CHAPTER

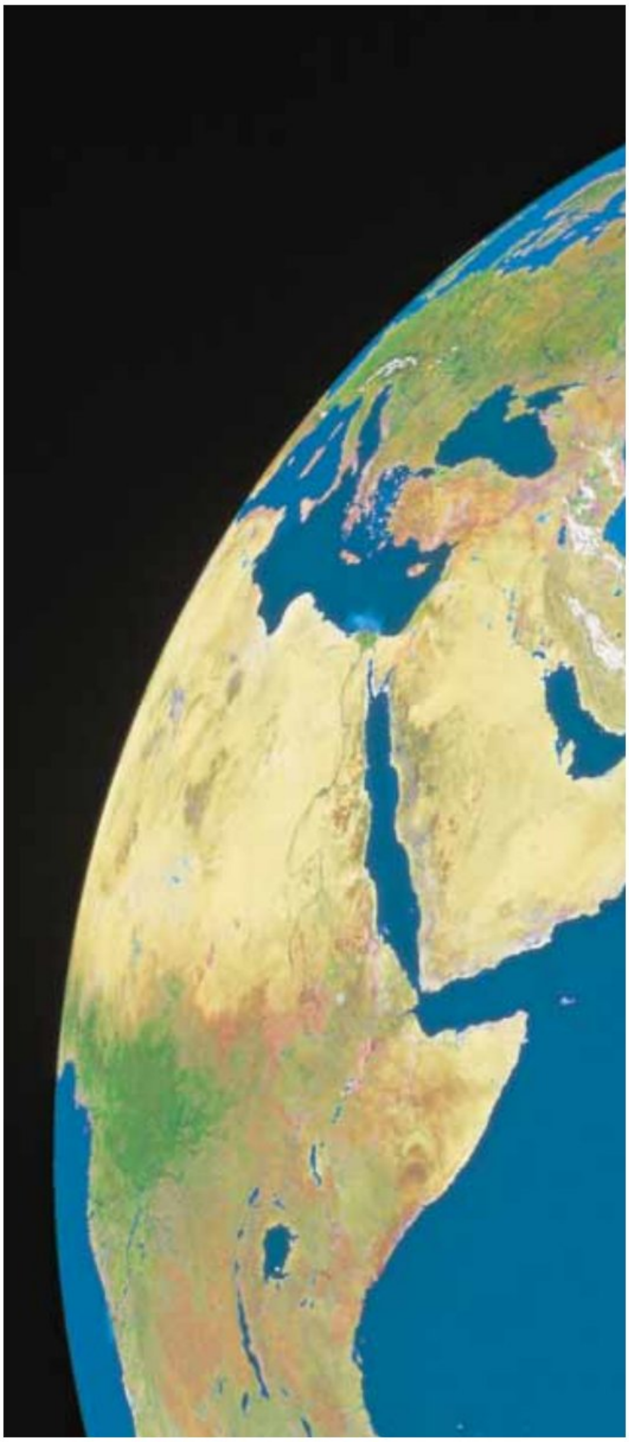
2

Plate Tectonics: A First Look

About 1 million earthquakes shake the Earth each year; most are so weak that we do not feel them, but the strongest demolish cities and kill thousands of people. Most of us have seen televised coverage of volcanic eruptions blasting molten rock and ash into the sky, destroying villages and threatening cities. Over geologic time, mountain ranges rise and then erode away, continents migrate around the globe, and ocean basins open and close.

Before 1960, no single theory explained all of these manifestations of the active Earth. In the early 1960s, geologists developed the **plate tectonics theory**, which provides a single, unifying framework that explains earthquakes, volcanic eruptions, mountain building, moving continents, and many other geologic events. It also allows geologists to identify many geologic hazards before they affect humans.

Because plate tectonics theory is so important to modern geology, it provides a foundation for many of the following chapters of this book. We describe and explain the basic aspects of the theory in this chapter. In following chapters we use the theory to explain the active Earth.



India collided with southern Asia to raise the Himalayas, the Earth's highest mountain chain. (Tom Van Sant/Geosphere Project, Santa Monica Photo Science Library)

2.1 AN OVERVIEW OF PLATE TECTONICS

Like most great, unifying scientific ideas, the plate tectonics theory is simple. Briefly, it describes the Earth's outer layer, called the **lithosphere**, as a shell of hard, strong rock. This shell is broken into seven large (and several smaller) segments called **tectonic plates**. They are also called lithospheric plates, and the two terms are interchangeable (Fig. 2–1). The tectonic plates float on the layer below, called the **asthenosphere**. The asthenosphere, like the lithosphere, is rock. But the asthenosphere is so hot that 1 to 2 percent of it is melted. As a result, it is plastic, and weak. The lithospheric plates glide slowly over the asthenosphere like sheets of ice drifting across a pond (Fig. 2–2). Continents and ocean basins make up the upper parts of the plates. As a tectonic plate glides over the asthenosphere, the continents and oceans move with it.

Most of the Earth's major geological activity occurs at **plate boundaries**, the zones where tectonic plates meet and interact. Neighboring plates can move relative to one another in three different ways (Fig. 2–3). At a **divergent boundary**, two plates move apart, or separate. At a **convergent boundary**, two plates move toward each other, and at a **transform boundary**, they slide horizontally past each other. Table 2–1 summarizes characteristics and examples of each type of plate boundary. Plate interactions at these boundaries build mountain ranges and create earthquakes and volcanic eruptions.

2.2 THE EARTH'S LAYERS

The energy released by an earthquake travels through the Earth as waves. Geologists have found that earthquake waves abruptly change both speed and direction at certain depths as they pass through the Earth's interior. Chapter 10 describes how these abrupt changes reveal that the Earth is a layered planet. Figure 2–4 and Table 2–2 describe the layers.

THE CRUST

The **crust** is the outermost and thinnest layer. Because the crust is relatively cool, it consists of hard, strong rock. Crust beneath the oceans differs from that of continents. Oceanic crust is 5 to 10 kilometers thick and is composed mostly of a dark, dense rock called **basalt**. In contrast, the average thickness of continental crust is about 20 to 40 kilometers, although under mountain ranges it can be as much as 70 kilometers thick.

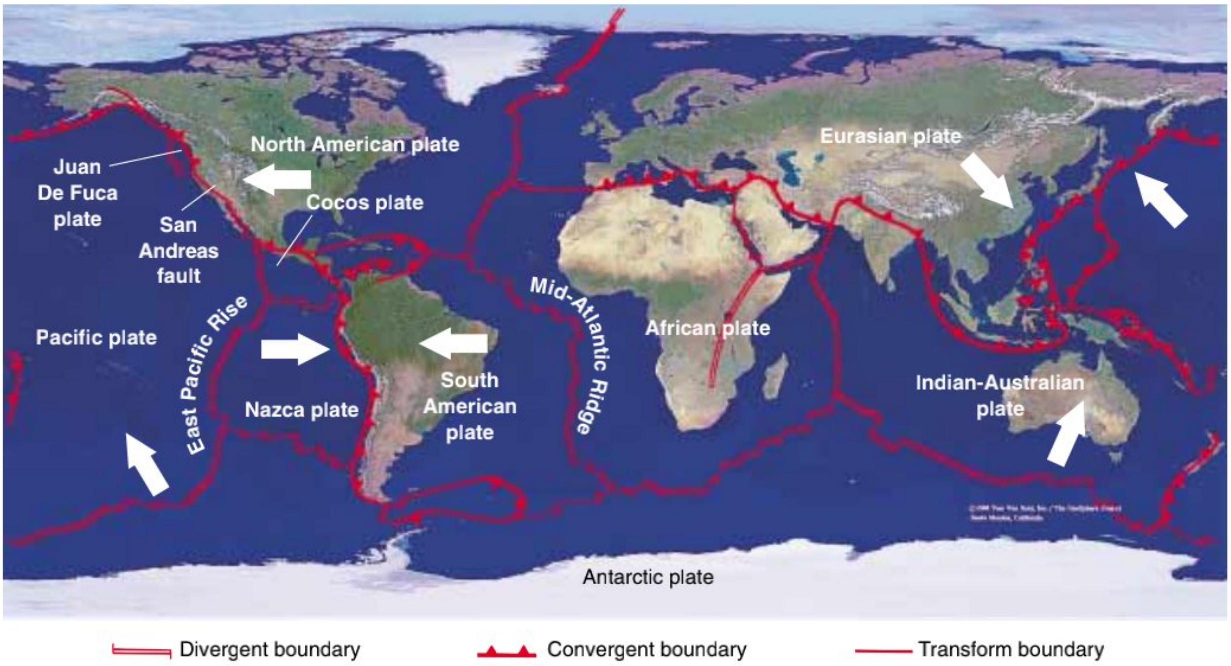


Figure 2–1 The Earth's lithosphere is broken into seven large plates, separated by the red lines; they are called the African, Eurasian, Indian–Australian, Antarctic, Pacific, North American, and South American plates. A few of the smaller plates are also shown. White arrows indicate directions of plate movement and show that the plates move in different directions. The red lines also distinguish the three types of plate boundaries. (Tom Van Sant, Geosphere Project)

