

Unit 5

The Dynamic Earth

The mountain shown in the photograph is Mount Fuji, an inactive volcano in Japan that towers above the surrounding landscape. Its snow-covered peak rises more than 3700 m above sea level to overlook five, interconnected lakes. How did this magnificent structure form? Earth's outermost layers are broken into enormous slabs that shift slowly across the planet's surface. The movements, which occur at rates of only a few centimeters per year, cause mountains to form, volcanoes to erupt, and earthquakes to shake our planet. In this unit, you will explore how and why these slabs of rock move to change Earth.

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Go to the [National Geographic Expedition](#) on page 886 to learn more about topics that are connected to this unit.



Mount Fuji, Japan

Chapter 17

What You'll Learn

- Why continental drift was not accepted when it was first proposed and what kinds of evidence led to its acceptance.
- How Earth's tectonic plates interact.
- What causes tectonic plates to move.

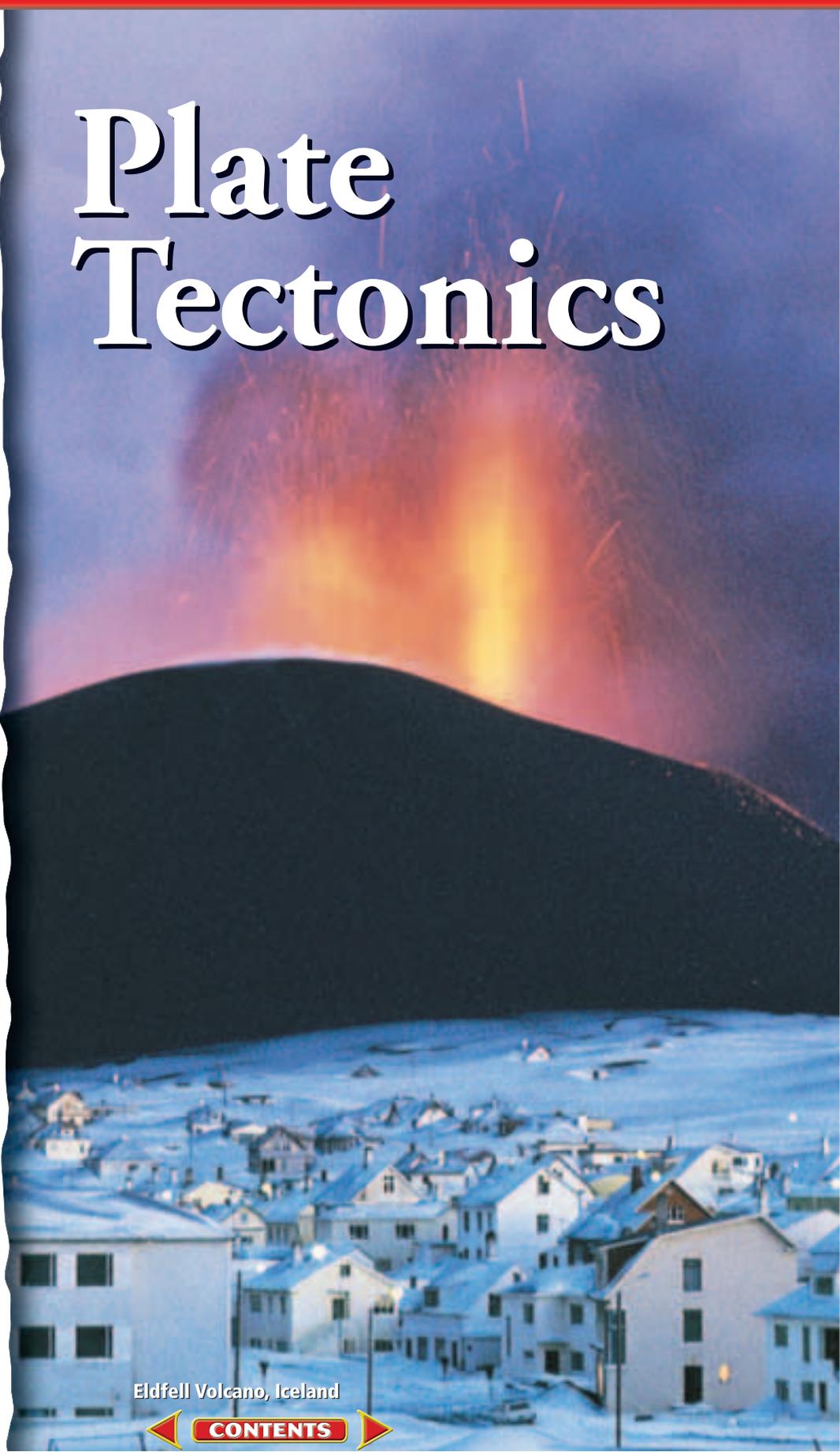
Why It's Important

Understanding the theory of plate tectonics is important because interactions between the enormous slabs of Earth's crust and rigid upper mantle result in the formation of many of Earth's surface features, including volcanoes and some mountain ranges. Many earthquakes are also caused by plate movements.



