6

The Active Earth: Plate Tectonics

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Chapter Introduction

This photograph of the Sinai Peninsula was shot in 1991 by astronauts aboard the U.S. Space Shuttle *Columbia* from an altitude of about 283 kilometers. The northern end of the Red Sea splits into the Gulf of Suez (left) and the Gulf of Aqaba (right). All three water bodies have formed as a result of tectonic extension (pulling apart). Ongoing extension in the Red Sea and the Gulf of Aqaba is causing the African and Arabian Plates to separate. That plate boundary projects beyond the northern tip of the Gulf of Aqaba through the Dead Sea, seen in the distance. The large water body at the top of the photo is the Mediterranean Sea.
We have to be prepared always for the possibility that each new discovery, no matter what science furnishes it, may modify the conclusions we draw.

Alfred L. Wegener

The Origins of Continents and Oceans

About 5 billion years ago, a ball of dust and gas, one among billions in the universe, collapsed into a slowly spinning disc. The inner portion of the disc condensed to form our Sun, while the outer parts coalesced to form planets orbiting the Sun. Our Earth is one of those planets.

Earth began to form as particles of dust and gas were drawn together by gravity and began to collide. These collisions caused the coalescing particles to become hotter and hotter. Frozen crystals of carbon dioxide, methane, and ammonia melted as the spinning mass—early Earth—slowly heated up. Eventually, ice melted. The young planet grew hotter as
asteroids, comets, and other space debris crashed into its surface. Additional heat was released by the decay of radioactive isotopes within its interior. By about 4.6 billion years ago, the planet became hot enough that it melted. Then, as the bombardment slowed down and radioactive isotopes decayed and became less abundant, much of Earth’s heat radiated into space and our planet began to cool and solidify.

Today, although Earth’s surface has cooled to temperatures that support living organisms, the interior remains hot, both from heat left over from the early melting event and from continued decay of radioactive isotopes. Consequently, Earth becomes hotter with depth. At its center, the Earth is close to 7,000°C—similar to the temperature of the Sun’s surface. This internal heat causes earthquakes, volcanic eruptions, mountain building, and continual movements of the continents and ocean basins. These effects, in turn, profoundly affect our environment—Earth’s atmosphere, hydrosphere, and biosphere. Earth’s internal heat engine and its effects are described in the theory of plate tectonics (A theory of global tectonics stating that the lithosphere is segmented into several plates that move about relative to one another by floating on and sliding over the plastic asthenosphere. Seismic and tectonic activity occur mainly at the plate boundaries.), a simple theory that provides a unifying framework for understanding the way Earth works and how Earth systems interact to create our environment. The term tectonics is taken from the Greek tektonikos, meaning “construction.”

Like most great scientific revolutions, the development of plate tectonics theory developed incrementally over many years, building on earlier observations, hypotheses, and theories. The story illustrates how a scientific theory evolves through the accumulation of evidence and how scientists rely on the work and discoveries of earlier scientists.

Chapter 6: The Active Earth: Plate Tectonics: 6-1 Alfred Wegener and the Origin of an Idea: The Continental Drift Hypothesis

6-1 Alfred Wegener and the Origin of an Idea: The Continental Drift Hypothesis

Although the theory of plate tectonics was not developed until the 1960s, it was foreshadowed early in the 20th century by a young German scientist named Alfred Wegener, who 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 (Figure 6.1). He realized that the apparent fit suggested that the continents had once been joined together and had later separated by thousands of kilometers to form the Atlantic Ocean.

Figure 6.1

The African and South American coastlines appear to fit together like adjacent pieces of a jigsaw puzzle on Wegener’s reconstruction map. Several of the distinctive rock types correlated between the two continents are shown. These include areas of Precambrian stable crust (green), Precambrian and Cambrian
mountain belts (blue lines), and the Cape and Sierra de la Ventana Fold Belts of Paleozoic age (orange). The darker, brown regions are the continental shelves, which are the actual edges of the continents.

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Wegener was not the first to make this observation, but he was the first scientist to pursue it with additional research. Studying world maps and making paper cutouts of each continent that he could move around, Wegener realized that not only did the continents on both sides of the Atlantic fit together, but other continents, when positioned correctly, fit like pieces of the same jigsaw puzzle (Figure 6.2). On his map, all the continents joined together formed one supercontinent that he called **Pangea** (The supercontinent that existed when all Earth's continents were joined together, about 300 million to 200 million years ago, first identified and named by Alfred Wegener.) , from the Greek root words for “all lands.” The northern part of Pangea is commonly called **Laurasia** (The northern part of Pangea, consisting of what is now North America and Eurasia.) and the southern part **Gondwana** (The southern part of Pangea, consisting of what is now South America, Africa, Antarctica, India, and Australia.)

**Figure 6.2**

Geographic distributions of plant and animal fossils on Wegener’s map indicate that a single supercontinent, called Pangea, existed between about 300 and 200 million years ago.
Wegener understood that the fit of the continents alone did not prove that a supercontinent had existed. He began seeking additional evidence in 1910 and continued work on the project until his death in 1930.

One line of evidence Wegener found in support of his hypothesis is the occurrence of uncommon rock types or distinctive sequences of rocks that are identical on one side of the Atlantic Ocean and the other. When he plotted the distinctive rocks on a map of Pangea, those presently on the east side of the Atlantic were continuous with their counterparts on the west side (Figure 6.1). For example, the deformed rocks of the Cape Fold Belt of South Africa are similar to rocks found in the Sierra de la Ventana Fold Belt of Argentina. Plotted on a map of Pangea, the two sequences of rocks appear as a single, continuous belt.

Using fossil evidence to support the existence of Pangea, Wegener compiled information regarding locations of certain fossil plant and animal species that could neither swim well nor fly so were unlikely to survive long oceanic crossings. Today, these fossils are found in Antarctica, Africa, Australia, South America, and India, all of which are separated by wide oceans. However, when Wegener plotted the same fossil localities on his reconstruction of Pangea, he found that they all occurred in the same region (Figure 6.2). Wegener deduced that rather than migrating across the wide oceans that presently separate the different fossil locations, each species had evolved and spread over a portion of Pangea before the supercontinent broke apart.
Wegener also cited evidence from sedimentary rocks known to form in specific climate zones to support the existence of Pangea. Glaciers and gravel deposited by glacial ice, for example, form in cold climates and are therefore typically found at high latitudes and high altitudes. Sandstones that preserve the structures of desert sand dunes form where deserts are common, near latitudes 30°C north and south. Coral reefs and coal swamps thrive in near-equatorial tropical climates. Thus, each rock type reflects an ancient environment characteristic of a specific latitude.

Wegener plotted 250-million-year-old glacial deposits on a map showing the modern distribution of continents (Figure 6.3A). Notice on this map that glacial deposits would have formed in tropical and subtropical zones. Figures 6.3B and 6.3C show the same glacial deposits and other geological indicators of climate plotted on Wegener’s Pangea map. In Wegener’s reconstruction of Pangea, the glaciers cluster neatly about the South Pole, coral reefs and coal both occur in equatorial positions, and desert environments formed around 30 degree north, similar to the modern distribution of these paleoclimate indicators.