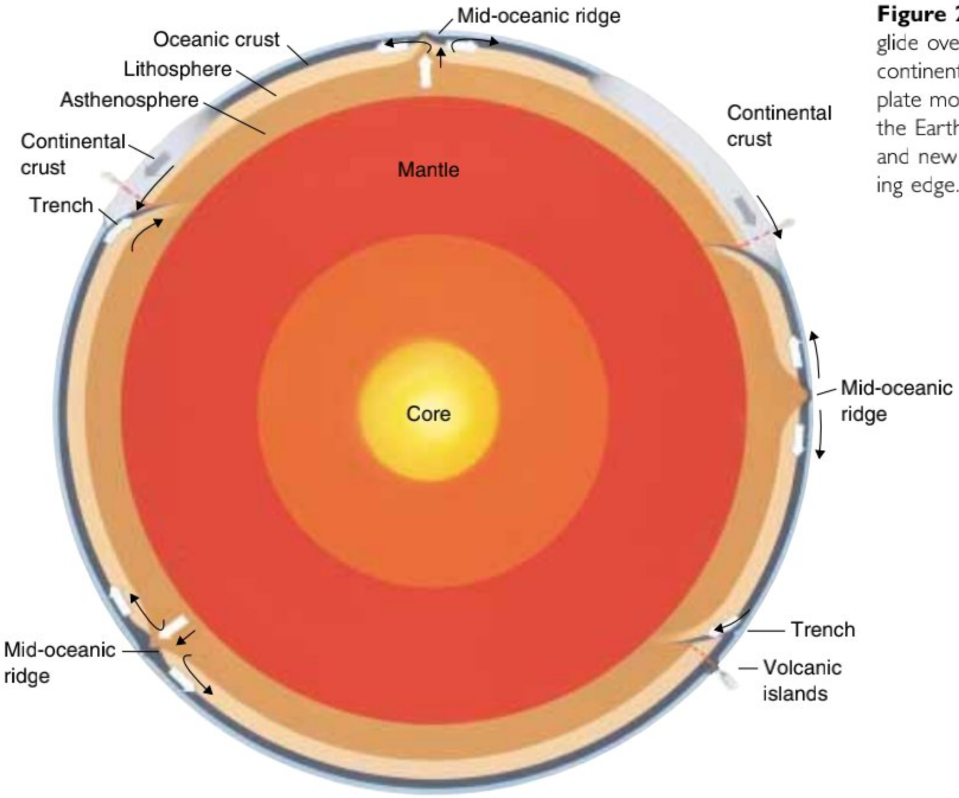
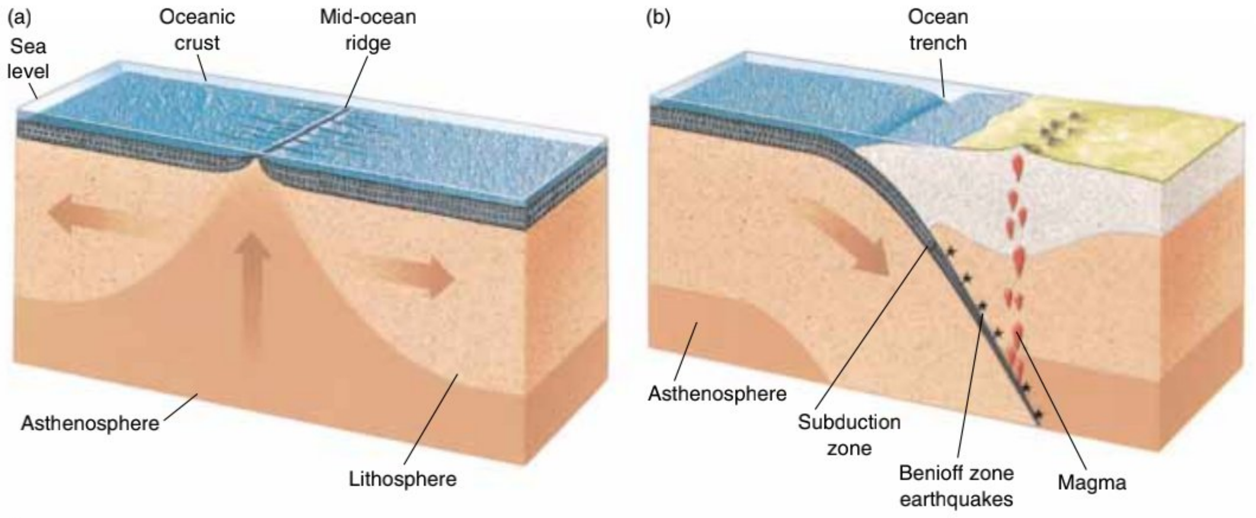


Figure 2–2 Plates of lithosphere glide over the asthenosphere, carrying continents and oceans with them. As a plate moves, old lithosphere sinks into the Earth's interior at its leading edge, and new lithosphere forms at the trailing edge.

Table 2–1 • CHARACTERISTICS AND EXAMPLES OF PLATE BOUNDARIES

TYPE OF BOUNDARY	TYPES OF PLATES INVOLVED	TOPOGRAPHY	GEOLOGIC EVENTS	MODERN EXAMPLES
Divergent	Ocean-ocean	Mid-oceanic ridge	Sea-floor spreading, shallow earthquakes, rising magma, volcanoes	Mid-Atlantic ridge
	Continent-continent	Rift valley	Continents torn apart, earthquakes, rising magma, volcanoes	East African rift
Convergent	Ocean-ocean	Island arcs and ocean trenches	Subduction, deep earthquakes, rising magma, volcanoes, deformation of rocks	Western Aleutians
	Ocean-continent	Mountains and ocean trenches	Subduction, deep earthquakes, rising magma, volcanoes, deformation of rocks	Andes
	Continent-continent	Mountains	Deep earthquakes, deformation of rocks	Himalayas
Transform	Ocean-ocean	Major offset of mid-oceanic ridge axis	Earthquakes	Offset of East Pacific rise in South Pacific
	Continent-continent	Small deformed mountain ranges, deformations along fault	Earthquakes, deformation of rocks	San Andreas fault



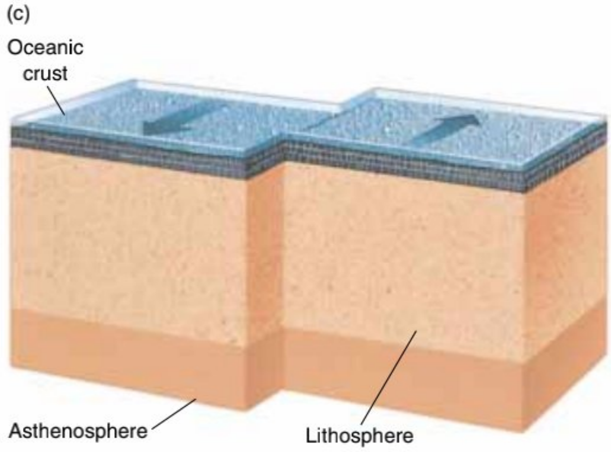


Figure 2–3 Three types of boundaries separate the Earth's tectonic plates: (a) Two plates separate at a divergent boundary. New lithosphere forms as hot asthenosphere rises to fill the gap where the two plates spread apart. The lithosphere is relatively thin at this type of boundary. (b) Two plates converge at a convergent boundary. If one of the plates carries oceanic crust, the dense oceanic plate sinks into the mantle in a subduction zone. Here an oceanic plate is sinking beneath a less dense continental plate. Magma rises from the subduction zone, and a trench forms where the subducting plate sinks. The stars mark Benioff zone earthquakes that occur as the sinking plate slips past the opposite plate (described in Chapter 10). (c) At a transform plate boundary, rocks on opposite sides of the fracture slide horizontally past each other.

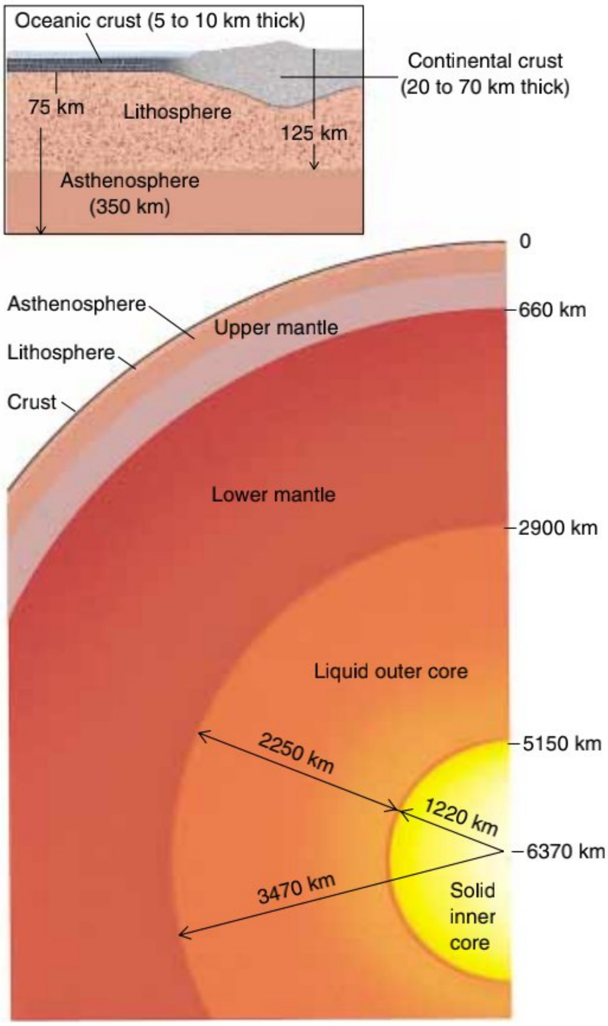


Figure 2–4 The Earth is a layered planet. The insert is drawn on an expanded scale to show near-surface layering.

Table 2–2 • THE LAYERS OF THE EARTH

	LAYER	COMPOSITION	DEPTH	PROPERTIES
Crust	Oceanic crust Continental crust	Basalt Granite	5–10 km 20–70 km	Cool, hard, and strong Cool, hard, and strong
Lithosphere	Lithosphere includes the crust and the uppermost portion of the mantle	Varies; the crust and the mantle have different compositions	75–125 km	Cool, hard, and strong
Mantle	Uppermost portion of the mantle included as part of the lithosphere			
	Asthenosphere	Entire mantle is ultramafic rock. Its mineralogy varies with depth	Extends to 350 km	Hot, weak, and plastic, 1% or 2% melted
	Remainder of upper mantle		Extends from 350 to 660 km	Hot, under great pressure, and mechanically strong
	Lower mantle		Extends from 660 to 2900 km	High pressure forms minerals different from those of the upper mantle
Core	Outer core	Iron and nickel	Extends from 2900 to 5150 km	Liquid
	Inner core	Iron and nickel	Extends from 5150 km to the center of the Earth	Solid

Continents are composed primarily of a light-colored, less dense rock called **granite**.

THE MANTLE

The **mantle** lies directly below the crust. It is almost 2900 kilometers thick and makes up 80 percent of the Earth's volume. Although the chemical composition may be similar throughout the mantle, Earth temperature and pressure increase with depth. These changes cause the strength of mantle rock to vary with depth, and thus they create layering within the mantle. The upper part of the mantle consists of two layers.

The Lithosphere

The uppermost mantle is relatively cool and consequently is hard, strong rock. In fact, its mechanical behavior is similar to that of the crust. The outer part of the Earth, including both the uppermost mantle and the crust, make up the lithosphere (Greek for "rock layer"). The lithosphere can be as thin as 10 kilometers where tectonic plates separate. However, in most regions, the lithosphere varies from about 75 kilometers thick beneath ocean basins to about 125 kilometers under the continents. A tectonic (or lithospheric) plate is a segment of the lithosphere.

The Asthenosphere

At a depth varying from about 75 to 125 kilometers, the strong, hard rock of the lithosphere gives way to the weak, plastic asthenosphere. This change in rock properties occurs over a vertical distance of only a few kilometers, and results from increasing temperature with depth. Although the temperature increases gradually, it crosses a threshold at which the rock is close to its melting point. As a result, 1 to 2 percent of the asthenosphere is liquid, and the asthenosphere is mechanically weak and plastic. Because it is plastic, the asthenosphere flows slowly, perhaps at a rate of a few centimeters per year. Two familiar examples of solid materials that flow are Silly Putty™ and hot road tar. However, both of these solids flow much more rapidly than the asthenosphere rock. The asthenosphere extends from the base of the lithosphere to a depth of about 350 kilometers. At the base of the asthenosphere, increasing pressure causes the mantle to become mechanically stronger, and it remains so all the way down to the core.

THE CORE

The **core** is the innermost of the Earth's layers. It is a sphere with a radius of about 3470 kilometers and is composed largely of iron and nickel. The outer core is molten because of the high temperature in that region. Near its center, the core's temperature is about 6000°C, as hot as the Sun's surface. The pressure is greater than 1 million times that of the Earth's atmosphere at sea level. The extreme pressure overwhelms the temperature effect and compresses the inner core to a solid.