To learn more about plate tectonics, visit the Earth Science Web Site at earthgeu.com

Plate Tectonics



Discovery Lab

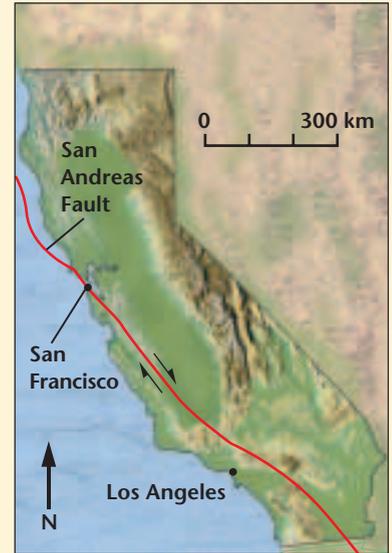
Coming Apart at the Seams?

Southwestern California is separated from the rest of the state by a system of cracks along which movement takes place. These cracks are called faults. One of these cracks, as you may already know, is the San Andreas Fault. Movement along this fault is sending southwestern California to the northwest in relation to the rest of North America at a rate of about 5 cm/y.

1. Use a metric ruler and the map scale to determine the actual distance between San Francisco and Los Angeles.

2. At the current rate of movement, when will these two cities be next-door neighbors?

Infer Infer what might be causing these large pieces of land to move. Describe your inference in your science journal.



SECTION

17.1

Drifting Continents

OBJECTIVES

- **Describe** one piece of early evidence that led people to suggest that Earth's continents may have once been joined.
- **Discuss** evidence of continental drift.
- **Explain** why continental drift was not accepted when it was first proposed.

VOCABULARY

continental drift
Pangaea

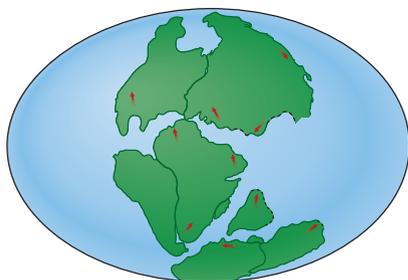
With the exception of events such as earthquakes, volcanic eruptions, and landslides, Earth's surface appears to remain relatively unchanged during the course of an average human lifetime. On the geologic time scale, however, Earth's surface is changing at rates almost too great to imagine! South America is moving away from Africa at a rate of 2 to 3 cm/y. The volcanic islands that make up Hawaii are migrating toward the northwest at a rate of 8 to 9 cm/y. And Mt. Everest, Earth's highest point, is slowly rising. What could be causing such enormous pieces of land to move?

EARLY OBSERVATIONS

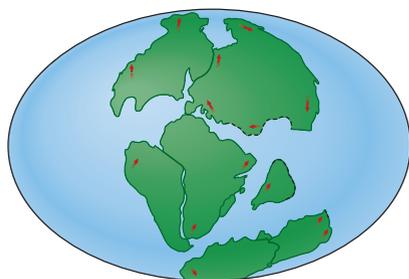
Some of the first people to consider the idea of moving landmasses were early mapmakers. In the late 1500s, Abraham Ortelius, a Dutch mapmaker, noticed the apparent fit of continents on either side of the Atlantic Ocean. He (incorrectly) proposed that North and South America had been separated from Europe and Africa by earthquakes and floods. Over the next 300 years, many people noticed and



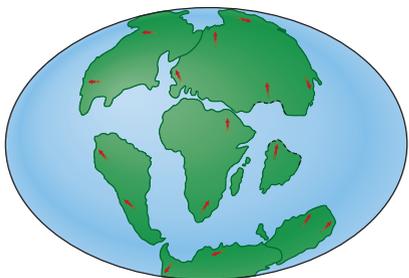
200 million years ago



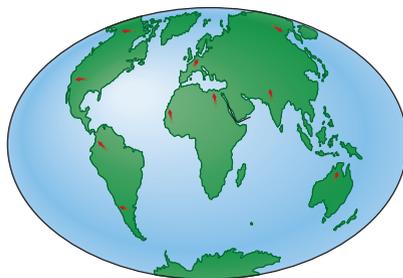
180 million years ago



135 million years ago



65 million years ago



Present

commented on the matching coastlines. In the late 1800s, Eduard Suess, an Austrian geologist, hypothesized that the present southern continents had once been joined as a single landmass that he named Gondwanaland. The first time that the idea of moving continents was proposed as a serious scientific hypothesis, however, occurred in the early 1900s. In 1912, a German scientist named Alfred Wegener presented his ideas about continental movement to the scientific community.