**Figure 6.3**

(A) 250-million-year-old glacial deposits are displayed in white on a map showing the modern distribution of continents. The black arrows show directions of glacial movement, indicated by glacial features described in Chapter 13. Notice that many of the arrows are pointing from the shoreline towards the continental interior, a situation that is difficult to explain because it would require the glaciers to move upslope over long distances. (B) 300-million-year-old glacial deposits and other climate-sensitive sedimentary rocks plotted on Wegener's map of Pangea. (C) A view of Gondwanal from the South Pole, showing the direction of ice movement 300 million years ago.
Wegener’s concept of a single supercontinent that broke apart to form the modern continents is called the theory of **continental drift** *(The theory proposed by Alfred Wegener that Earth’s continents were once joined together and later split and drifted apart. The continental drift theory has been replaced by the more complete plate tectonics theory.)*. Wegener first presented the framework of his theory in 1912 and published a more thorough treatment in 1915 in the first edition of his book *The Origin of Continents and Oceans*.

In one of the great examples scientific feudalism, the reaction to Wegener’s hypothesis was overwhelmingly negative and in some cases exceptionally scathing. Thomas Chamberlin, geology professor at the University of Chicago, wrote, “Wegener’s hypothesis in general is of the footloose type…and is less bound by restrictions or tied down by awkward, ugly facts than most of its rival theories.” Stanford geology professor Bailey Willis remarked, “further discussion of [Wegener’s hypothesis] merely incumbers the literature and befogs the mind…”
The strongly negative reaction to Wegener’s ideas regarding continental drift was the result of three factors. First, Wegener did not provide alternatives for his theory of continental drift, so some scientists viewed his approach as subjective, biased, and downright unscientific. Second, in the early 20th century many geologists had begun to turn away from traditional field-based observations towards more-detailed, quantitative laboratory measurement of rock properties. As a result, many scientists considered Wegener’s field-based evidence to be old-fashioned, unsophisticated, and vague. Third, and perhaps most importantly, Wegener had concentrated on developing evidence that continents had drifted and not on exactly how they could move. Perhaps as an afterthought to what he considered the important part of his theory, Wegener suggested two possible mechanisms to explain how continents moved:

1. that continents plow their way through oceanic crust, shoving it aside as a ship plows through water; or

2. that continental crust slides over oceanic crust.

Physicists quickly 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 paper boat through heavy tar and would deform the continents into an unrecognizable state. Furthermore, frictional resistance is too great for continents to slide over oceanic crust.

These conclusions and the scientific fashions of the day caused most scientists to reject Wegener’s theory of continental drift. However, 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. Nevertheless, in the roughly 30-year period between Wegener’s death in 1930 and about 1960, continental drift was largely forgotten, although a few persistent geologists continued to report evidence in support of the idea.

Much of the hypothesis of continental drift is similar to modern 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.

Chapter 6: The Active Earth: Plate Tectonics: 6-2 The Earth’s Layers
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**6-2 The Earth’s Layers**

The energy released by an earthquake travels through Earth as waves. After Wegener died and his theory was mostly forgotten, geologists discovered that both the speed and the direction of these waves change abruptly at certain depths, as the waves pass through Earth. They soon realized that these changes reveal that Earth is a layered planet. *Figure 6.4* and *Table 6.1* describe the layers. It is necessary to understand Earth’s layers to consider
the theory of plate tectonics.

**Figure 6.4**

Earth is a layered planet. The insert is drawn on an expanded scale to show near-surface layering. Note that the average thickness of the lithosphere varies from about 75 kilometers beneath the oceans to about 125 kilometers beneath continents.

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**6-2a The Crust**

The crust is the outermost and thinnest layer. Because it is cool relative to the layers below, the crust consists of hard, strong rock (**Figure 6.4**). Crust beneath the oceans differs from that of continents.
Oceanic crust is between 4 and 7 kilometers thick and is composed mostly of dark, dense basalt. In contrast, the average thickness of continental crust is about **20** to **40** kilometers, although under some mountain ranges it can be as much as **70** kilometers thick. Continents are composed primarily of granite, which is lighter colored and less dense than basalt.

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### 6-2b The Mantle

The mantle lies directly below the crust. It is almost **2,900** kilometers thick and makes up **80** percent of Earth’s volume. The mantle is composed mainly of peridotite, a rock that is denser than the basalt and granite of the crust.

Although the chemical composition may not vary much throughout the entire mantle, temperature and pressure increase with depth. **Figure 6.5A** shows that the temperature at the top of the mantle is near **1,000°C** and that near the mantle/core boundary it is about **3,300°C**. These changes cause the strength of mantle rock to vary with depth. The differences in strength create layering. **Figure 6.5B** shows that internal pressure also increases with depth.

**Figure 6.5**

(A) Earth’s internal temperature increases with depth. At the center of Earth, the temperature is close to **7,000°C**, about as hot as the Sun’s surface. For reference, the temperature of an oven baking a chocolate cake is about **175°C** and a heated steel bar turns cherry red at **746°C**. (B) In contrast with temperature, Earth’s internal pressure increases almost linearly with depth.
At this point, it is important to understand the effects of temperature and pressure on rocks. Most people understand that increasing temperature will eventually melt a rock. Less obvious, however, is the fact that high pressure inhibits melting, because rock expands by about 10 percent when it melts. High pressure makes it more difficult for a rock to expand and therefore impedes melting. If the combined effects of temperature and pressure are close to—but just below—a rock’s melting point, the rock remains solid but loses strength, so it becomes weak and plastic. In such a weakened state, rock can flow slowly, similar to the way honey spills from a jar. At that point, if temperature rises or pressure decreases, the rock will begin to melt.

Table 6.1

<table>
<thead>
<tr>
<th>Layer</th>
<th>Composition</th>
<th>Depth</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crust</td>
<td>Oceanic crust</td>
<td>Extends from surface to between 4 and 7 km</td>
<td>Cool, hard, and strong</td>
</tr>
<tr>
<td>Continental crust</td>
<td>Granite</td>
<td>Extends from surface to between 20 and 70 km</td>
<td>Cool, hard, and strong</td>
</tr>
<tr>
<td>Lithosphere</td>
<td>The crust and the uppermost portion of the mantle</td>
<td>Varies; the crust and the mantle lithosphere have different compositions</td>
<td>Extends from surface to between 75 and 125 km</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Mantle (excluding the uppermost portion, which is part of the lithosphere)</td>
<td>Asthenosphere</td>
<td>Plastic, ultramafic rock, mainly peridotite, throughout entire mantle; mineralogy varies with depth</td>
<td>Extends from base of lithosphere to 350 km</td>
</tr>
<tr>
<td>Remainder of upper mantle</td>
<td>Extends from 350 to 660 km</td>
<td>Hot, under great pressure, and mechanically strong</td>
<td></td>
</tr>
<tr>
<td>Lower mantle</td>
<td>Extends from 660 to 2,900 km</td>
<td>High pressure forms minerals different from those of the upper mantle</td>
<td></td>
</tr>
<tr>
<td>Core</td>
<td>Outer core</td>
<td>Iron and nickel</td>
<td>Extends from 2,900 to 5,150 km</td>
</tr>
<tr>
<td>Inner core</td>
<td>Iron and nickel</td>
<td>Extends from 5,150 km to the center of Earth</td>
<td>Solid</td>
</tr>
</tbody>
</table>