To visualize the relative thickness of the Earth's layers, let us return to an analogy used in Chapter 1. Imagine that you could drive a magical vehicle at 100 kilometers per hour through the Earth, from its center to its surface. You would pass through the core in about 35 hours and the mantle in 29 hours. You would drive through oceanic crust in only 6 minutes, and most continental crust in about half an hour. When you arrived at the surface, you would have spent the last 3$\frac{1}{2}$ hours traversing the entire asthenosphere and lithosphere.

2.3 PLATES AND PLATE TECTONICS

In most places, the lithosphere is less dense than the asthenosphere. Consequently, it floats on the asthenosphere much as ice floats on water. Figure 2–1 shows that the lithosphere is broken into seven large tectonic plates and several smaller ones. Think of the plates as irregularly shaped ice floes, packed tightly together floating on the sea. Ice floes drift over the sea surface and, in a similar way, tectonic plates drift horizontally over the asthenosphere. The plates move slowly, at rates ranging from less than 1 to about 16 centimeters per year (about as fast as a fingernail grows). Because the plates move in different directions, they bump and grind against their neighbors at plate boundaries.

The great forces generated at a plate boundary build mountain ranges and cause volcanic eruptions and earthquakes. These processes and events are called **tectonic** activity, from the ancient Greek word for "construction." Tectonic activity "constructs" mountain chains and ocean basins. In contrast to plate boundaries, the interior portion of a plate is usually tectonically quiet because it is far from the zones where two plates interact.

DIVERGENT PLATE BOUNDARIES

At a divergent plate boundary, also called a **spreading center** and a **rift zone**, two lithospheric plates spread apart (Fig. 2–5). The underlying asthenosphere then oozes upward to fill the gap between the separating plates. As the asthenosphere rises between separating plates, some of it melts to form molten rock called **magma**.[1] Most of the magma rises to the Earth's surface, where it cools to form new crust, the top layer of the lithosphere. Most of this activity occurs beneath the seas because most divergent plate boundaries lie in the ocean basins.

Both the asthenosphere and the lower lithosphere (the part beneath the crust) are parts of the mantle and thus have similar chemical compositions. The main difference between the two layers is one of mechanical strength. The hot asthenosphere is weak and plastic, but the cooler lithosphere is strong and hard. As the asthenosphere rises, it cools, gains mechanical strength, and, therefore, transforms into new lithosphere. In this way, new lithosphere continuously forms at a divergent boundary.

At a spreading center, the rising asthenosphere is hot, weak, and plastic. Only the upper 10 to 15 kilometers cools enough to gain the strength and hardness of lithosphere rock. As a result, the lithosphere, including the crust and the upper few kilometers of mantle rock, can be as little as 10 or 15 kilometers thick at a spreading center. But as the lithosphere spreads, it cools from the top downward. When the lithosphere cools, it becomes thicker because the boundary between the cool, strong rock of the lithosphere and the hot, weak asthenosphere migrates downward. Consequently, the thickness of the lithosphere increases as it moves away from the spreading center. Think of ice freezing on a pond. On a cold day, water under the ice freezes and the

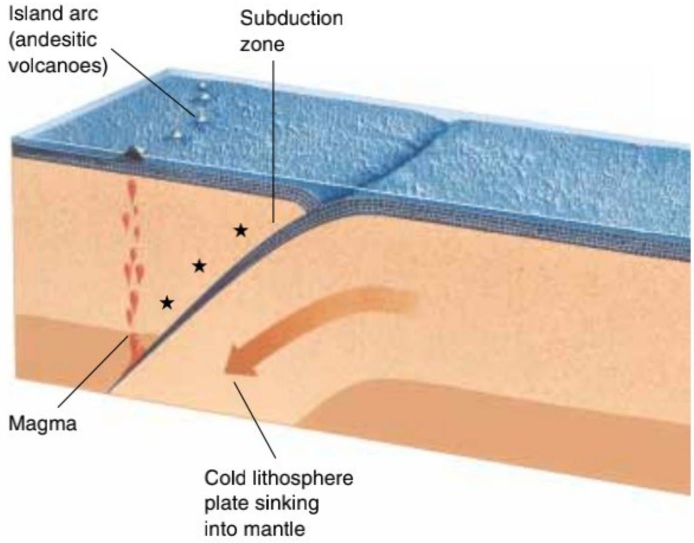


Figure 2–5 Lithospheric plates move away from a spreading center by gliding over the weak, plastic asthenosphere. In the center of the drawing, new lithosphere forms at a spreading center. At the sides of the drawing, old lithosphere sinks into the mantle at subduction zones.

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[1] It seems counterintuitive that the rising, cooling asthenosphere should melt to form magma, but the melting results from decreasing pressure rather than a temperature change. This process is discussed in Chapter 5.

ice becomes thicker. The lithosphere continues to thicken until it attains a steady state thickness of about 75 kilometers beneath an ocean basin, and as much as 125 kilometers beneath a continent.

The Mid-Oceanic Ridge: Rifting in the Oceans

A spreading center lies directly above the hot, rising asthenosphere. The newly formed lithosphere at an oceanic spreading center is hot and therefore of low density. Consequently, the sea floor at a spreading center floats to a high elevation, forming an undersea mountain chain called the **mid-oceanic ridge** (Fig. 2–6). But as lithosphere migrates away from the spreading center, it cools and becomes denser and thicker; as a result, it sinks. For this reason, the sea floor is high at the mid-oceanic ridge and lower away from the ridge. Thus, the average depth of the sea floor away from the mid-oceanic ridge is about 5 kilometers. The mid-oceanic ridge rises 2 to 3 kilometers above the surrounding sea floor and, thus, comes within 2 kilometers of the sea surface.

If you could place two bright red balls on the sea floor, one on each side of the ridge axis, and then watch them over millions of years, you would see the balls migrate away from the rift as the plates separated. The balls would also sink to greater depths as the hot rocks cooled (Fig. 2–7).

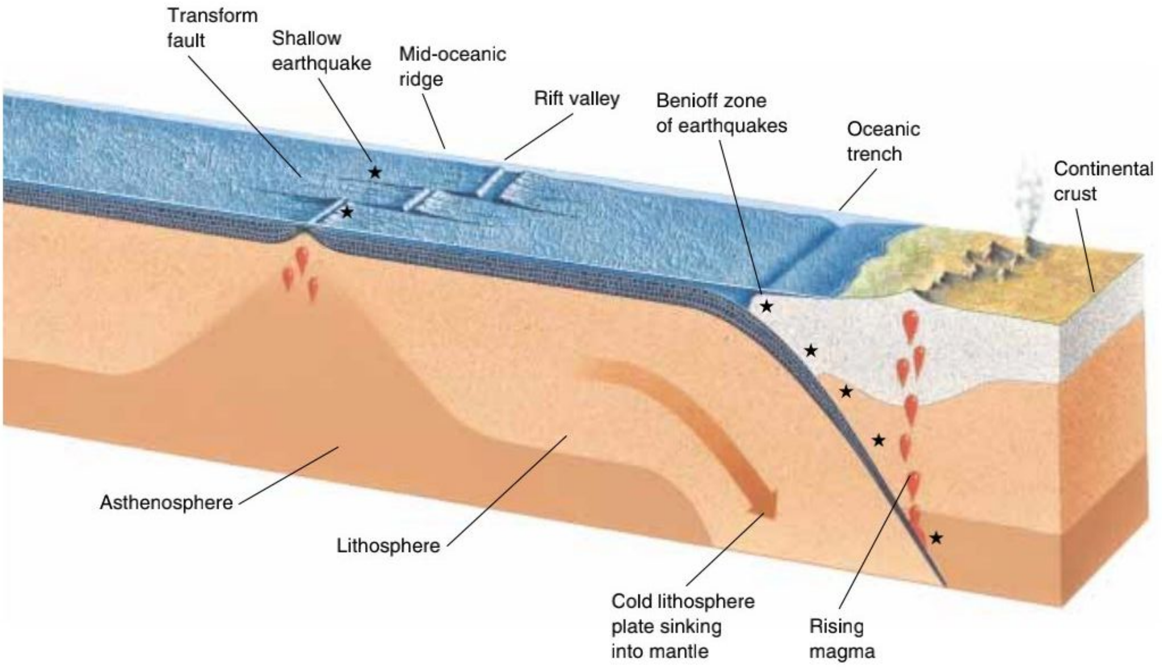
Oceanic rifts completely encircle the Earth, running around the globe like the seam on a baseball. As a result, the mid-oceanic ridge system is the Earth's longest mountain chain. The basaltic magma that oozes onto the sea floor at the ridge creates approximately 6.5×10^{18} (6,500,000,000,000,000,000) tons of new oceanic crust each year. The mid-oceanic ridge system and other features of the sea floor are described further in Chapter 11.

Splitting Continents: Rifting in Continental Crust

A divergent plate boundary can rip a continent in half in a process called **continental rifting**. A **rift valley** develops in a continental rift zone because continental crust stretches, fractures, and sinks as it is pulled apart. Continental rifting is now taking place along a zone called the East African rift (see Fig. 2–1). If the rifting continues, eastern Africa will separate from the main portion of the continent, and a new ocean basin will open between the separating portions of Africa. The Rio Grande rift is a continental rift extending from southern Colorado to El Paso, Texas. It is unclear whether rifting is still taking place here or the process has ended.

