern United States.

In summary, we see that plate tectonics is linked to many geologic processes operating on Earth's surface that are linked to natural hazards.

2.6 CHECK your understanding

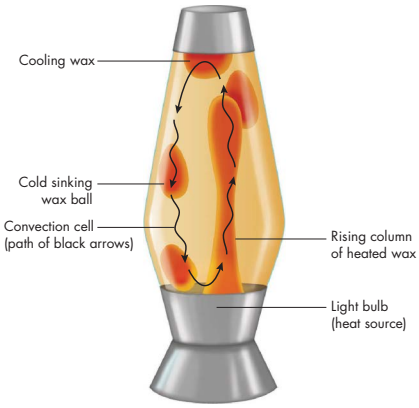
1. Explain why convergent plate boundaries represent a greater hazard than other plate boundaries.

CONCEPTS in review

2.1 Internal Structure of Earth

LO:1 Describe the basic internal structure and processes of Earth.

- The internal structure of Earth can be divided into layers or concentric shells, based on either composition (what it's made of) or physical properties (e.g., solid or liquid, weak or strong). The compositional layers include the core, mantle, and crust.
- The uppermost physical layer of Earth is known as the lithosphere and is relatively strong and rigid compared with the soft asthenosphere underlying it.
- A convection cell is a temperature-driven circulation pattern that is assumed to operate within Earth and may be involved in driving plate tectonics.



KEY WORDS

asthenosphere (p. 40), **convection** (p. 41), **crust** (p. 40), **inner core** (p. 40), **lithosphere** (p. 40), **mantle** (p. 40), **Moho** (p. 40), **outer core** (p. 40)

2.2 Plate Tectonics

LO:2 Summarize the various lines of evidence that support the theory of plate tectonics.

LO:3 Compare and contrast the different types of plate boundaries.

- The lithosphere is broken into large pieces called tectonic plates that move relative to one another. Most earthquakes and volcanoes worldwide are associated with plate boundaries.
- The three types of plate boundaries are divergent (mid-ocean ridges, spreading centers), convergent (subduction zones and continental collisions), and transform faults. At some locations, three plates meet in areas known as triple junctions. Rates of plate movement are generally a few centimeters per year.
- Evidence supporting plate tectonic theory includes seafloor spreading, continental drift, the configurations of hot spots and chains of volcanoes, and Wadati–Benioff zones.



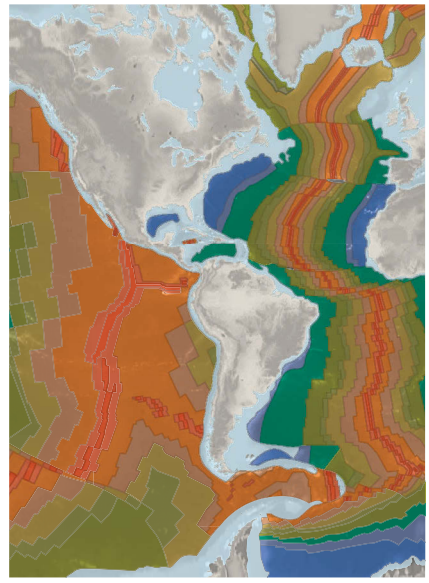
KEY WORDS

continental drift (p. 41), **convergent boundary** (p. 45), **divergent boundary** (p. 44), **mid-ocean ridge** (p. 41), **plate tectonics** (p. 41), **seafloor spreading** (p. 41), **spreading center** (p. 41), **subduction zone** (p. 42), **submarine trench** (p. 45), **transform boundary** (p. 47), **triple junction** (p. 47), **Wadati–Benioff zone** (p. 43)

2.3 A Detailed Look at Seafloor Spreading

LO:4 Explain the mechanisms of plate tectonics.