Because both temperature and pressure increase with depth in Earth, their combined effects change the physical properties of rocks with increasing depth. These changes create two distinctly different layers in the upper mantle. The strength of the rocks is very different between the two layers, although the composition of mantle rock in each layer is similar.
### 6-2c The Lithosphere

*Figure 6.5* shows that the uppermost mantle is cool and its pressure is low, conditions similar to those in the crust. Both factors combine to produce hard, strong rock similar to that of the crust. Recall from Chapter 1 that the outer part of Earth, including both the crust and the uppermost mantle, make up the lithosphere. The average thickness of the lithosphere is about 100 kilometers but ranges from about 75 kilometers beneath ocean basins to about 125 kilometers under the continents (*Figure 6.4*). The lithosphere, then, consists mostly of the cold, strong uppermost mantle; the crust is just a thin layer of buoyant rock forming the top of the lithosphere.

### 6-2d The Asthenosphere

At a depth varying from 75 to 125 kilometers beneath Earth’s surface, the temperature and pressure conditions are close to the melting point of mantle rock. As a result, at this depth the mantle abruptly loses strength relative to the overlying rock and becomes weak and plastic (*Figure 6.5*). About 1 to 2 percent of the rock melts, although the rest remains solid. This weak, plastic, and partly molten character extends to a depth of about 350 kilometers, where increasing pressure overwhelms temperature and the rock becomes stronger again. This layer of weak mantle rock extending from about 100 to 350 kilometers deep is the asthenosphere (The portion of the upper mantle just beneath the lithosphere, extending from a depth of about 100 kilometers to about 350 kilometers below the surface of Earth and consisting of weak, plastic rock where magma may form.) (from the Greek for “weak layer”). The average temperature in the asthenosphere is about 1,800°C, although the temperature increases with depth as it does in other Earth layers. Pressure in the asthenosphere rises from about 35 kilobars near the top to about 120 kilobars at the base.

If you apply force to a plastic solid, it deforms slowly, much like the spilled honey. The soft, plastic rock of the asthenosphere behaves in this way, relative to the strong, hard lithosphere that lies on top of it. The lithosphere is not rigidly supported by the rock beneath it, but instead floats on the soft, plastic rock of the asthenosphere. This concept of a floating lithosphere is important to our understanding of plate tectonics and Earth’s internal processes.

### 6-2e The Mantle below the Asthenosphere

At the base of the asthenosphere, the increasing pressure overcomes the effect of rising temperature, and the strength of the mantle increases again (*Figure 6.5*). Although the
mantle below 350 kilometers is stronger than the asthenosphere, it is not as strong as the lithosphere, but rather is plastic and capable of flowing slowly over geologic time.

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6-2f The Core

As you learned in Chapter 1, the core is the innermost of Earth’s layers. It is a sphere with a radius of about 3,470 kilometers, about the same size as Mars, and is composed largely of iron and nickel. The outer core is molten because of the high temperature and relatively lower pressure there. In contrast, the temperature of the inner core is close to 7,000°C, roughly similar to the temperature of the Sun’s surface, and the pressure is 3.5 million times that of Earth’s atmosphere at sea level. This extreme pressure compresses the inner core to a solid, despite the fact that it is even hotter than the molten outer core.

Chapter 6: The Active Earth: Plate Tectonics: 6-3 The Seafloor Spreading Hypothesis
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6-3 The Seafloor Spreading Hypothesis

Shortly after World War II, scientists began to explore the floors of Earth’s oceans. Although these studies ultimately played a large role in the development of plate tectonics theory, they were initially undertaken for military and economic reasons. Defense strategists wanted detailed maps of seafloor topography for submarine warfare, and the same information was needed to lay undersea telephone cables. As they mapped the seafloor, oceanographers discovered the largest mountain chain on Earth, now called the **Mid-Oceanic Ridge system** (The undersea mountain chain that forms at the boundary between divergent tectonic plates within oceanic crust. It circles the planet like the seam on a baseball, forming Earth’s longest mountain chain.) (Figure 6.6). One branch of this huge submarine mountain range, called the **Mid-Atlantic Ridge** (The portion of the Mid-Oceanic Ridge system that lies in the middle of the Atlantic Ocean, halfway between North America and South America to the west, and Europe and Africa to the east.), lies directly in the middle of the Atlantic Ocean, halfway between North and South America to the west, and Europe and Africa to the east.

**Figure 6.6**

A color-coded image of the seafloor. The Mid-Oceanic Ridge system is a submarine mountain chain that encircles the globe like the seam on a baseball. On this image, the most visible parts of the Mid-Oceanic Ridge system are those segments that bisect the Atlantic Ocean and that extend to the southwest of the Gulf of California. Other parts of the Mid-Oceanic Ridge system are visible in the Indian Ocean east of Africa.
As you learned in Chapter 3, oceanic crust is composed mostly of basalt, an igneous rock rich in iron. As basaltic lava cools and forms solid rock, the iron-rich mineral crystals in the basalt operate like weak magnets. The magnetic fields of these minerals align parallel to the Earth’s magnetic field. Thus, the basalt preserves a record of the orientation and strength of Earth’s magnetic field at the time the rock cools.

By towing devices called magnetometers behind their research vessels, oceanographers have been able to detect and record magnetic patterns in the basalt forming the deep-ocean floors. Figure 6.7 shows the magnetic orientations of seafloor rocks near a part of the Mid-Atlantic Ridge southwest of Iceland. In this figure, green stripes represent basalt with a magnetic orientation parallel to Earth’s current magnetic field, called normal magnetic polarity (A magnetic orientation the same as that of Earth’s current magnetic field). The intervening blue stripes represent rocks with magnetic orientations that are exactly opposite to the current magnetic field, called reversed magnetic polarity (Magnetic orientations in rock that are opposite to the current orientation of Earth’s magnetic field). Notice that the stripes form a symmetric pattern of normal and reversed polarity about the axis of the ridge, and that the central stripe is green, indicating that basalt at the ridge axis has a magnetic orientation parallel to that of Earth’s magnetic field today.

**Figure 6.7**

The Mid-Atlantic Ridge, shown in red, runs through Iceland. Magnetic orientation of seafloor rocks near the ridge is shown in the lower-left portion of the map. The green stripes represent seafloor rocks with normal magnetic polarity, and the blue stripes represent rocks with reversed polarity. The stripes form a symmetrical pattern of alternating normal and reversed polarity on each side of the ridge.
Why do the seafloor rocks have alternating normal and reversed polarity, and why is the pattern symmetrically distributed across the Mid-Oceanic Ridge? In the mid-1960s, three scientists—a Cambridge graduate student named Frederick Vine; his professor, Drummond Matthews; and Lawrence Morley, a Canadian working independently of the other two—proposed an explanation for these odd magnetic patterns on the seafloor. They knew that other scientists had been studying the magnetism preserved in layers of basalt forming the Hawaiian Islands and discovered that Earth’s magnetic field has reversed its polarity on the average of every 500,000 years during the past 65 million years. The data from Hawaii indicated that when a magnetic reversal (a change in Earth's magnetic field in which the north magnetic pole becomes the south magnetic pole and vice versa; has occurred on average every 500,000 years over the past 65 million years) of Earth’s field occurs, the north magnetic pole becomes the south magnetic pole, and vice versa.