CONVERGENT PLATE BOUNDARIES

At a convergent plate boundary, two lithospheric plates move toward each other. Convergence can occur (1) between a plate carrying oceanic crust and another carrying continental crust, (2) between two plates carrying oceanic crust, and (3) between two plates carrying continental



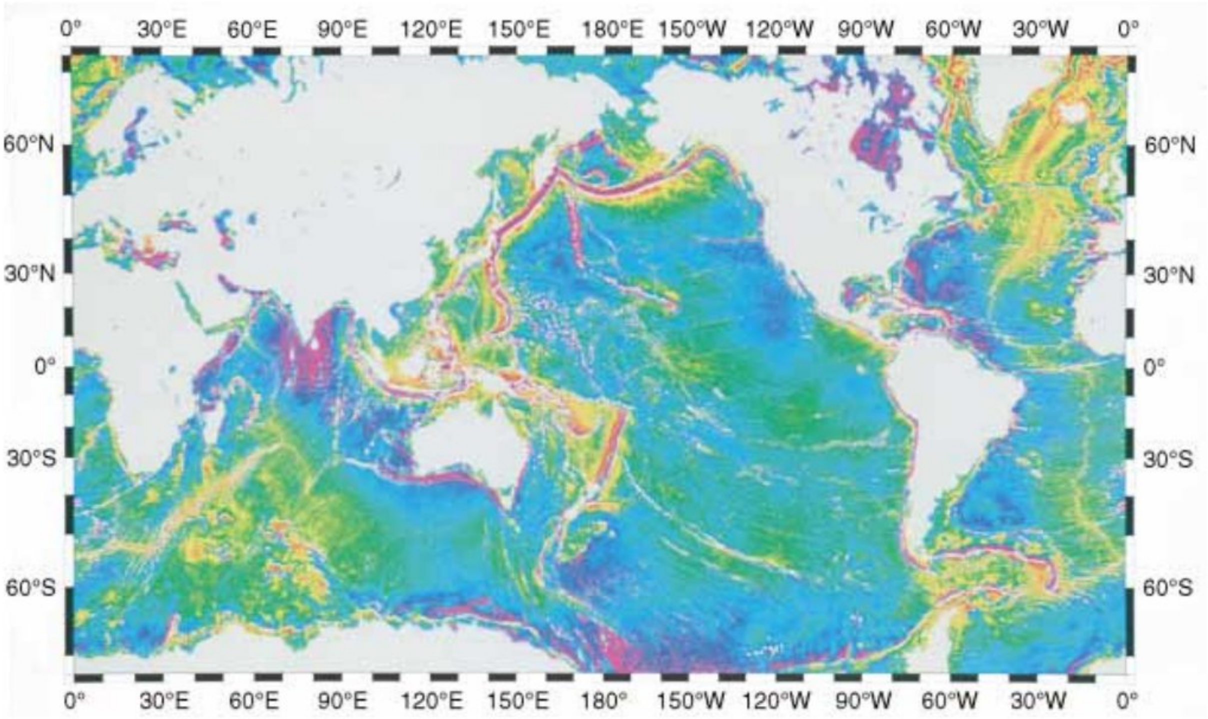


Figure 2–6 Sea floor topography is dominated by huge undersea mountain chains called mid-oceanic ridges and deep trenches called subduction zones. Mid-oceanic ridges form where tectonic plates separate, and subduction zones form where plates converge. The green areas represent the relatively level portion of the sea floor that lies about 5 kilometers underwater. The yellow-orange-red hues are mountains, primarily the mid-oceanic ridges. The blue-violet-magenta areas are trenches. (Scripps Institution of Oceanography, University of California, San Diego)

crust. Differences in density determine what happens where two plates converge. Think of a boat colliding with a floating log. The log is denser than the boat, so it sinks beneath the boat.

When two plates converge, the denser plate dives beneath the lighter one and sinks into the mantle. This process is called **subduction**. Generally, only oceanic lithosphere can sink into the mantle. Attempting to stuff

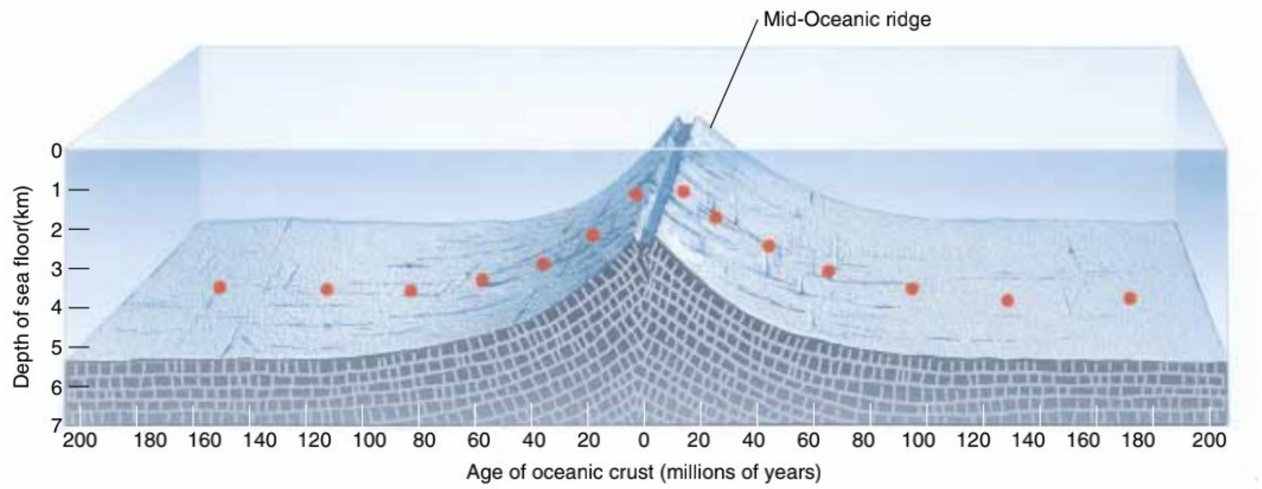


Figure 2–7 Red balls placed on the sea floor trace the spreading and sinking of new oceanic crust as it cools and migrates away from the mid-oceanic ridge.

a low-density continent down into the mantle would be like trying to flush a marshmallow down a toilet: It will not go because it is too light. In certain cases, however, small amounts of continental crust may sink into the mantle at a subduction zone. These cases are discussed in Chapter 12.

A **subduction zone** is a long, narrow belt where a lithospheric plate is sinking into the mantle. On a worldwide scale, the rate at which old lithosphere sinks into the mantle at subduction zones is equal to the rate at which new lithosphere forms at spreading centers. In this way, global balance is maintained between the creation of new lithosphere and the destruction of old lithosphere.

The oldest sea-floor rocks on Earth are only about 200 million years old because oceanic crust continuously recycles into the mantle at subduction zones. Rocks as old as 3.96 billion years are found on continents because subduction consumes little continental crust.

Convergence of Oceanic Crust with Continental Crust

When an oceanic plate converges with a continental plate, the denser oceanic plate sinks into the mantle beneath the edge of the continent. As a result, many subduction zones are located at continental margins. Today, oceanic plates are sinking beneath the western edge of South America; along the coasts of Oregon, Washington, and British Columbia; and at several other continental margins (see Fig. 2–1). We will return to this subject in Chapters 11 and 12.

Convergence of Two Plates Carrying Oceanic Crust

Recall that newly formed oceanic lithosphere is hot, thin, and light, but as it spreads away from the mid-oceanic ridge, it becomes older, cooler, thicker, and denser. Thus, the density of oceanic lithosphere increases with its age. When two oceanic plates converge, the denser one sinks into the mantle. Oceanic subduction zones are common in the southwestern Pacific Ocean and are discussed in Chapter 11.

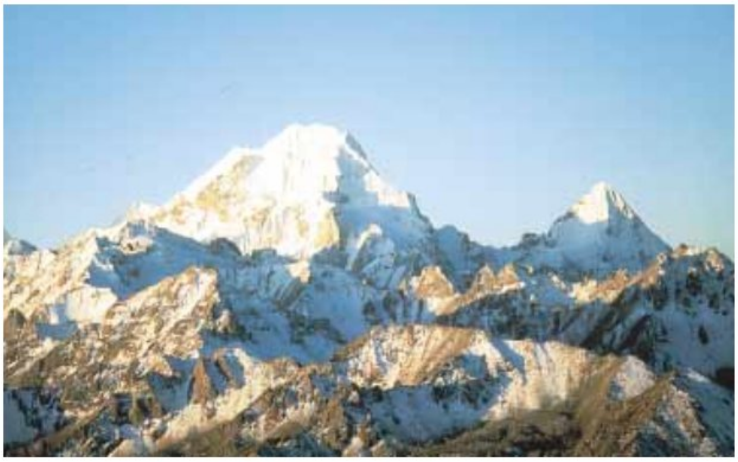


Figure 2–8 A collision between India and Asia formed the Himalayas. This figure shows Rushi Konka, eastern Tibet.

Convergence of Two Plates Carrying Continents

If two converging plates carry continents, neither can sink into the mantle because of their low densities. In this case, the two continents collide and crumple against each other, forming a huge mountain chain. The Himalayas, the Alps, and the Appalachians all formed as results of continental collisions (Fig. 2–8). These processes are discussed in Chapter 12.

TRANSFORM PLATE BOUNDARIES

A transform plate boundary forms where two plates slide horizontally past one another as they move in opposite directions (Fig. 2–3C). California's San Andreas fault is the transform boundary between the North American plate and the Pacific plate. This type of boundary can occur in both oceans and continents and is discussed in Chapters 10, 11, and 12.

2.4 THE ANATOMY OF A TECTONIC PLATE

The nature of a tectonic plate can be summarized as follows:

1. A plate is a segment of the lithosphere; thus, it includes the uppermost mantle and all of the overlying crust.
2. A single plate can carry both oceanic and continental crust. The average thickness of lithosphere covered by oceanic crust is 75 kilometers, whereas that of lithosphere covered by a continent is 125 kilometers (Fig. 2–9). Lithosphere may be as little as 10 to 15 kilometers thick at an oceanic spreading center.
3. A plate is composed of hard, mechanically strong rock.
4. A plate floats on the underlying hot, plastic asthenosphere and glides horizontally over it.
5. A plate behaves like a large slab of ice floating on a pond. It may flex slightly, as thin ice does when a skater goes by, allowing minor vertical movements. In general, however, each plate moves as a large, intact sheet of rock.
6. A plate margin is tectonically active. Earthquakes and volcanoes are common at plate boundaries. In contrast, the interior of a lithospheric plate is normally tectonically stable.

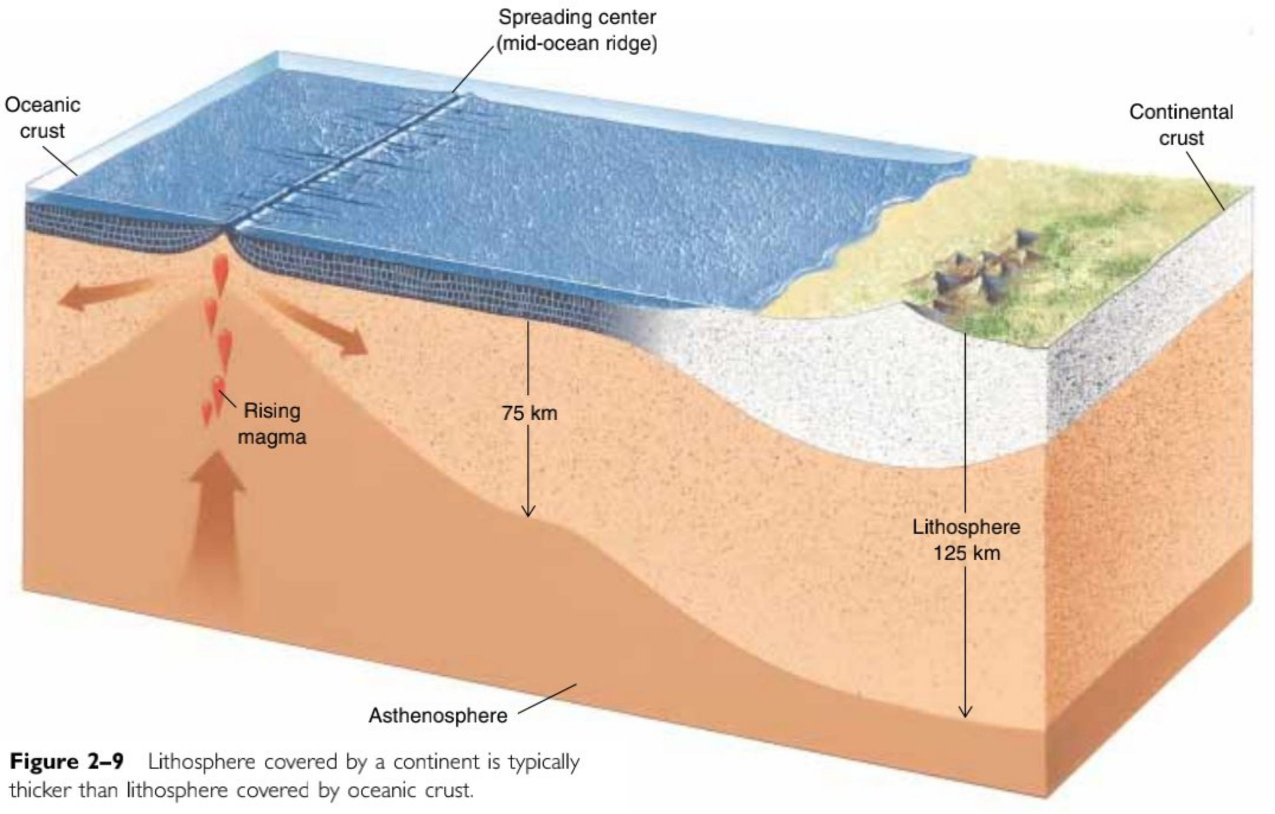


Figure 2–9 Lithosphere covered by a continent is typically thicker than lithosphere covered by oceanic crust.