CONTINENTAL DRIFT

Wegener called his hypothesis **continental drift**, which proposed that Earth's continents had once been joined as a single landmass. He called this supercontinent **Pangaea**, a Greek word that means "all the earth." Wegener proposed that Pangaea began to break apart about 200 million years ago. Since that time, he reasoned, the continents had continued to slowly move to their present positions, as shown in *Figure 17-1*.

Wegener was one of the first supporters of the concept of drifting continents to base his hypothesis on more than just the puzzlike fit of continental coastlines on either side of the Atlantic Ocean. For Wegener, these gigantic puzzle pieces were just the beginning. He also collected and organized rock, fossil, and climatic data to support his hypothesis.

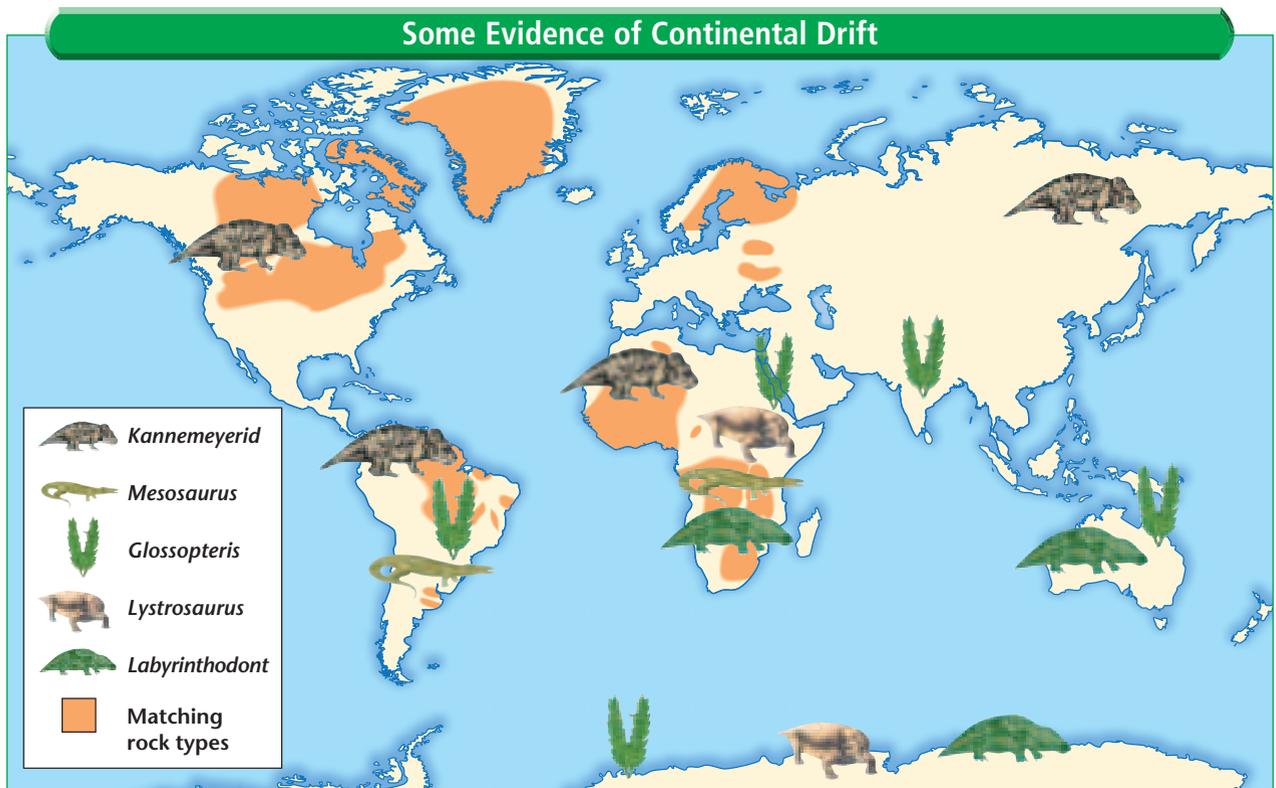
Evidence from Rock Formations Wegener reasoned that when Pangaea began to break apart, large geologic structures, such as mountain ranges, would have fractured as the continents separated. Using this reasoning, Wegener hypothesized that there should be areas of similar rock types on opposite sides of the Atlantic Ocean. He observed that some of the rocks of the Appalachian Mountains in the United States shared similar features with rocks in Greenland and Europe. These similar groups of rocks, all older than 200 million years, supported Wegener's idea that the continents had once been joined. What other groups of rocks shown in *Figure 17-2* suggest the existence of a single landmass in the past?