Vine, Matthews, and Morley suggested that the symmetrical magnetic stripes they observed in the seafloor were produced by the continuous spreading of newly formed oceanic crust away from the Mid-Oceanic Ridges, like two conveyor belts moving outward, away from each other (Figure 6.8). They recognized that the seafloor and oceanic crust become older with increasing distance from the ridge axis. New basalt lava rises through cracks that form at the ridge axis as the two sides of the seafloor separate. As the lava cools and solidifies, the basalt records the strength and orientation of Earth’s field. Because Earth’s field periodically reverses, the magnetism preserved in the basalt of the ocean floor acquires a striped pattern.

**Figure 6.8**
As new oceanic crust cools at the Mid-Oceanic Ridge, it acquires the magnetic orientation of Earth’s field. Alternating stripes of normal (colored) and reversed (black stippled pattern) polarity record reversals in Earth’s magnetic field that occurred as the crust spread outward from the ridge. The three frames show the evolution of the spreading center through time from oldest (A) to youngest (C).

At the same time as these seafloor magnetic patterns were being detected and explained, oceanographers discovered that the layer of mud overlying the seafloor basalt in most parts of the oceans typically is thinnest at the Mid-Oceanic Ridge and becomes progressively thicker at greater distance from the ridge. They reasoned that if mud settles onto the seafloor at the same rate everywhere, and if the ridge is the newest part of the seafloor, the mud layer would be thinnest there. Because oceanic crust is progressively older with increased distance from the ridge axis, more time has elapsed for mud to accumulate, so the layer of mud becomes progressively thicker.

The oceanographers also found that fossils in the deepest layers of mud overlying basalt are very young at the ridge axis but become progressively older with increasing distance from the ridge. This discovery, too, indicated that the seafloor becomes older with increasing distance from the ridge axis.
Symmetrical magnetic patterns and similar mud age and thickness trends were quickly discovered along other parts of the Mid-Oceanic Ridge system and in other ocean basins; therefore, the hypothesis of seafloor spreading (The hypothesis that segments of oceanic crust are separating at the Mid-Oceanic Ridge) was proposed as a general model for the origin of all oceanic crust. In a very few years, the seafloor spreading hypothesis became the basis for development of the much broader theory of plate tectonics.

Chapter 6: The Active Earth: Plate Tectonics: 6-4 The Theory of Plate Tectonics

6-4 The Theory of Plate Tectonics

Like many great unifying scientific ideas, the plate tectonics theory is simple. Briefly, it states that the lithosphere is a shell of hard, strong rock about 100 kilometers thick that floats on the hot, plastic asthenosphere (Figure 6.9). As you learned in Chapter 1, the lithosphere is broken into seven large (and several smaller) segments called tectonic plates (Figure 6.10). They are also called lithospheric plates or, simply, plates—the terms are interchangeable. The tectonic plates slide slowly over the asthenosphere at rates ranging from less than 1 to about 16 centimeters per year, about as fast as your fingernails grow. Continents and ocean basins make up the upper parts of the lithospheric plates, so as the plates slide over the asthenosphere, the continents and oceans move with them.

Figure 6.9

A cutaway view of Earth shows that the lithosphere glides horizontally across the asthenosphere. The top of the lithosphere includes the crust that forms continents and ocean basins, so both move horizontally at rates of a few centimeters each year. The mantle and lithosphere circulate in elliptical cells. In this illustration, the circulating cells involve the entire mantle, although some geologists have suggested that mantle convection may involve two layers, with relatively shallow convection above 660-kilometer depth and deeper convection below this depth. The thickness of the lithosphere is exaggerated here for clarity.
A **plate boundary** (A fracture or boundary that separates two tectonic plates.) is a fracture that separates one plate from another. Neighboring plates can move relative to one another at these boundaries in three ways, shown by the insets in Figure 6.10. At a **divergent boundary** (A plate boundary where tectonic plates move apart from each other and new lithosphere is continuously forming; also called a *spreading center* or a *rift zone.*), two plates move apart from each other; at a **convergent boundary** (A plate boundary where two tectonic plates move toward each other and collide.), two plates move toward each other; and at a **transform boundary** (A plate boundary where two tectonic plates slide horizontally past one another.), they slide horizontally past each other. Table 6.2 summarizes characteristics and examples of each type of plate boundary.

The great forces generated at plate boundaries build mountain ranges, cause earthquakes,
and produce many of Earth’s volcanoes. In contrast, the interior portions of plates usually are tectonically quiet because they are further from the zones where two plates interact.

**Figure 6.10**

Earth’s lithosphere is broken into eight large tectonic plates, called the African, Arabian, Eurasian, Indian-Australian, Antarctic, Pacific, North American, and South American Plates. The white arrows show how the plates move in different directions. The three different types of plate boundaries are shown below the map:

At a transform plate boundary, rocks on opposite sides of the fracture slide horizontally past each other. Two plates move toward each other at a convergent boundary. Two plates move apart at a divergent boundary.

<table>
<thead>
<tr>
<th>Table 6.2</th>
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<tbody>
<tr>
<td><strong>Characteristics and Examples of Plate Boundaries</strong></td>
</tr>
<tr>
<td>Type of</td>
</tr>
<tr>
<td>---------</td>
</tr>
</tbody>
</table>

OAR/National Undersea Research Program (NURP)
<table>
<thead>
<tr>
<th>Boundary</th>
<th>Plates Involved</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divergent</td>
<td>Ocean–ocean</td>
<td>Seafloor spreading, shallow earthquakes, rising magma, volcanoes</td>
</tr>
<tr>
<td></td>
<td>Mid-Oceanic Ridge</td>
<td>Mid-Atlantic Ridge</td>
</tr>
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<td>Continent–continent</td>
<td>Continents torn apart, earthquakes, rising magma, volcanoes</td>
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<td>Rift valley</td>
<td>East African Rift</td>
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<td>Subduction, deep earthquakes, rising magma, volcanoes, deformation of rocks</td>
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<td>Island arcs and ocean trenches</td>
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<td>Continent–continent</td>
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<td>Transform</td>
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<td>Major offset of Mid-Oceanic Ridge axis</td>
<td>Offset of East Pacific Rise</td>
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<td>Ocean–continent</td>
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<td>Linear, deformed mountain ranges</td>
<td>Northern portion of San Andreas Fault</td>
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<td>Linear</td>
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6-4a Divergent Plate Boundaries

At a divergent plate boundary (also called a spreading center or a rift zone), two plates spread apart from one another, as shown at the center of Figure 6.11. The underlying asthenosphere rises upward to fill the gap between the separating plates. As it rises, the decrease in pressure causes the hot asthenosphere to melt and form magma. As this magma continues to rise, it cools to form new crust. Most of this activity occurs at divergent plate boundaries within the ocean basins, but it also can occur between two continental plates that are rifting apart, as in East Africa.