7. Tectonic plates move at rates that vary from less than 1 to 16 centimeters per year.

▶ 2.5 CONSEQUENCES OF MOVING PLATES

As we mentioned previously, the plate tectonics theory provides a unifying explanation for earthquakes, volcanoes, mountain building, moving continents, and many other manifestations of the Earth's dynamic nature. In this section, we introduce some of these consequences of plate tectonics processes.

VOLCANOES

A volcanic eruption occurs where hot magma rises to the Earth's surface. Volcanic eruptions are common at both divergent and convergent plate boundaries. Three factors can melt rock to form magma and cause volcanic eruptions. The most obvious is rising temperature. However, hot rocks also melt to form magma if pressure decreases or if water is added to them. These magma-forming processes are discussed further in Chapter 4.

At a divergent boundary, hot asthenosphere rises to fill the gap left between the two separating plates (Fig. 2–7). Pressure decreases as the asthenosphere rises. As a result, portions of the asthenosphere melt to form huge quantities of basaltic magma, which erupts onto the Earth's surface. The mid-oceanic ridge is a submarine chain of volcanoes and lava flows formed at a divergent plate boundary. Volcanoes are also common in continental rifts, including the East African rift and the Rio Grande rift.

At a convergent plate boundary, cold, dense oceanic lithosphere dives into the asthenosphere. The sinking plate carries water-soaked mud and rock that once lay on the sea floor. As the sinking plate descends into the mantle, it becomes hotter. The heat drives off the water, which rises into the hot asthenosphere beneath the opposite plate. The water melts asthenosphere rock to form huge amounts of magma in a subduction zone. The magma then rises through the overlying lithosphere. Some solidifies within the crust, and some erupts from volcanoes on the Earth's surface. Volcanoes of this type are common in the Cascade Range of Oregon, Washington, and British Columbia; in western South America; and near most other subduction zones (Fig. 2–10).

EARTHQUAKES

Earthquakes are common at all three types of plate boundaries, but less common within the interior of a tectonic plate. Quakes concentrate at plate boundaries simply because those boundaries are zones of deep fractures in the lithosphere where one plate slips past another. The slippage is rarely smooth and continuous. Instead, the fractures may be locked up for months or for hundreds of years. Then, one plate suddenly slips a few centimeters or even a few meters past its neighbor. An earthquake is vibration in rock caused by these abrupt movements.

MOUNTAIN BUILDING

Many of the world's great mountain chains, including the Andes and parts of the mountains of western North America, formed at subduction zones. Several processes combine to build a mountain chain at a subduction zone. The great volume of magma rising into the crust thickens the crust, causing mountains to rise. Volcanic eruptions build chains of volcanoes. Additional crustal thickening may occur where two plates converge for the same reason that a mound of bread dough thickens when you compress it from both sides.

Great chains of volcanic mountains form at rift zones because the new, hot lithosphere floats to a high level, and large amounts of magma form in these zones. The mid-oceanic ridge, the East African rift, and the Rio Grande rift are examples of such mountain chains.

OCEANIC TRENCHES

An **oceanic trench** is a long, narrow trough in the sea floor that develops where a subducting plate sinks into the mantle (Figs. 2–3b and 2–5). To form the trough, the sinking plate drags the sea floor downward. A trench can form wherever subduction occurs—where oceanic crust sinks beneath the edge of a continent, or where it sinks beneath another oceanic plate. Trenches are the deepest parts of the ocean basins. The deepest point on Earth is in the Mariana trench in the southwestern Pacific Ocean, where the sea floor is as much as 10.9 kilometers below sea level (compared with the average sea-floor depth of about 5 kilometers).

MIGRATING CONTINENTS AND OCEANS

Continents migrate over the Earth's surface because they are integral parts of the moving lithospheric plates; they simply ride piggyback on the plates. Measurements of these movements show that North America is now moving away from Europe at about 2.5 centimeters per year, as the mid-Atlantic ridge continues to separate. South America is drawing away from Africa at a rate of about 3.5 centimeters per year. As the Atlantic Ocean widens, the Pacific is shrinking at the same rate. Thus, as continents move, ocean basins open and close over geologic time.

Figure 2–10 Mount Hood in Oregon is a volcanic peak that lies near a convergent plate boundary.

2.6 THE SEARCH FOR A MECHANISM

Geologists have accumulated ample evidence that lithospheric plates move and can even measure how fast they move (Fig. 2–11). However, geologists do not agree on an explanation for why the plates move. Studies of the Earth's interior show that the mantle flows slowly beneath the lithosphere. Some geologists have suggested that this mantle flow drags the lithospheric plates along. Others suggest that another force moves the plates, and the movement of the plates causes the mantle to flow.

MANTLE CONVECTION

Convection occurs when a fluid is heated. For example, as a pot of soup is heated on a stove, the soup at the bottom of the pot becomes warm and expands. It then rises because it is less dense than the soup at the top. When the hot soup reaches the top of the pot, it flows along the surface until it cools and sinks (Fig. 2–12). The convection continues as long as the heat source persists. A similar process might cause convection in the Earth's mantle.

The mantle is heated internally by radioactive decay and from below by the hot core. Although the mantle is solid rock (except for small, partially melted zones in the asthenosphere), it is so hot that over geologic time it flows slowly. According to one hypothesis, hot rock rises from deep in the mantle to the base of the lithosphere.

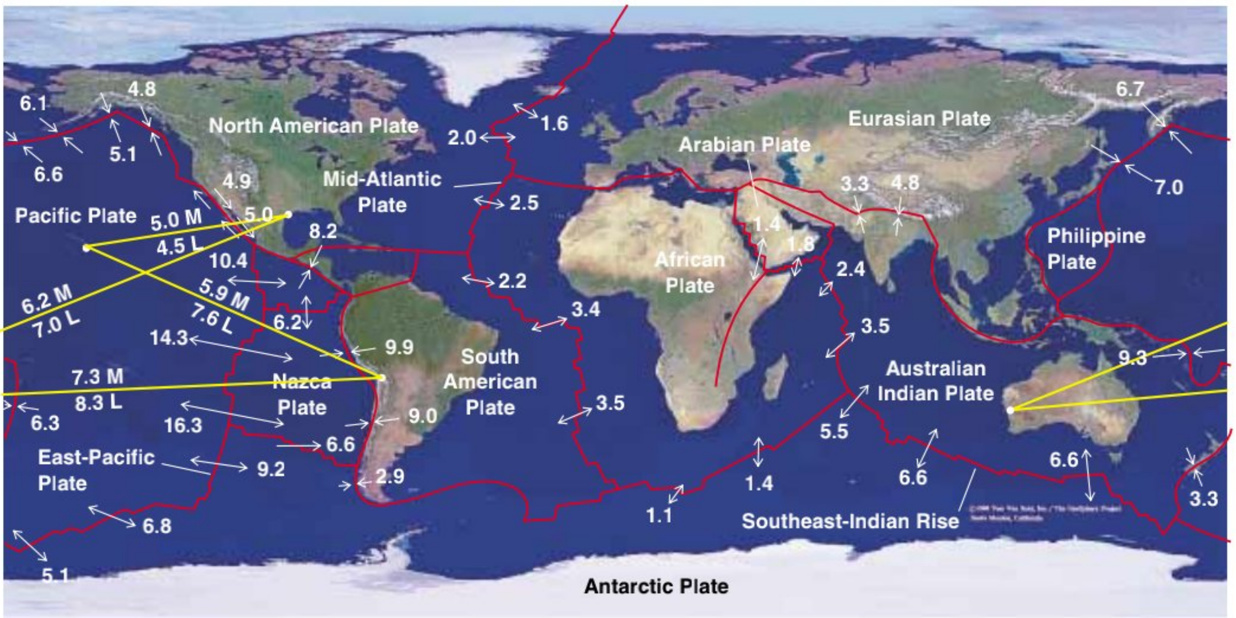


Figure 2–11 Plate velocities in centimeters per year. Numbers along the mid-oceanic ridge system indicate the rates at which two plates are separating, based on magnetic reversal patterns on the sea floor (discussed in Chapter 11). The arrows indicate the directions of plate motions. The yellow lines connect stations that measure present-day rates of plate motions with satellite laser ranging methods. The numbers followed by L are the present-day rates measured by laser. The numbers followed by M are the rates measured by magnetic reversal patterns. (Modified from NASA report, Geodynamics Branch, 1986. Tom Van Sant, Geosphere Project)

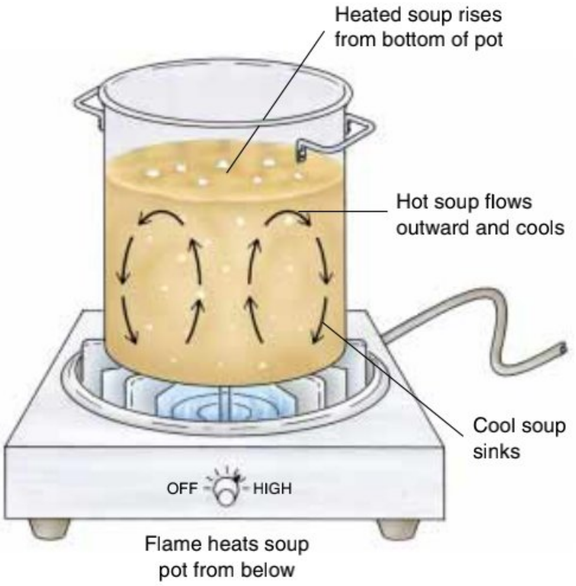


Figure 2–12 Soup convects when it is heated from the bottom of the pot.