Figure 17-1 Pangaea was an ancient landmass that was made up of Earth's continents. Pangaea began to break apart about 200 million years ago.

Evidence from Fossils Wegener also gathered evidence of the existence of Pangaea from fossils. Similar fossils of several different animals and plants that once lived on land had been found on widely separated continents, as shown in **Figure 17-2**. Wegener reasoned that the land-dwelling animals, such as *Kannemeyrid* and *Labyrinthodont*, could not have swum the great distances that now exist between continents. Wegener also argued that because fossils of *Mesosaurus*, an aquatic reptile, had been found only in freshwater rocks, it was unlikely that this species could have crossed the oceans. The ages of these different fossils also predated Wegener's time frame for the breakup of Pangaea, which gave him the confidence he needed to move forward with his hypothesis.

Another fossil that Wegener used to support his hypothesis of continental drift was *Glossopteris*, a seed fern that resembled low shrubs. Fossils of this plant had been found on many continents, which today have very different climates. Because he had a strong background in meteorology, Wegener was able to reason that the area separating these fossil finds was too large to have had a single climate. This led him to conclude that the rocks containing these fossil ferns had once been joined. Wegener also argued that because *Glossopteris* grew in temperate climates, the places where these fossils had been found were once closer to the equator.

Figure 17-2 Alfred Wegener used fossils and the similarity of rock formations on opposite sides of the Atlantic Ocean as evidence that Earth's continents were once joined.



Ancient Climatic Evidence Recall from Chapter 6 that sedimentary rocks provide clues to past environments and climates. By studying various sedimentary rocks, Wegener found evidence of vast climatic changes on some continents. Coal deposits, for example, had been found in Antarctica. Coal forms from dead swamp plants. Swamps are areas of wet, spongy land often covered by water. The existence of coal beds in Antarctica, then, indicated that this frozen land once had a temperate, rainy climate. Wegener used this evidence to conclude that Antarctica must have been closer to the equator sometime in the geologic past.

Another piece of climatic evidence came from glacial deposits found in Africa, India, Australia, and South America. The presence of these 290-million-year-old deposits, some of which are shown in **Figure 17-3**, suggested to Wegener that these areas had once been covered by thick ice caps. Because continental glaciers do not presently exist on these continents, Wegener proposed that they once were located near the south pole, as shown in **Figure 17-4**, before Pangaea began to fracture. Furthermore, because the south pole is not presently located near Africa or India, Wegener suggested two possibilities to explain the glacial deposits. The first was that the pole had shifted its position, and the second was that these landmasses had

drifted away from the pole. Wegener argued that it was more likely that the landmasses drifted away from the south pole than that Earth changed its axis of rotation.

Figure 17-3 These glacial deposits in Africa helped support Wegener's hypothesis of continental drift.



A REJECTED HYPOTHESIS

In the early 1900s, many people in the scientific community strongly believed that the continents and ocean basins were permanent, fixed features of Earth's surface. Even though Wegener had compiled an impressive collection of data, most scientists of his day rejected his hypothesis of continental drift. Wegener's hypothesis had two major flaws that prevented it from being widely accepted. First, Wegener could not satisfactorily explain what was causing the continents to move. What force could be strong enough to move such large masses of rock over such great distances? Wegener suggested that the rotation of Earth could be responsible. Physicists, though, were able to show that this force was not great enough to move continents.

Scientists also had questions about how the continents were moving. Wegener had proposed that the continents were plowing through a stationary ocean floor. His peers, however, argued that continents could not push through the ocean floor without fracturing, because crustal rock is too brittle. Also, because no evidence for such fracturing had been found, geologists argued that the continents could not be moving as Wegener had proposed. These two unanswered questions—what forces could move continents and how continents could move without shattering—were the main reasons that the hypothesis of continental drift was rejected when it was first proposed.

Alfred Wegener did not give up when his hypothesis was not accepted by most other scientists of his time. He continued to search for evidence to support his hypothesis of continental drift. Wegener died in 1930 on an expedition to Greenland, but the controversy over his hypothesis remained alive for several decades after his death. It wasn't until the early 1960s that new evidence revealed a process that could explain why and how the continents move. This evidence, which was found on the seafloor, will be discussed in the next section.



Figure 17-4 Glacial deposits nearly 300 million years old on several continents led Wegener to propose that these landmasses may have once been joined and covered with ice. The extent of the ice is shown by the dashed line.