Figure 6.11

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. The lithosphere beneath the spreading center is only 10 or 15 kilometers thick, but it becomes thicker as the new lithosphere moves away from the spreading center and cools. At the sides of the drawing, old lithosphere sinks into the mantle at subduction zones.
Both the lower lithosphere (the part beneath the crust) and the asthenosphere are parts of the mantle and have similar chemical compositions. The main differences between the two layers are in temperature, pressure, and mechanical strength. The cool lithosphere is strong and hard, but the hot asthenosphere is weak and plastic. As the asthenosphere rises closer to Earth’s surface between two separating plates, it cools and gains mechanical strength, and therefore transforms into new lithosphere. In this way, new lithosphere continuously forms at a divergent boundary.

At a divergent boundary, 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 rock, 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 and thickens (Figure 6.11).

As it spreads outward and cools, the new lithosphere also thickens because the boundary between cool rock and hot rock 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 ice becomes thicker. In a similar fashion, the cooling lithosphere thickens to about 75 kilometers beneath ocean basins and to about 125 kilometers beneath continents.

6-4b The Mid-Oceanic Ridge: Rifting in the Oceans

New lithosphere at an oceanic spreading center is hotter than older lithospheric rock farther away from the divergent boundary, and so the new lithosphere has lower density. Therefore, it floats to a higher level, forming the undersea mountain chain called the Mid-Oceanic Ridge system (Figure 6.6). But as lithosphere migrates away from a spreading center, it cools and becomes denser. As a result, the lithosphere sinks into the soft, plastic asthenosphere (Figure 6.11), causing the depth of the seafloor to increase with distance from the Mid-Oceanic Ridge.

6-4c Splitting Continents: Rifting in Continental Crust

A divergent plate boundary can split apart continental crust in a process called continental rifting (The process by which a continent is pulled apart at a divergent plate boundary.). 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 the East African Rift (Figure 6.12). If the rifting continues, eastern Africa will separate from the main portion of the continent and a new ocean basin will open between the diverging portions of
lithosphere.

**Figure 6.12**

The continent of Africa is splitting apart along the East African Rift.

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**6-4d Convergent Plate Boundaries**

At a convergent plate boundary, two lithospheric plates move toward each other. Not all lithospheric plates are made of equally dense rock. Where two plates of different densities converge, the denser plate sinks into the mantle beneath the less dense one. This sinking process is called **subduction** *(The process in which two lithospheric plates of different densities converge and the denser one sinks into the mantle beneath the other.)* and is shown on both the right and left sides of **Figure 6.11**. A **subduction zone** *(A long, narrow region at a convergent boundary where a lithospheric plate is sinking into the mantle)*
during subduction; also referred to as subduction boundary.) 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, Earth maintains a global balance between the creation of new lithosphere and the destruction of old lithosphere.

Plate 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 crust.

**Convergence of Oceanic Crust with Continental Crust**

Recall that oceanic crust is generally denser than continental crust. In fact, the entire lithosphere beneath the oceans is denser than continental lithosphere. When an oceanic plate converges with a continental plate, subduction occurs and the denser oceanic plate plunges into the mantle beneath the edge of the continent. As a result, many subduction zones are located at continental margins. Today, oceanic plates are subducting beneath the western edge of South America; along the coasts of Oregon, Washington, and British Columbia; and at several other continental margins shown in Figure 6.10. When the descending plate reaches the asthenosphere, large quantities of magma are generated by processes explained in Chapter 8. Magma rises through the lithosphere of the overriding plate; much of the magma reaches the surface, where it erupts from a chain of volcanoes that form parallel to the subduction zone. Chapter 9 describes how the Andes—a chain of volcanic mountains—formed as a result of the subduction of a Pacific oceanic plate beneath the west coast of South America.

The oldest seafloor rocks on Earth are only about 200 million years old, because oceanic crust continuously is being destroyed where it subducts and is melted. In contrast, rocks as old as 4.03 billion years are found on continents because subduction consumes little continental crust.

Continental crust generally is too thick to subduct. In addition, continental crust is made of mostly granite, a lower-density rock than basalt. Relative to oceanic lithosphere, this lower density provides continental lithosphere with buoyancy and further inhibits its ability to subduct.

**Convergence of Two Plates Carrying Oceanic Crust**

Recall that newly formed oceanic lithosphere is hot, thin, and of relatively low density, 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 older, denser one subducts into the mantle. Oceanic subduction zones are common in the southwestern Pacific Ocean (Figure 6.10) and also formed the Aleutian Islands. The effects of subduction zones on the geology of the seafloor are described in Chapter 15.
Convergence of Two Plates Carrying Continents

If two converging plates carry continents, the relatively low density of the continental lithosphere prevents either plate from subducting deeply into the mantle. Continental lithosphere does not normally sink into the mantle at a subduction zone for the same reasons that a log does not sink into a lake: both are of lower density than the material beneath them. Rather, when two plates with continental lithosphere do collide, they crumple against each other and form a huge mountain chain. The Himalayas, the Alps, and the Appalachians all formed as a result of continental collisions. The formation of the Himalayas is described in Chapter 9.

6-4e Transform Plate Boundaries

A transform plate boundary forms where two plates slide horizontally past one another as they move in opposite directions (Figure 6.10). This type of boundary can occur in both oceans and continents and can result in frequent earthquakes. California’s San Andreas Fault is a transform boundary between the North American Plate and the Pacific Plate.

6-5 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 the overlying crust.

2. A single plate can carry both oceanic crust and continental crust. The average thickness of a lithospheric plate covered by oceanic crust is 75 kilometers, whereas that of lithosphere covered by a continent is 125 kilometers. Lithosphere is thinnest at oceanic spreading centers and thickest where continent–continent collisions are taking place.

3. A plate is composed of hard, mechanically strong rock.

4. A plate floats on the underlying hot, plastic asthenosphere and slides horizontally over it.

5. A plate behaves like a 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. Plate margins are tectonically active. Earthquakes, mountain ranges, and volcanoes are common at plate boundaries. In contrast, the interior of a lithospheric plate normally is tectonically stable.

7. Tectonic plates move at rates that vary from less than 1 to about 16 centimeters per year. Continents and oceans are carried on the upper parts of the moving lithosphere and migrate across Earth's surface at the same rates at which the plates move. For example, because of seafloor spreading in the Mid-Atlantic Ridge system, Manhattan Island is now nine meters farther from London than it was when the Declaration of Independence was written in 1776. Alfred Wegener was correct in saying that continents drift across Earth's surface.

Chapter 6: The Active Earth: Plate Tectonics: 6-6 Why Plates Move: The Earth as a Heat Engine

6-6 Why Plates Move: The Earth as a Heat Engine

After geologists had developed the theory of plate tectonics, they began to ask, “Why do the great slabs of lithosphere move?” Research has shown that subduction can continue slowly all the way to the core–mantle boundary, to a depth of 2,900 kilometers. At the same time, hot rock rises from the deep mantle towards the surface to replace the lithosphere lost to subduction.