At the same time, nearby parts of the cooler upper mantle sink. Thus, convection currents develop as in the soup pot.

Imagine a block of wood floating on a tub of honey. If you heated the honey so that it started to convect, the horizontal flow of honey along the surface would drag the block of wood along with it. Some geologists suggest that lithospheric plates are dragged along in a similar manner by a convecting mantle (Fig. 2–13).

GRAVITATIONAL SLIDING AS A CAUSE OF PLATE MOVEMENT

In Section 2.3, we explained why the lithosphere becomes thicker as it moves away from a spreading center. As a result of this thickening, the base of the lithosphere slopes downward from the spreading center with a grade as steep as 8 percent, steeper than most paved roads in North America (Fig. 2–14). Calculations show that if the slope is as slight as 0.3 percent, gravity would cause a plate to slide away from a spreading center at a rate of a few centimeters per year, like a sled gliding slowly down a snowy hill.

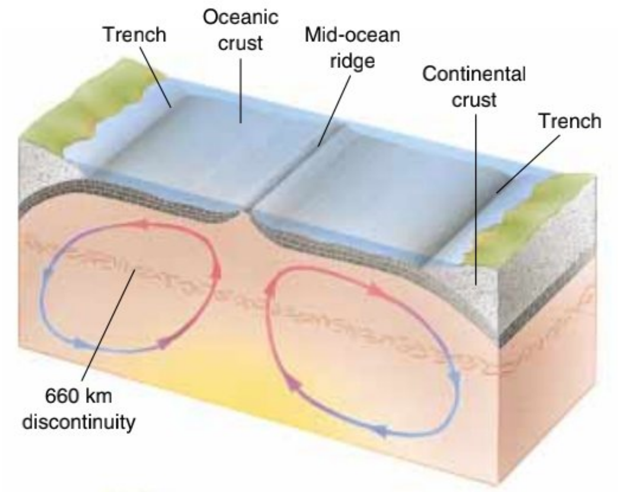


Figure 2–13 According to one explanation, a convecting mantle drags lithospheric plates.

In addition, the lithosphere becomes more dense as it cools and moves away from a spreading center. Eventually, old lithosphere may become denser than the asthenosphere below. Consequently, it can no longer float on the asthenosphere and begins to sink into the mantle, initiating subduction.

As an old, cold lithospheric plate sinks into the mantle, it pulls on the rest of the plate, like a weight pulling on the edge of a tablecloth. Many geologists now think that plates move because they glide downslope from a spreading center and, at the same time, are pulled along by their sinking ends. This combined mechanism is called the push-pull model of plate movement.

Some geologists now feel that this mechanism causes movement of lithospheric plates, and, in turn, the plate movements cause mantle convection. Return to our analogy of the block of wood and the tub of honey. If you dragged the block of wood across the honey, friction between the block and the honey would make the honey flow. Similarly, if the push-pull forces caused the plates to move, their motion would cause the mantle to flow.

(Continued on p. 33)

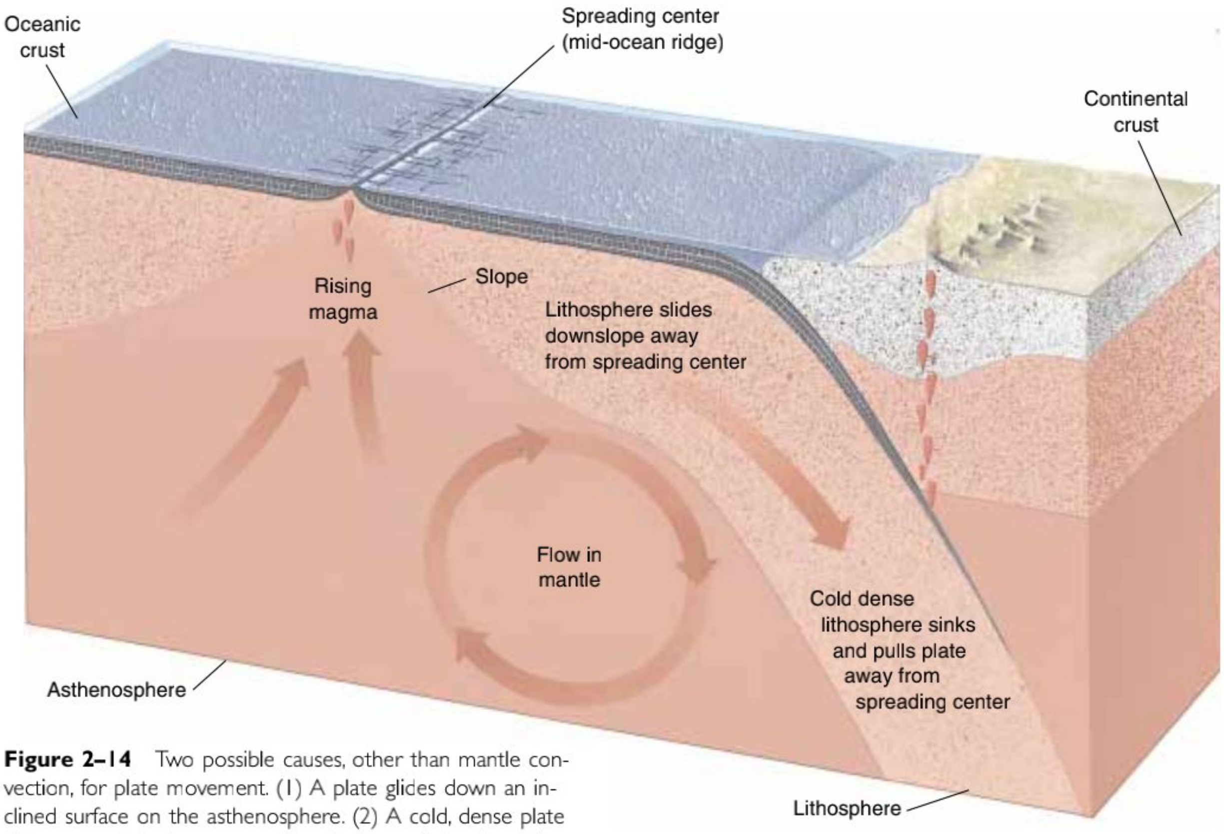


Figure 2–14 Two possible causes, other than mantle convection, for plate movement. (1) A plate glides down an inclined surface on the asthenosphere. (2) A cold, dense plate sinks at a subduction zone, pulling the rest of the plate along with it. In this drawing, both mechanisms are operating simultaneously.

FOCUS ON

ALFRED WEGENER AND THE ORIGIN OF AN IDEA

In the early twentieth century, a young German scientist named Alfred Wegener noticed that the African and South American coastlines on opposite sides of the Atlantic Ocean seemed to fit as if they were adjacent pieces of a jigsaw puzzle (Fig. 1). He realized that the apparent fit suggested that the continents had once been joined together and had later separated to form the Atlantic Ocean.

Although Wegener was not the first to make this suggestion, he was the first scientist to pursue it with additional research. Studying world maps, Wegener realized that not only did the continents on both sides of the Atlantic fit together, but other continents, when moved properly, also fit like additional pieces of the same jigsaw puzzle (Fig. 2). On his map, all the continents together formed one supercontinent that he called Pangea, from the Greek root words for "all lands." The northern part of Pangea is commonly called Laurasia and the southern part Gondwanaland.

Wegener understood that the fit of the continents alone did not prove that a supercontinent had existed. Therefore, he began seeking additional evidence in 1910 and continued work on the project until his death in 1930.

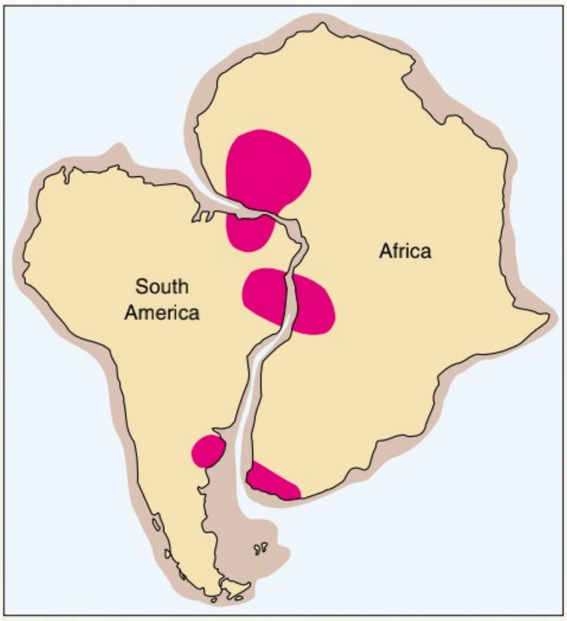


Figure 1 The African and South American coastlines appear to fit together like adjacent pieces of a jigsaw puzzle. The pink areas show locations of distinctive rock types in South America and Africa.

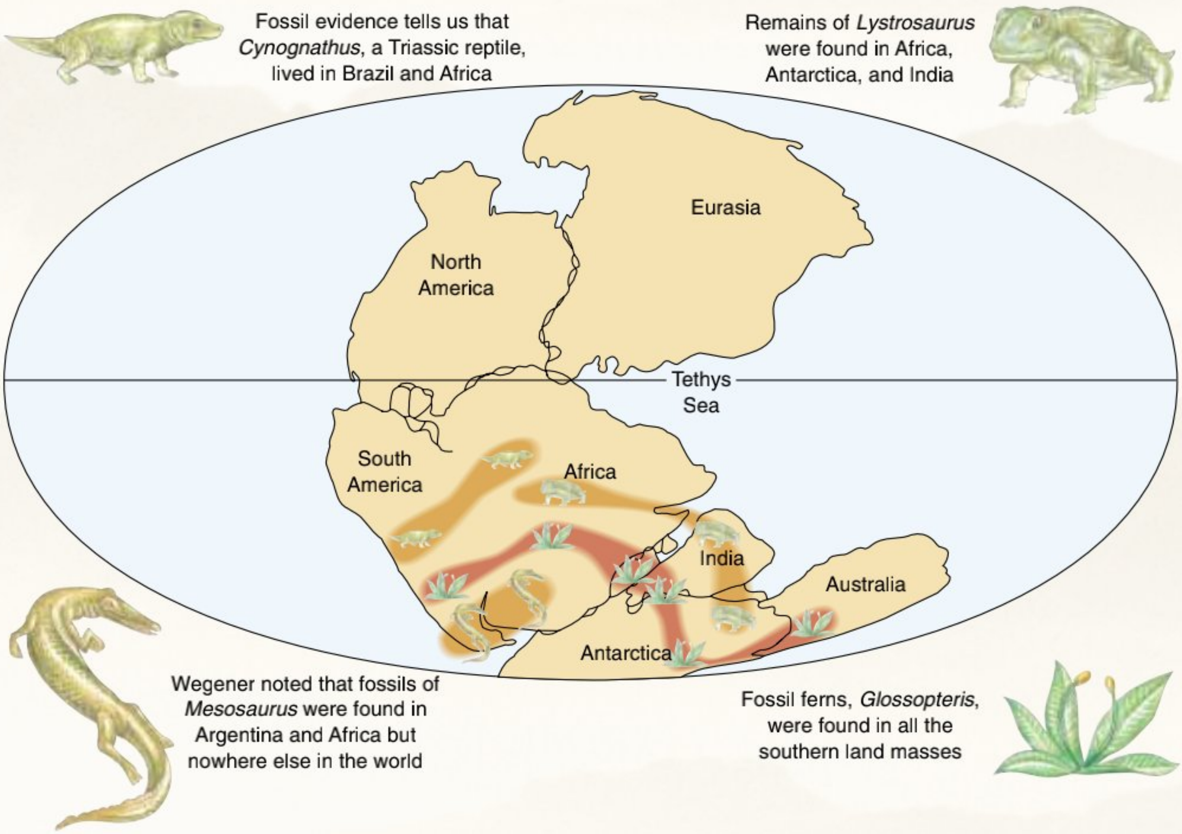
He mapped the locations of fossils of several species of animals and plants that could neither swim well nor fly. Fossils of the same species are now found in Antarctica, Africa, Australia, South America, and India. Why would the same species be found on continents separated by thousands of kilometers of ocean? When Wegener plotted the same fossil localities on his Pangea map, he found that they all lie in the same region of Pangea (Fig. 2). Wegener then suggested that each species had evolved and spread over that part of Pangea rather than mysteriously migrating across thousands of kilometers of open ocean.