SECTION ASSESSMENT

1. What early evidence suggested that Earth's continents might be moving?
2. How do ancient glacial deposits in Africa, India, Australia, and South America support the idea of continental drift?
3. How did Alfred Wegener use rock and fossil evidence to support his hypothesis?
4. Why was Wegener's hypothesis rejected by most scientists of the early 1900s?
5. **Thinking Critically** Oil deposits approximately 200 million years old have been

discovered in Brazil. Where might geologists find oil deposits of a similar age? Explain.

SKILL REVIEW

6. **Comparing and Contrasting** Compare and contrast the different types of evidence used by Wegener to support his idea of continental drift. Which type do you think provides the strongest support for his hypothesis? Why? For more help, refer to the *Skill Handbook*.

OBJECTIVES

- **Summarize** the evidence that led to the discovery of seafloor spreading.
- **Explain** the significance of magnetic patterns on the seafloor.
- **Explain** the process of seafloor spreading.

VOCABULARY

magnetometer
 paleomagnetism
 magnetic reversal
 isochron
 seafloor spreading

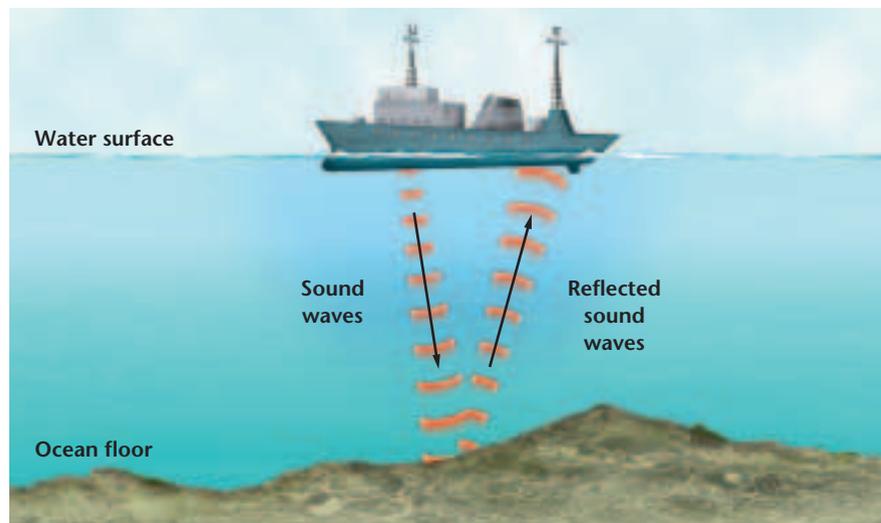
Until the mid-1900s, most people, including many scientists, thought that the ocean floor, unlike the continents, was essentially flat. Many people also had the misconceptions that oceanic crust was unchanging and was much older than continental crust. Advances in technology during the 1940s and 1950s, however, proved all of these widely accepted ideas to be wrong.

HELP FROM TECHNOLOGY

One advance that allowed scientists to study the ocean floor in great detail was the development of echo-sounding methods. One type of echo sounding is sonar, which uses sound waves to measure water depth. As shown in *Figure 17-5*, regular pulses of sound are sent out from a device aboard a ship. The sound waves travel through the water and are reflected from the ocean floor. The time it takes for these waves to travel from the device and back to a receiver can be used to calculate the distance from the sonar device to the ocean floor. Look again at *Figure 17-5*. How would the travel times of waves differ at various points along this hypothetical ocean bottom?

Another technological advance that was used to study the ocean floor was the magnetometer. A **magnetometer** is a device that can detect small changes in magnetic fields. Magnetometers towed by ships record the magnetic field strength in the rocks that make up the ocean floor. The measurements are then used to construct magnetic maps of the seafloor. You'll learn more about magnetism and how it supports the hypothesis of continental drift later in this section.

Figure 17-5 Sonar is an echo-sounding technique that has been used to map ocean-floor topography. The travel times of the sound waves can be used to calculate the distance to the ocean floor.