The term convection (The upward and the downward flow of fluid material in response to density changes produced by heating and cooling. Convection occurs slowly in Earth’s mantle and much more quickly in the oceans and the atmosphere.) refers to the circulating flow of fluid material in response to heating and cooling. The process of mantle convection continually stirs the entire mantle as rock that is hotter than its surroundings rises toward Earth's surface and old plates that are colder than their surroundings sink into the mantle. In this way, the entire mantle–lithosphere system slowly circulates in cells that carry rock from as deep as the core–mantle boundary towards Earth's surface and then back into the deepest mantle (Figure 6.9).

A soup pot on a hot stove illustrates the process of convection. Rising temperature causes most materials, including soup (or rock), to expand. When soup at the bottom of the pot is heated by the underlying stove, it 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 (Figure 6.13).

Figure 6.13
Soup convects when it is heated from the bottom of the pot.
Although the circulation of soup in a hot pot provides a good illustration of convection, the circulation of the mantle is considerably more complex than that. Not only is the mantle not shaped like a pot, but the circulation of the mantle is driven by three processes: heat from the core below, radioactive decay of unstable isotopes within the mantle, and the cooling of the upper surface that is in contact with the lithosphere.

Today, the specifics of mantle convection are not well understood, although there is general agreement that mantle convection and plate tectonics are part of the same system and that mantle convection is the main mechanism for transport of heat away from Earth’s interior to the surface. What is less certain is the structure of the circulating mantle rock. For example, upwelling of hot mantle beneath mid-ocean ridges is quite shallow and not related to deep-mantle circulation. In this case, it appears to be the diverging motion of the lithospheric plates that causes upwelling of mantle from shallow depths, and not the other way around.

Two other processes, shown in Figure 6.14, may facilitate the movement of tectonic plates. Notice that the base of the lithosphere slopes downward from a spreading center; the grade can be as steep as 8 percent, steeper than most paved highways. Calculations show that even if the slope were less steep, gravity would cause the lithosphere to slide away from a spreading center over the soft, plastic asthenosphere at a rate of a few centimeters per year. This downslope sliding of the lithosphere away from a spreading center is called “ridge push” and may contribute to the movement of plates.

**Figure 6.14**

New lithosphere glides downslope away from a spreading center. At the same time, the old, cool part of the plate sinks into the mantle at a subduction zone, pulling the
rest of the plate along with it. (The steepness of the slope at the base of the lithosphere is exaggerated in this figure.)

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As the lithosphere moves away from a spreading center and cools, it becomes denser. Eventually, old lithosphere may become denser than the asthenosphere below. Consequently, it can no longer float on the asthenosphere and sinks into the mantle in a subduction zone, pulling the trailing plate along with it in a phenomenon referred to as “slab pull.” Both ridge push and slab pull are considered to contribute to the movement of a lithospheric plate as it slides over the asthenosphere.

Chapter 6: The Active Earth: Plate Tectonics: 6-6a Mantle Plumes and Hot Spots
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6-6a Mantle Plumes and Hot Spots

In contrast to the huge, ridge-shaped mass of mantle that rises beneath a spreading center, a mantle plume (A relatively small rising column of mantle rock that is hotter than surrounding rock. As pressure decreases in a rising plume, the rock partially melts, forming magma.) is a relatively small rising column of plastic mantle rock that is hotter than surrounding rock. Some plumes appear to rise from great depths in the mantle, probably because small zones of rock near the core–mantle boundary become hotter and more buoyant than surrounding regions of the deep mantle. Others form as a result of heating in shallower portions of the mantle.
As pressure decreases in a rising plume, rock melts to form magma. The rising heat and magma produce a **hot spot** (The hot upper mantle rock located within a plume and associated with a volcanic center that forms on the overlying lithosphere.) in the upper mantle which in turn heats the overlying lithosphere, forming a volcanic center. The Hawaiian Island chain is an example of a volcanic center over a hot spot (Figure 6.15). The volcanic center in the middle of the Pacific tectonic plate because the plume originates deep in the mantle, far from any plate boundary and below the level of lateral plate motion.

**Figure 6.15**

Lava flows on Hawaii provide direct evidence of heat associated with the mantle hot spot and plume below.

Some researchers have suggested that the mantle consists of two primary layers, with each layer undergoing convection. The shallower layer, located above 660 kilometers in depth, behaves dynamically and is characterized by relatively rapid convection. Below 660 kilometers, convection is more sluggish. This two-layered mantle model explains why the chemical composition of basalts from mid-ocean ridges is different than those that erupt at hot spots such as Hawaii. Basalt erupting at mid-ocean ridges is part of the shallow convection system, where the mantle is well mixed. In contrast, the basalts erupting in Hawaii are more primitive and come from a plume of mantle welling up from the deeper convection system.

Although the two-layered convection model explains some observations, it is not consistent with others. For example, seismologists have been able to use variations in the velocity of earthquake waves passing through the mantle to identify zones of cooler temperature,
attributed to mantle downwelling or old subducted oceanic lithosphere. These data suggest that the relatively cool remnants of some subducted slabs extend completely through the mantle to the core–mantle boundary.

6-7 Supercontinents

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 islands of the southwest Pacific Ocean probably dotted a global ocean basin. Then, between 2 billion and 1.8 billion years ago, tectonic plate movements brought these microcontinents together to form a single landmass called a supercontinent (A continent, such as Alfred Wegener’s Pangea, consisting of all or most of Earth’s continental crust joined together to form a single, large landmass. At least three supercontinents are thought to have existed during the past 2 billion years, and each broke apart after a few hundred million years.) After a few hundred million years, this supercontinent, called Nuna, developed rifts and broke into fragments. The fragments then separated, each riding away from the others on its own tectonic plate. About 1 billion years ago, the fragments of continental crust reassembled, forming a second supercontinent, called Rodinia. In turn, this continent fractured and the continental fragments reassembled into a third supercontinent about 300 million years ago, 70 million years before the appearance of dinosaurs. This third supercontinent is Alfred Wegener’s Pangea, which began to break apart about 235 million years ago, in late Triassic time. The tectonic plates have continued their slow movement to create the mosaic of continents and ocean basins that shape the map of the world as we know it today, and will continue to shape it into the future. One recent model of future plate motions suggests that the current configuration of continents will rearrange to form the next supercontinent, named Amasia, about 100 million years from now, near the present-day North Pole.

6-8 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, the underlying asthenosphere flows laterally away from that region to make space for the settling lithosphere.

But how is mass added or subtracted from the lithosphere? One process that adds and removes mass is the growth and melting of large glaciers. When a glacier grows, the weight of ice forces the lithosphere downward and causes the asthenosphere to move.
laterally away from the depressed region. For example, the Hudson Bay region of Canada was depressed during the last glaciation by an ice sheet about 3,000 meters thick. Conversely, when a glacier melts, the continent rises, or rebounds. Because the rate of rebound is slower than the rate at which the ice melts, the surface formerly below thick glacial ice can remain depressed for thousands of years after all the ice is gone. Thus, the Hudson Bay region of Canada remains below sea level, although it is slowly rising at a rate of about one centimeter per year as the underlying asthenosphere slowly flows back into the region.