Certain types of sedimentary rocks form in specific climatic zones. Glaciers and gravel deposited by glacial ice, for example, form in cold climates and are therefore found at high latitudes and high altitudes. Sandstones that preserve the structures of desert sand dunes form where deserts are common, near latitudes 30° north and south. Coral reefs and coal swamps thrive in near-equatorial tropical climates. Thus, each of these rocks reflect the latitudes at which they formed.

Wegener plotted 300-million-year-old glacial deposits on a map showing the modern distribution of continents (Fig. 3a). The area inside the line shows how large the ice mass would have been if the continents had been in their present positions. Notice that the glacier would have crossed the equator, and glacial deposits would have formed in tropical and subtropical zones. Figure 3b shows the same glacial deposits, and other climate-indicating rocks, plotted on Wegener's Pangea map. Here the glaciers cluster neatly about the South Pole. The other rocks are also found in logical locations.

Wegener also noticed several instances in which an uncommon rock type or a distinctive sequence of rocks on one side of the Atlantic Ocean was identical to rocks on the other side. When he plotted the rocks on a Pangea map, those on the east side of the Atlantic were continuous with their counterparts on the west side (Fig. 1). For example, the deformed rocks of the Cape Fold belt of South Africa are similar to rocks found in the Buenos Aires province of Argentina. Plotted on a Pangea map, the two sequences of rocks appear as a single, continuous belt.

Wegener's concept of a single supercontinent that broke apart to form the modern continents is called the theory of **continental drift**. The theory of continental drift was so revolutionary that skeptical scientists demanded an explanation of how continents could



Fossil evidence tells us that *Cynognathus*, a Triassic reptile, lived in Brazil and Africa

Remains of *Lystrosaurus* were found in Africa, Antarctica, and India

Wegener noted that fossils of *Mesosaurus* were found in Argentina and Africa but nowhere else in the world

Fossil ferns, *Glossopteris*, were found in all the southern land masses

Figure 2 Geographic distributions of plant and animal fossils indicate that a single supercontinent, called Pangea, existed about 200 million years ago.

move. They wanted an explanation of the mechanism of continental drift. Wegener had concentrated on developing evidence that continents had drifted, not on how they moved. Finally, perhaps out of exasperation and as an afterthought to what he considered the important part of his theory, Wegener suggested two alternative possibilities: first, that continents plow their way through oceanic crust, shoving it aside as a ship plows through water; or second, that continental crust slides over oceanic crust. These suggestions turned out to be ill considered.

Physicists immediately proved that both of Wegener's mechanisms were impossible. Oceanic crust is too strong for continents to plow through it. The attempt would be like trying to push a matchstick boat through heavy tar. The boat, or the continents, would break apart. Furthermore, frictional resistance is too great for continents to slide over oceanic crust.

These conclusions were quickly adopted by most scientists as proof that Wegener's theory of continental drift was wrong. Notice, however, that the physicists' calculations proved only that the mechanism proposed by Wegener was incorrect. They did not disprove, or even consider, the huge mass of evidence indicating that the continents were once joined together. During the 30-year period from about 1930 to 1960, a few geologists supported the continental drift theory, but most ignored it.

Much of the theory of continental drift is similar to plate tectonics theory. Modern evidence indicates that the continents *were* together much as Wegener had portrayed them in his map of Pangea. Today, most geologists recognize the importance of Wegener's contributions.

DISCUSSION QUESTION

Compare the manner in which Wegener developed the theory of continental drift with the processes of the scientific method described in the "Focus On" box in Chapter 1. Explain why Wegener's theory was later rejected and, more recently, revived.

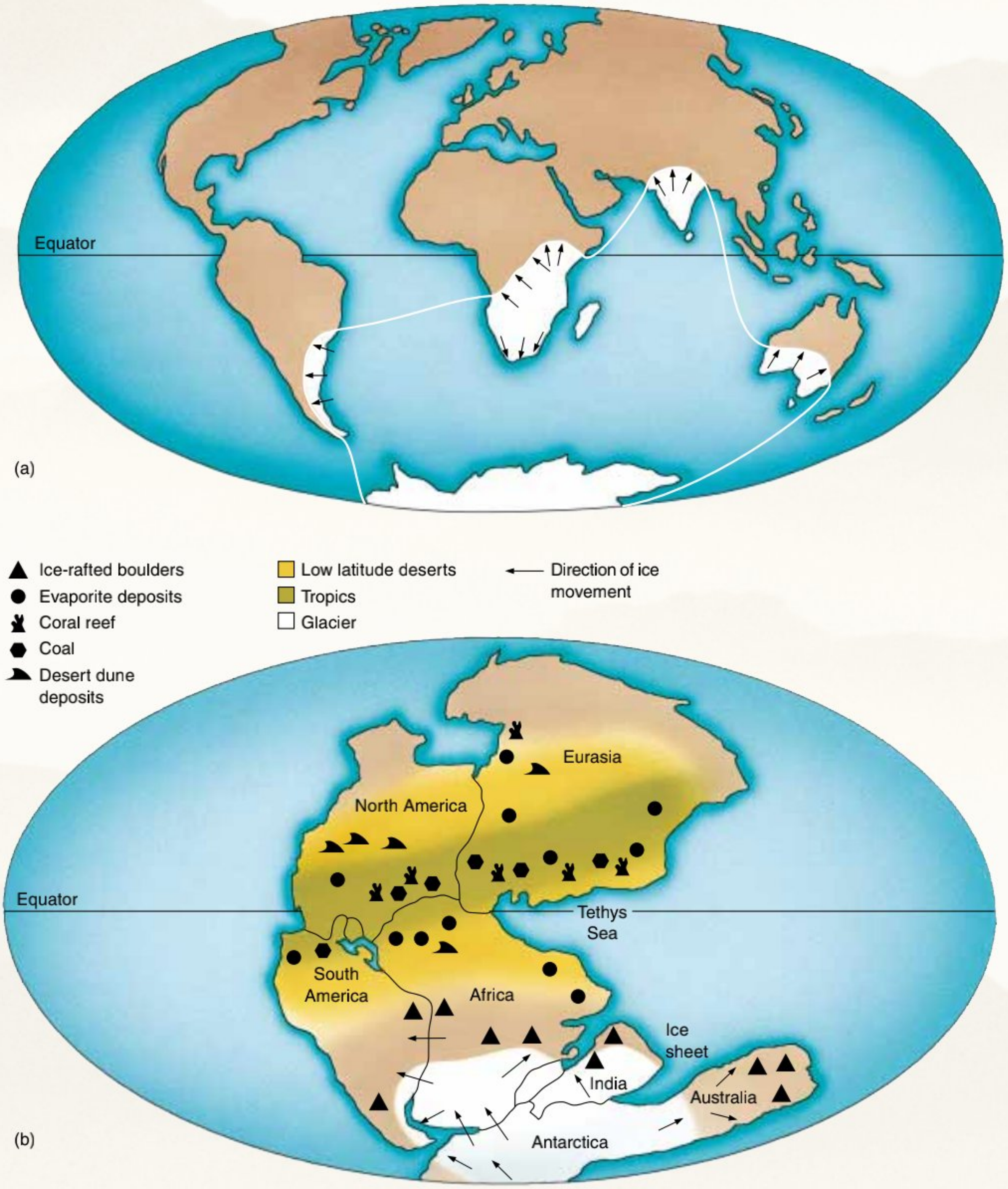


Figure 3 (a) Three-hundred-million-year-old glacial deposits plotted on a map showing the modern distribution of continents. (b) Three-hundred-million-year-old glacial deposits and other climate-sensitive sedimentary rocks plotted on a map of Pangea.

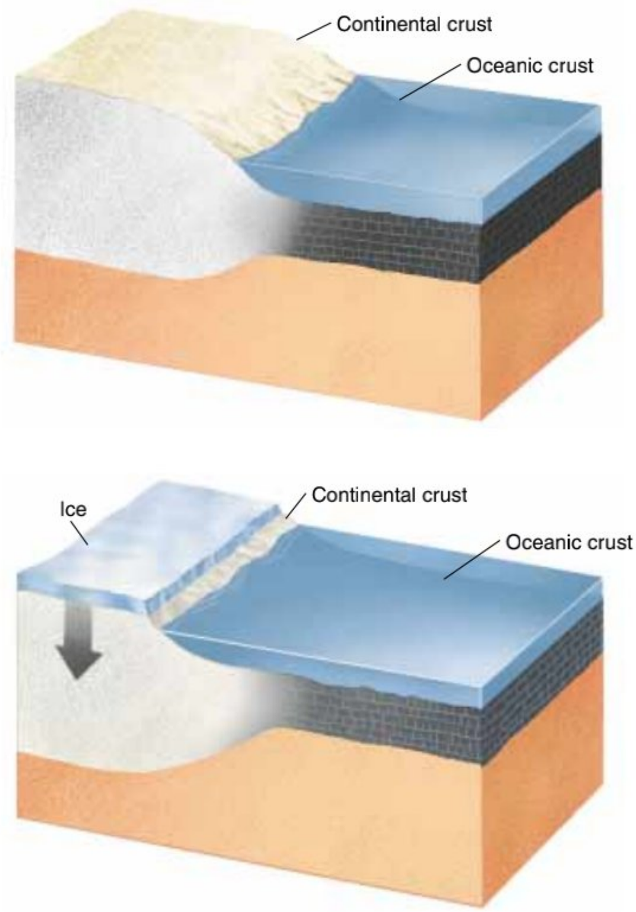


Figure 2–15 The weight of an ice sheet causes continental crust to sink isostatically.