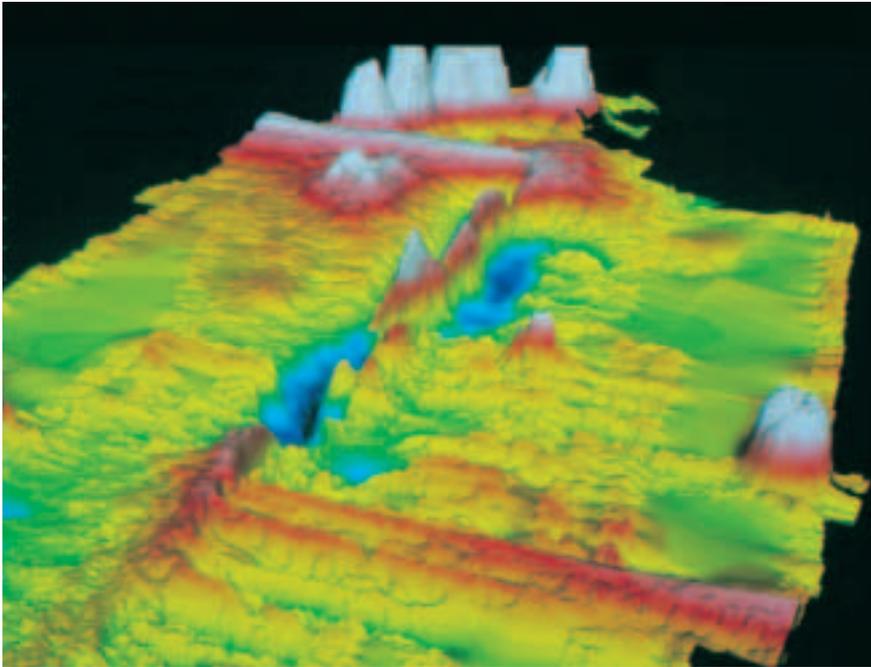


Figure 17-6 This is a false-color photo of a part of the East Pacific Rise. The red areas are areas of volcanism. Earthquakes are common in the areas colored blue.

OCEAN FLOOR TOPOGRAPHY

The maps made from the data collected by sonar and magnetometers surprised many scientists. Vast, underwater mountain chains called ocean ridges were discovered. These features of the ocean floor form the longest continuous mountain range on Earth. When they were first discovered, these ridges generated much discussion simply because of their size. Later, scientists discovered that earthquakes and volcanism are common along the ridges. A false-color photo of part of the East Pacific Rise, which is a ridge in the Pacific Ocean, is shown in *Figure 17-6*.

Maps generated with sonar data also revealed that these underwater mountain chains had counterparts called deep-sea trenches. Recall from Chapter 16 that a deep-sea trench is a narrow, elongated depression in the seafloor with very steep sides. Trenches can be thousand of kilometers long and are extremely deep. The deepest trench is in the Pacific Ocean. This chasm, called the Mariana Trench, is just over 11 km deep!

These two topographic features of the ocean floor—deep-sea trenches and ocean ridges—puzzled geologists for over a decade after their discovery. What could have formed an underwater mountain range that extended around Earth? What is the source of the volcanism that is associated with these mountains? What kinds of forces could depress Earth's crust far enough to create trenches nearly six times as deep as the Grand Canyon? You'll find out the answers to these questions later in this chapter.

OCEAN ROCKS AND SEDIMENTS

In addition to making maps, scientists collected samples of deep-sea sediments and the underlying crust to try to better understand Earth's ocean floors. Analysis of the rocks and sediments produced two important discoveries. First, the ages of the rocks that make up the seafloor vary in different places, and these variations change in a predictable way. Rock samples taken from areas near ocean ridges were younger than samples taken from areas near deep-sea trenches. Detailed analysis showed that the age of oceanic crust consistently increases with distance from a ridge, shown in **Figure 17-7**. Scientists also discovered from the rock samples that the oldest part of the seafloor is geologically young at about 180 million years old. Why are ocean-floor rocks so young compared to continental rocks, some of which are 3.8 billion years old? Geologists knew that oceans had existed for more than 180 million years. Where, then, they wondered, is the ocean crust from those earlier oceans?

The second discovery involved the sediments that are deposited on the ocean floor. Measurements showed that the thickness of ocean-floor sediment is, in general, much less than expected. Ocean-floor sediments are typically a few hundred meters thick. Large areas of continents, on the other hand, are blanketed with sedimentary rocks from a few kilometers to about 20 kilometers thick. Scientists knew that erosion and deposition were at work in Earth's oceans. Why, then, they asked, aren't seafloor sediments as thick as their continental counterparts? Could the relatively thin blanket of ocean sediments be a result of the age of the ocean crust? Careful observations of ocean-floor sediments also revealed that the thickness of the sediments increases with distance from an ocean ridge, as shown in **Figure 17-7**.



Topic: Ocean Floor Depths

To learn more about Earth's ocean floors, visit the Earth Science Web Site at earthgeu.com

Activity: Research the deepest places in the ocean. Draw a graph comparing the five deepest places on the ocean floor.