The Great Lakes, located near the former southern margin of the ice sheet, also are slowly rebounding following the melting of glacial ice. The rebound is faster on the northern side of the lakes because the ice was thicker there. Similarly, in Scandinavia geologists have discovered ice-age beaches that are tens of meters above modern sea level. The beaches formed when glaciers had depressed the Scandinavian crust to sea level, but they now lie well above that elevation because the land rose as the ice melted.

The concept that the lithosphere is in floating equilibrium on the asthenosphere is called **isostasy** (The concept that the lithosphere floats on the asthenosphere as an iceberg floats on water.), and the vertical movement in response to a changing burden is called **isostatic adjustment** (Figure 6.16).

**Figure 6.16**

Isostatic adjustment. The weight of an ice sheet causes continental lithosphere to sink in response to the added burden. Notice that thicker ice will depress the lithosphere to a greater degree.
The iceberg pictured in Figure 6.17 illustrates an additional effect of isostasy. A large iceberg has a high peak, but its base extends deeply below the water’s surface. The lithosphere behaves in a similar manner. Continents rise high above sea level, and the lithosphere beneath a continent has a “root” that extends as much as 125 kilometers into the asthenosphere.

**Figure 6.17**

(A) Icebergs illustrate some of the effects of isostasy. A large iceberg has a deep root and also a high peak. (B) In an analogous manner, continental lithosphere extends more deeply into the asthenosphere beneath high mountains than it does
under lowerelevation regions. In this cartoon, which is not to scale, the mountains were formed by the collision of two small continental fragments.

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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 do low plains, just as the bottom of a large iceberg is deeper than the base of a small one.

Chapter 6: The Active Earth: Plate Tectonics: 6-9 How Plate Tectonics Affect Earth’s Surface
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6-9 How Plate Tectonics Affect Earth’s Surface

The movements of tectonic plates generate volcanic eruptions and earthquakes, which help shape Earth’s surface. They also build mountain ranges and change the global distributions of continents and oceans. Tectonic activities strongly affect our environment in other ways by impacting global and regional climate, the atmosphere, the hydrosphere, and the biosphere.
6-9a Volcanoes

Most of Earth’s volcanoes result from plate movements. At a divergent boundary (spreading center), hot asthenosphere oozes upward to fill the gap left between the two separating plates. Portions of the rising asthenosphere melt to form basaltic magma, which erupts onto Earth’s surface. Thus, the Mid-Oceanic Ridge is in part a chain of submarine volcanoes. Volcanoes are common in continental rifts as well, such as the East African Rift and the Rio Grande Rift in the southwestern United States.

Huge quantities of magma also form in the descending lithosphere of a subduction zone. Some of the magma solidifies within the crust, and some erupts at the Earth’s surface from a chain of volcanoes that forms parallel to the subduction zone. The Aleutian Islands of Alaska, the Andes Mountains in South America, and the Cascade Range of the Pacific Northwest all are examples of volcano chains formed in this manner (Figure 6.18).

Figure 6.18

Mount St. Helens, which last erupted in 1980, is an active volcano in the Cascade Range of Washington near a convergent plate boundary.
6-9b Earthquakes

Earthquakes are common at all three types of plate boundaries but are generally uncommon within the interior of a tectonic plate. As a result, changes in the land surface resulting from earthquakes are most common near plate boundaries. Quakes concentrate at plate boundaries simply because these are zones where one plate slips past another.

The slippage of one plate relative to its neighbor is rarely smooth and continuous. Rather, stress builds up along the plate boundary and is stored in the rock as energy. Eventually, the stress level causes the rock to suddenly break, releasing the stored energy and causing rock on one side of the break to lurch violently past rock on the other. An earthquake is the vibration of the rock due to this sudden movement and rapid release of energy. During a single earthquake, the ground surface can be broken, forming a topographic feature called a scarp (A break in the land surface caused by an earthquake). Earthquakes also can cause major landslides and even change the course of rivers and streams. We will learn more about earthquakes in the next chapter.

Chapter 6: The Active Earth: Plate Tectonics: 6-9c Mountain Building

6-9c Mountain Building

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. Along subduction zones, long, linear mountain chains form as magma from the descending oceanic lithosphere melts and some of it ascends to the surface. If two continents collide at a convergent plate boundary, the ground surface will rise for the same reason that a mound of bread dough thickens when you compress it from both sides. Such continent–continent collisions thrust great masses of rock upward, creating huge mountain chains such as the Himalayas, the Alps, and the Appalachians.

Chapter 6: The Active Earth: Plate Tectonics: 6-10 How Plate Tectonics Affect Earth’s Climate

6-10 How Plate Tectonics Affect Earth’s Climate

The tectonic movements of the continents and the opening and closing of ocean basins through rifting and subduction profoundly alter Earth’s oceanic and atmospheric systems. Ocean currents carry warm water from the equator toward the poles, and cool water from polar regions toward the equator, warming polar regions and cooling the tropics. Similarly, winds transport heat and moisture over the globe.
Changes in ocean currents and wind patterns, in turn, have far-reaching consequences for regional climate. For example, widespread glaciation across Antarctica began between 38 and 28 million years ago as seafloor spreading caused the continent to drift further away from the southern tips of South America, Africa, and Australia. These tectonic movements not only isolated Antarctica over the South Pole, but also established the **Antarctic Circumpolar Current** (a strong west-to-east ocean current that circulates clockwise around Antarctica and prevents warmer water from getting close to the shores of the continent), a strong west-to-east ocean current that continuously flows in a clockwise direction around the continent. As it formed, this current prevented warmer water from the southern Atlantic, Pacific, and Indian Oceans from reaching Antarctica, effectively putting the continent into a deep freeze that continues today.

Tectonic movements also have altered the composition of the atmosphere and oceans, producing major changes in global climate. For example, some scientists have proposed that the Cenozoic uplift of the Tibetan Plateau in Asia—the largest such uplift in the world—caused a strengthening of the Asian monsoon that led to Earth’s recent glaciations. According to this idea, the additional monsoonal rainfall and widespread exposure of new rock as the plateau was uplifted significantly increased the rate of chemical weathering of silicate minerals, including those containing calcium. Once released, the calcium ions combined with CO₂ molecules from the atmosphere to form calcite. In this way, CO₂ (a greenhouse gas) was removed from the atmosphere, causing the Earth to cool and contributing to the development of major glaciations during late Cenozoic time.

With these changes in environments and climates come changes in the ecosystems supported by them; thus, tectonic processes also affect the biosphere. Streams and drainage patterns must respond to changes in slope direction and altered distributions of precipitation. Lakes may dry up, or new lakes form. Ultimately, plants and animals may die or migrate away, to be replaced by new species that are adapted to the new climatic conditions.

Chapter 6: The Active Earth: Plate Tectonics Chapter Review

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**Chapter Review**

**Key Terms**

- **Antarctic Circumpolar Current** (A strong west-to-east ocean current that circulates clockwise around Antarctica and prevents warmer water from getting close to the shores of the continent.)