- Convection currents in Earth's liquid outer core generate a magnetic field that is sufficiently strong to be recorded in rocks that contain magnetic minerals. Over the past few hundred million years, periodic flips of the magnetic field between normal and reverse polarity are preserved in the rock record, the study of which is known as paleomagnetism.
- The seafloor spreading hypothesis proposed a mechanism for continental drift. The hypothesis suggested that new ocean lithosphere was created along mid-ocean ridges and moved laterally away with time, pushing the continents apart. Seafloor spreading is confirmed using the paleomagnetic signature of the seafloor centered around the mid-ocean ridges. A symmetrical pattern of magnetic anomolies, recording normal and reverse polarity, indicates that the age of the seafloor gets older away from the mid-ocean ridge, validating the seafloor spreading hypothesis.
- The age of the seafloor is everywhere younger than 200 million years old, which is 20 times younger than the age of continents. This suggests that the seafloor is recycled back into the mantle while the less dense continents are too buoyant to subduct.
- Hot spots are plumes of hot rock that rise from deep in the mantle and cause volcanoes above them at Earth's surface. Unlike the moving tectonic plates, hot spots are fixed and, therefore, as the plate moves across the hot spot a chain of volcanoes is formed, such as the Hawaiian Islands.



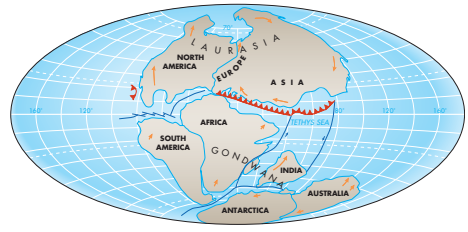
KEY WORDS

hot spot (p. 51), **magnetic reversal** (p. 49), **paleomagnetism** (p. 49)

2.4 Pangaea and Present Continents

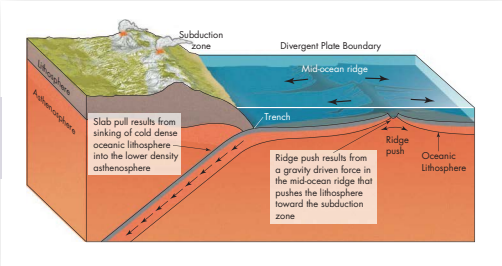
LO:5 Outline how plate tectonics has changed the appearance of Earth's surface over time.

- Alfred Wegener's continental drift hypothesis suggested that all of Earth's continents were in the past assembled in a single enormous continent, known as Pangaea. We now know that this was the case about 200 million years ago.
- With the validation of the seafloor spreading, continental drift was confirmed and several long-standing geologic problems have been resolved, including (1) the existence of the fossil plants and animals on continents separated by oceans, and (2) the distribution of ancient glaciations on several continents.



2.5 How Plate Tectonics Works: Putting It Together

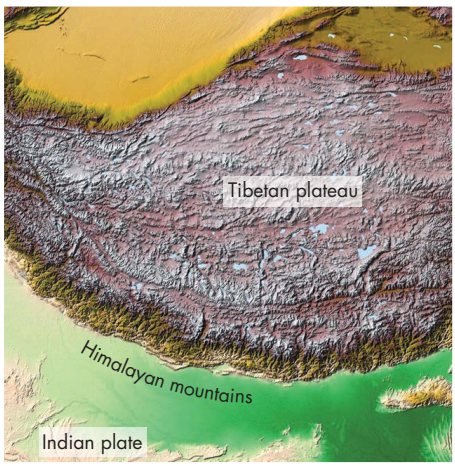
LO:6 Compare and contrast the two fundamental processes that drive plate tectonics.



- The driving forces in plate tectonics are ridge push and slab pull. At present, we believe the process of slab pull is more significant than ridge push for moving tectonic plates from spreading centers to subduction zones.

2.6 Plate Tectonics and Hazards

LO:7 Link plate tectonic processes to natural hazards.



- Plate tectonics is extremely important in determining the occurrence and frequency of volcanic eruptions, earthquakes, and other natural hazards. Divergent plate boundaries are linked to earthquakes and volcanic eruptions but, with the exception of Iceland and East Africa, the risk associated with these hazards is low because they do not occur on land.
- Transform boundaries are linked to earthquakes and represent an appreciable risk as these faults occur on land and stretch for long distance, often through populated regions.
- Convergent plate boundaries are zones of greatest risk as these are linked to the largest recorded earthquakes, explosive volcanic eruptions, and tsunamis.
- Convergent plate boundaries also generate high mountains, which are prone to mass wasting, flooding, and severe weather and can affect global climate.

CRITICAL thinking questions

1. Assume that the supercontinent Pangaea (see Figure 2.18a) never broke up. Now deduce how Earth processes, landforms, and environments might be different from how they are today with the continents spread all over the globe. *Hint:* Think about what the breakup of the continents did in terms of building mountain ranges and producing ocean basins that affect climate and so forth.

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