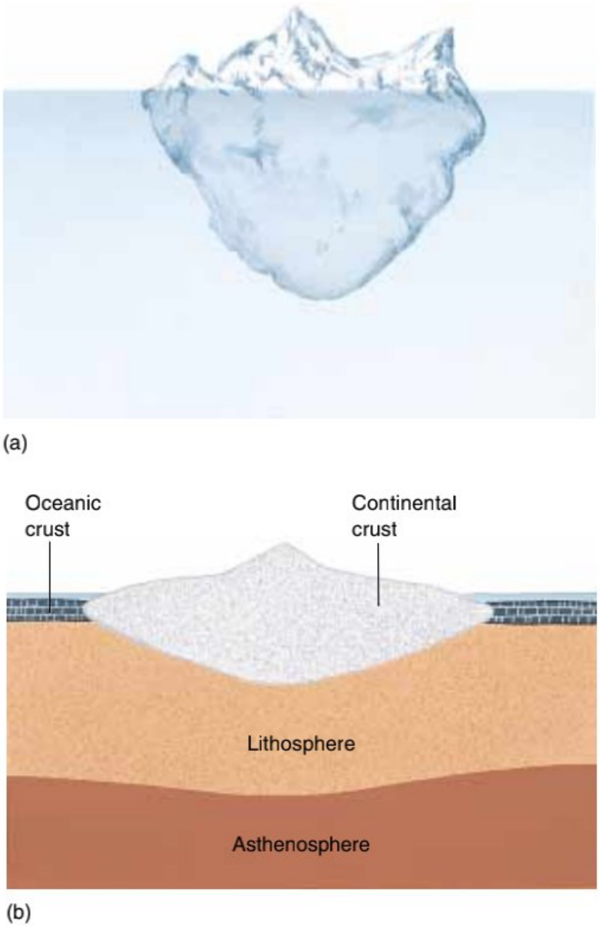


Figure 2–16 (a) Icebergs illustrate some of the effects of isostasy. The large iceberg has a deep root and also a high peak. (b) Lithosphere covered by continental crust extends more deeply into the asthenosphere than lithosphere covered by oceanic crust.

MANTLE PLUMES

The push-pull model provides a mechanism to maintain plate movement once a lithospheric plate has begun to move, but does not explain why a plate should start moving. A **mantle plume** is a rising column of hot, plastic mantle rock that originates deep within the mantle. It rises because rock in a certain part of the mantle becomes hotter and more buoyant than surrounding regions of the mantle. The Earth's core may provide the heat source to create a mantle plume, or the heat may come from radioactive decay within the mantle. Large quantities of magma form in mantle plumes, and rise to erupt from volcanoes at locations called **hot spots** at the Earth's surface. The island of Hawaii is an example of a volcanic center at such a hot spot. Because mantle plumes form deep within the mantle, hot spot volcanoes commonly erupt within tectonic plates, and well away from plate boundaries.

Some geologists have suggested that a mantle plume might cause a new spreading center to develop within the lithosphere. Once spreading started, the push-pull mechanism would then keep the plates moving, even if the original mantle plume died out. Mantle plumes and their consequences are discussed further in Chapter 4.

► 2.7 SUPERCONTINENTS

Many geologists now suggest that movements of tectonic plates have periodically swept the world's continents together to form a single supercontinent. Each supercontinent lasted for a few hundred million years and then broke into fragments, each riding away from the others on its own tectonic plate.

Prior to 2 billion years ago, large continents as we know them today may not have existed. Instead, many—

perhaps hundreds—of small masses of continental crust and island arcs similar to Japan, New Zealand, and the modern island arcs of the southwestern Pacific Ocean dotted a global ocean basin. Then, between 2 billion and 1.8 billion years ago, tectonic plate movements swept these microcontinents together, forming the first **supercontinent**, which we call **Pangea I** after Alfred Wegener's Pangea, a word meaning "all lands" (see Focus On: Alfred Wegener and the Origin of an Idea).

After Pangea I split up about 1.3 billion years ago, the fragments of continental crust reassembled, forming a second supercontinent called **Pangea II**, about 1 billion years ago. In turn, this continent fractured and the continental fragments reassembled into **Pangea III** about 300 million years ago, 70 million years before the appearance of dinosaurs. Pangea III is Alfred Wegener's Pangea, described in the "Focus On" box.

▶ 2.8 ISOSTASY: VERTICAL MOVEMENT OF THE LITHOSPHERE

If you have ever used a small boat, you may have noticed that the boat settles in the water as you get into it and rises as you step out. The lithosphere behaves in a similar manner. If a large mass is added to the lithosphere, it sinks and the underlying asthenosphere flows laterally away from that region to make space for the settling lithosphere.

But how is weight added to or subtracted from the lithosphere? One process that adds and removes weight is the growth and melting of large glaciers. When a glacier grows, the weight of ice forces the lithosphere downward. For example, in the central portion of Greenland, a 3000-meter-thick ice sheet has depressed the continental crust below sea level. Conversely, when a glacier melts, the continent rises—it rebounds. Geologists have discovered Ice Age beaches in Scandinavia tens of meters above modern sea level. The beaches formed when glaciers depressed the Scandinavian crust. They now lie well above sea level because the land rose as the ice melted. The concept that the lithosphere is in floating equilibrium on the asthenosphere is called **isostasy**, and the vertical movement in response to a changing burden is called **isostatic adjustment** (Fig. 2–15).

The iceberg pictured in Figure 2–16 illustrates an additional effect of isostasy. A large iceberg has a high peak, but its base extends deep below the surface of the water.

The lithosphere behaves in a similar manner. Continents rise high above sea level, and the lithosphere beneath a continent has a "root" that extends 125 kilometers into the asthenosphere. In contrast, most ocean crust lies approximately 5 kilometers below sea level, and oceanic lithosphere extends only about 75 kilometers into the asthenosphere. For similar reasons, high mountain ranges have deeper roots than low plains, just as the bottom of a large iceberg is deeper than the base of a small one.

SUMMARY

The **plate tectonics theory** provides a unifying framework for much of modern geology. It is the concept that the **lithosphere**, the outer, 75 to 125-kilometer-thick layer of the Earth, floats on the **asthenosphere**. The lithosphere is segmented into seven major **plates**, which move relative to one another by gliding over the asthenosphere. Most of the Earth's major geological activity occurs at **plate boundaries**. Three types of plate boundaries exist: (1) New lithosphere forms and spreads outward at a **divergent boundary**, or **spreading center**; (2) two lithospheric plates move toward each other at a **convergent boundary**, which develops into a **subduction zone** if at least one plate carries oceanic crust; and (3) two plates slide horizontally past each other at a **transform plate boundary**. Volcanoes, earthquakes, mountain building, and **oceanic trenches** occur near plate boundaries. Interior parts of lithospheric plates are tectonically stable. Tectonic plates move horizontally at rates that vary from 1 to 16 centimeters per year. Plate movements carry continents across the globe and cause ocean basins to open and close. The Earth is a layered planet. The **crust** is its outermost layer and varies from 5 to 70 kilometers thick. The **mantle** extends from the base of the crust to a depth of 2900 kilometers, where the core begins. The **lithosphere** is the cool outer 75 to 125 kilometers of the Earth; it includes all of the crust and the uppermost mantle. The lithosphere floats on the hot, plastic **asthenosphere**, which extends to 350 kilometers in depth. The **core** is mostly iron and nickel and consists of a liquid outer layer and a solid inner sphere.

Mantle convection may cause plate movement. Alternatively, a plate may move because it slides downhill from a spreading center, as its cold leading edge sinks into the mantle and drags the rest of the plate along. **Supercontinents** may assemble, split apart, and reassemble every 500 million to 700 million years.

The concept that the lithosphere floats on the asthenosphere is called **isostasy**. When weight such as a glacier is added to or removed from the Earth's surface, the lithosphere sinks or rises. This vertical movement in response to changing burdens is called **isostatic adjustment**.

KEY WORDS

plate tectonics theory *16*
lithosphere *18*
tectonic plate *18*
asthenosphere *18*
plate boundary *18*
divergent boundary *18*
convergent boundary *18*
transform plate boundary *18*
crust *18*
basalt *18*
granite *21*
mantle *21*
core *21*
spreading center *22*
rift zone *22*
magma *22*
mid-oceanic ridge *23*
continental rifting *23*
rift valley *23*
subduction *24*
subduction zone *25*
oceanic trench *27*
mantle convection *27*
mantle plume *33*
hot spot *33*
supercontinent *34*
Pangea *34*
isostasy *34*
isostatic adjustment *34*

REVIEW QUESTIONS

1. Draw a cross-sectional view of the Earth. List all the major layers and the thickness of each.
2. Describe the physical properties of each of the Earth's layers.
3. Describe and explain the important differences between the lithosphere and the asthenosphere.
4. What properties of the asthenosphere allow the lithospheric plates to glide over it?
5. Describe some important differences between the crust and the lithosphere.
6. Describe some important differences between oceanic crust and continental crust.
7. How is it possible for the solid rock of the mantle to flow and convect?
8. Summarize the important aspects of the plate tectonics theory.
9. How many major tectonic plates exist? List them.
10. Describe the three types of tectonic plate boundaries.
11. Explain why tectonic plate boundaries are geologically active and the interior regions of plates are geologically stable.
12. Describe some differences between the lithosphere beneath a continent and that beneath oceanic crust.
13. Describe a reasonable model for a mechanism that causes movement of tectonic plates.
14. Why would a lithospheric plate floating on the asthenosphere suddenly begin to sink into the mantle to create a new subduction zone?
15. How many supercontinents have formed in Earth's history?
16. Describe the mid-Atlantic ridge and the mid-oceanic ridge.
17. Why are the oldest sea-floor rocks only about 200 million years old, whereas some continental rocks are 3.96 billion years old?

DISCUSSION QUESTIONS

1. Discuss why a unifying theory, such as the plate tectonics theory, is desirable in any field of science.
2. Central Greenland lies below sea level because the crust is depressed by the ice cap. If the glacier were to melt, would Greenland remain beneath the ocean? Why or why not?
3. At a rate of 5 centimeters per year, how long would it take for a continent to drift the width of your classroom? The distance between your apartment or dormitory and your classroom? The distance from New York to London?
4. Why do most major continental mountain chains form at convergent plate boundaries? What topographic and geologic features characterize divergent and transform plate boundaries in continental crust? Where do these types of boundaries exist in continental crust today?
5. If you were studying photographs of another planet, what features would you look for to determine whether or not the planet is or has been tectonically active?
6. The largest mountain in the Solar System is Olympus Mons, a volcano on Mars. It is 25,000 meters high, nearly three times the elevation of Mount Everest. Speculate on the factors that might permit such a large mountain on Mars.
7. The core's radius is 3470 kilometers, and that of the mantle is 2900 kilometers, yet the mantle contains 80 percent of the Earth's volume. Explain this apparent contradiction.
8. If you built a model of the Earth 1 meter in radius, how thick would the crust, lithosphere, asthenosphere, mantle, and core be?
9. Look at the map in Figure 2–1 and name a tectonic plate that is covered mostly by continental crust. Name one that is mostly ocean. Name two plates that are about half ocean and half continent.