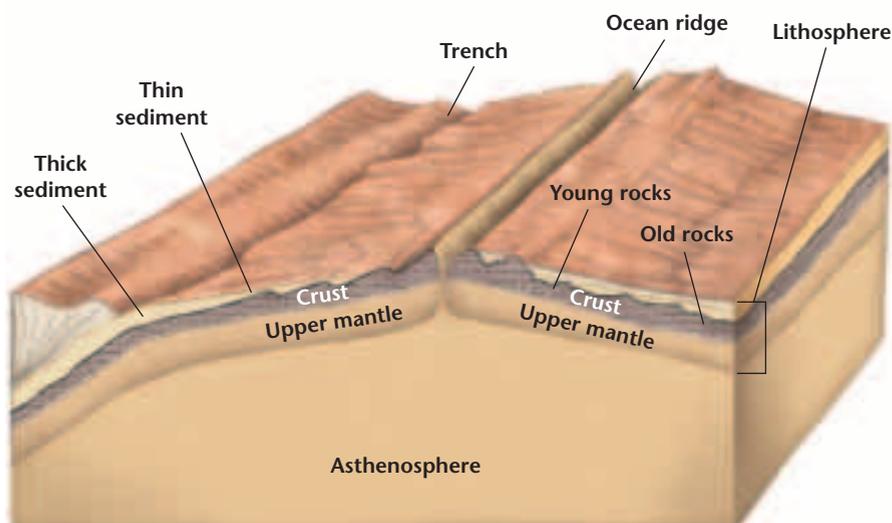


Figure 17-7 The ages of ocean crust and the thicknesses of ocean-floor sediments increase with distance from an ocean ridge.

MAGNETISM

Prior to their studies of the seafloor, scientists knew that rocks containing iron-bearing minerals provided a record of Earth's magnetic field. The study of this magnetic record is called **paleomagnetism**. Basalt, because it is rich in iron-bearing minerals, provides an accurate record of ancient magnetism. As basaltic lava cools, the iron-bearing minerals become oriented parallel to Earth's magnetic field. These minerals are, in effect, compass needles. When the lava hardens, the magnetic orientation is locked in place and provides a record of Earth's magnetic field at that time.

The Geomagnetic Time Scale Studies of continental basalt flows in the early 1960s revealed a pattern of magnetic reversals over geologic time. A **magnetic reversal** is a change in Earth's magnetic field. A magnetic field that has the same orientation as Earth's present field is said to have normal polarity. A magnetic field that is opposite to the present field has reversed polarity. The data gathered from continental basalt flows allowed scientists to construct the geomagnetic time scale, shown in *Figure 17-8*.

To find out how the continental basalt-flow data compared with the basalts that make up the ocean floor, scientists proposed that magnetometers be towed behind ships to measure the magnetic field of the ocean floor. A very interesting pattern emerged. In some places, the magnetic field strength was greater than normal. In other places, the field strength was lower than normal. In places where the magnetic readings of the ocean floor matched Earth's present field, the two fields combined. This produced a stronger-than-normal reading (+). In places where the magnetic data were reversed in relation to Earth's present magnetic field, the two fields partially cancelled one another. In these cases, a lower-than-normal reading (-) was recorded, as shown in *Figure 17-9*.