- **asthenosphere** (The portion of the upper mantle just beneath the lithosphere, extending from a depth of about 100 kilometers to about 350 kilometers below the surface of Earth and consisting of weak, plastic rock where magma may form.)

- **continental drift** (The theory proposed by Alfred Wegener that Earth’s continents...
were once joined together and later split and drifted apart. The continental drift theory has been replaced by the more complete plate tectonics theory.

- **continental rifting** (The process by which a continent is pulled apart at a divergent plate boundary.)

- **convection** (The upward and the downward flow of fluid material in response to density changes produced by heating and cooling. Convection occurs slowly in Earth’s mantle and much more quickly in the oceans and the atmosphere.)

- **convergent boundary** (A plate boundary where two tectonic plates move toward each other and collide.)

- **divergent boundary** (A plate boundary where tectonic plates move apart from each other and new lithosphere is continuously forming; also called a spreading center or a rift zone.)

- **Gondwana** (The southern part of Pangea, consisting of what is now South America, Africa, Antarctica, India, and Australia.)

- **hot spot** (The hot upper mantle rock located within a plume and associated with a volcanic center that forms on the overlying lithosphere.)

- **isostasy** (The concept that the lithosphere floats on the asthenosphere as an iceberg floats on water.)

- **Laurasia** (The northern part of Pangea, consisting of what is now North America and Eurasia.)

- **magnetic reversal** (A change in Earth’s magnetic field in which the north magnetic pole becomes the south magnetic pole and vice versa; has occurred on average every 500,000 years over the past 65 million years.)

- **mantle plume** (A relatively small rising column of mantle rock that is hotter than surrounding rock. As pressure decreases in a rising plume, the rock partially melts, forming magma.)

- **Mid-Atlantic Ridge** (The portion of the Mid-Oceanic Ridge system that lies in the middle of the Atlantic Ocean, halfway between North America and South America to the west, and Europe and Africa to the east.)

- **Mid-Oceanic Ridge system** (The undersea mountain chain that forms at the boundary between divergent tectonic plates within oceanic crust. It circles the planet like the seam on a baseball, forming Earth’s longest mountain chain.)

- **normal magnetic polarity** (A magnetic orientation the same as that of Earth’s current magnetic field.)

- **Pangea** (The supercontinent that existed when all Earth’s continents were joined
together, about 300 million to 200 million years ago, first identified and named by Alfred Wegener.)

- **plate boundary** (A fracture or boundary that separates two tectonic plates.)

- **plate tectonics** (A theory of global tectonics stating that the lithosphere is segmented into several plates that move about relative to one another by floating on and sliding over the plastic asthenosphere. Seismic and tectonic activity occur mainly at the plate boundaries.)

- **reversed magnetic polarity** (Magnetic orientations in rock that are opposite to the current orientation of Earth’s magnetic field.)

- **scarp** (A break in the land surface caused by an earthquake.)

- **seafloor spreading** (The hypothesis that segments of oceanic crust are separating at the Mid-Oceanic Ridge.)

- **subduction** (The process in which two lithospheric plates of different densities converge and the denser one sinks into the mantle beneath the other.)

- **subduction zone** (A long, narrow region at a convergent boundary where a lithospheric plate is sinking into the mantle during subduction; also referred to as subduction boundary.)

- **supercontinent** (A continent, such as Alfred Wegener’s Pangea, consisting of all or most of Earth’s continental crust joined together to form a single, large landmass. At least three supercontinents are thought to have existed during the past 2 billion years, and each broke apart after a few hundred million years.)

- **transform boundary** (A plate boundary where two tectonic plates slide horizontally past one another.)
Alfred Wegener’s hypothesis of continental drift foreshadowed the theory of plate tectonics, which provides a unifying framework for much of modern geology.

6-2

**The Earth’s Layers**

Earth is a layered planet. The crust is its outermost layer and varies from 4 to 70 kilometers thick. The mantle extends from the base of the crust to a depth of 2,900 kilometers, where the core begins. The lithosphere is the cool, hard, strong outer 75 to 125 kilometers of Earth; it includes all of the crust and the uppermost mantle. The hot, plastic asthenosphere 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.

**Figure 6.4**

Earth is a layered planet. The insert is drawn on an expanded scale to show near-surface layering. Note that the average thickness of the lithosphere varies from about 75 kilometers beneath the oceans to about 125 kilometers beneath continents.
The Seafloor Spreading Hypothesis

The hypothesis of seafloor spreading was proposed as a general model for the origin of all oceanic crust.

The Theory of Plate Tectonics

Plate tectonics theory is the concept that the lithosphere floats on the asthenosphere and is segmented into seven major tectonic plates, which move relative to one another by gliding over the asthenosphere. Most of 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; and
3. two plates slide horizontally past each other at a transform boundary.

The Anatomy of a Tectonic Plate

Volcanoes, earthquakes, and mountain building 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, cause ocean basins to open and close, and affect climate and the distribution of plants and animals.

Why Plates Move: The Earth as a Heat Engine

Mantle convection and movement of lithospheric plates can occur because the mantle is hot, plastic, and capable of flowing. The entire mantle, from the top of the core to the crust, convects in huge cells. Horizontally moving tectonic plates are the uppermost portions of convection cells. Convection occurs
because

1. the mantle is hottest near its base,

2. new lithosphere glides downslope away from a spreading center, and

3. the cold leading edge of a plate sinks into the mantle and drags the rest of the plate along.

6-7

**Supercontinents**

Supercontinents may assemble, split apart, and reassemble every few hundred million years.

6-8

**Isostasy: Vertical Movement of the Lithosphere**

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

6-9

**How Plate Tectonics Affect Earth's Surface**

The movements of tectonic plates generate volcanic eruptions and earthquakes, which help shape Earth's surface. They also build mountain ranges and change the global distributions of continents and oceans. Tectonic activities strongly affect our environment in other ways—impacting global and regional climate, the atmosphere, the hydrosphere, and the biosphere.

6-10

**How Plate Tectonics Affect Earth's Climate**

The tectonic movements of the continents and the opening and closing of ocean basins through rifting and subduction profoundly alter Earth's oceanic and atmospheric systems. Ocean currents carry warm water from the equator toward the poles, and cool water from polar regions toward the equator, warming polar regions and cooling the tropics. Similarly, winds transport heat and moisture over the globe. Changes in ocean currents and
wind patterns, in turn, have far-reaching consequences for regional climate.

Chapter Review

Review Questions

1. Briefly describe Alfred Wegener’s theory of continental drift. What evidence supported his ideas? How does Wegener’s theory differ from the modern theory of plate tectonics?

2. Briefly describe the seafloor spreading hypothesis and the evidence used to develop the hypothesis. How does this idea differ from Wegener’s theory and the theory of plate tectonics?

3. Draw a cross-sectional view of Earth. List all the major layers and the thickness of each.

4. Describe the physical properties of each of Earth’s layers.

5. Describe and explain the important differences between the lithosphere and the asthenosphere.

6. What properties of the asthenosphere allow the lithospheric plates to glide over it?

7. Describe some important differences between the crust and the mantle.

8. Describe some important differences between oceanic crust and continental crust.