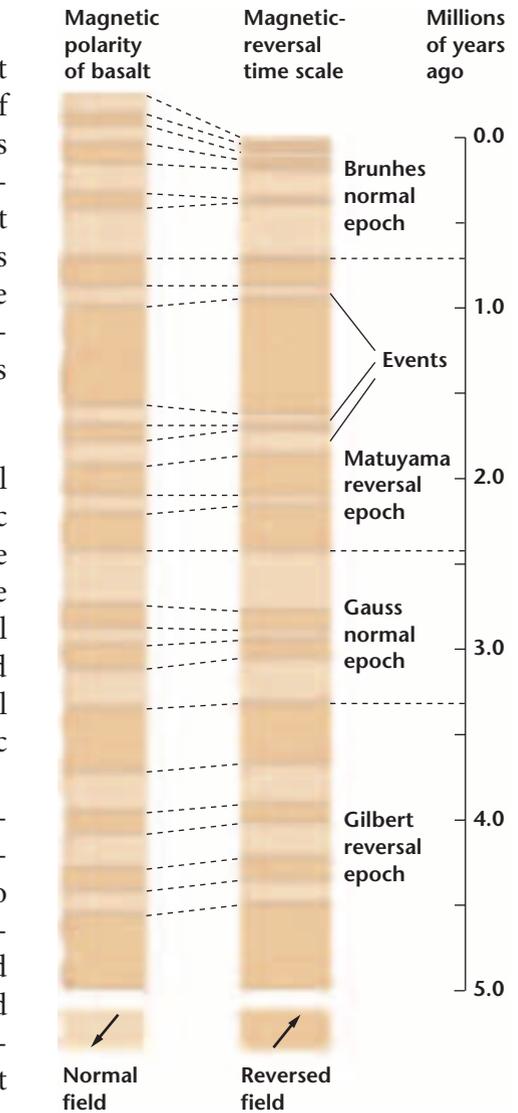
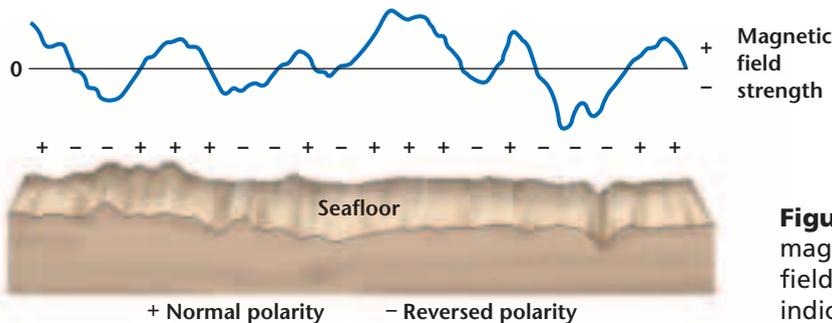
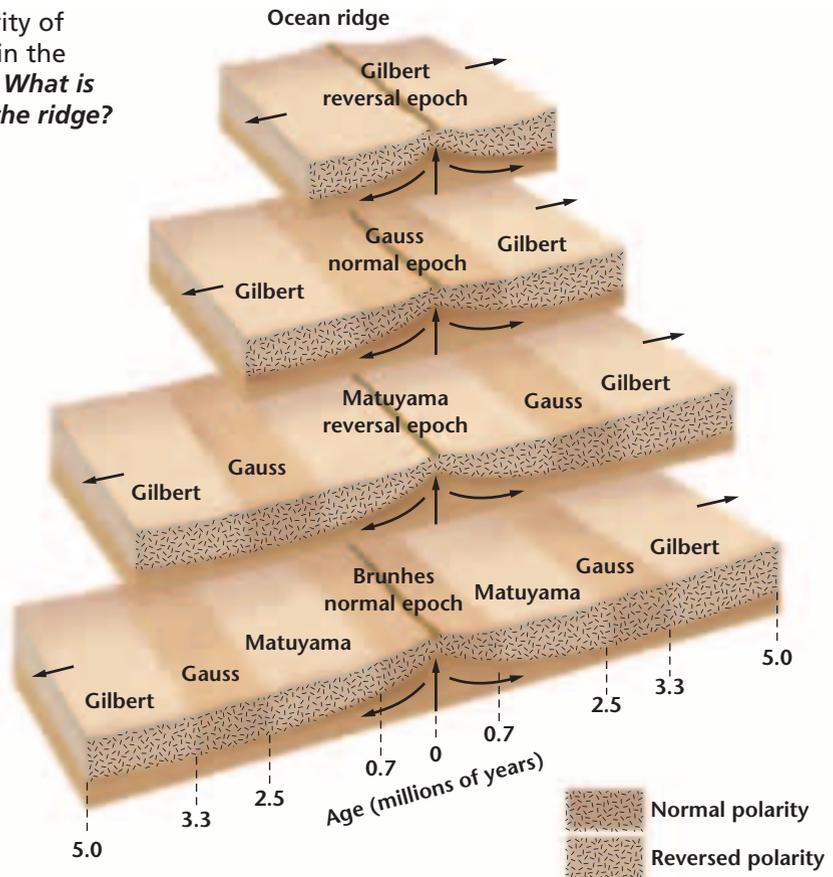


Figure 17-8 Continental basalt flows were used to construct the geomagnetic time scale. Long term changes in Earth's magnetic field are called epochs. Short term changes are called events.

Figure 17-9 A stronger-than-normal magnetic reading (+) indicates a normal field. A weaker-than-usual reading (-) indicates a field with reversed polarity.

Figure 17-10 Reversals in the polarity of Earth's magnetic field are recorded in the rocks that make up the ocean floor. *What is the polarity of the rocks closest to the ridge?*



Using Math

Using Numbers
 Refer to *Figure 17-8*. What is the average time interval between reversals? Over the last 4.5 million years, how many years has the field experienced reversed polarity? Normal polarity? What is the percentage of the total time spent in each orientation?

Magnetic Symmetry As more data were collected, scientists noticed that the positive and negative areas formed a series of stripes that were parallel to ocean ridges. Compare the magnetic pattern on opposite sides of the ocean ridge shown in *Figure 17-10*. How would you describe this pattern? The magnetic pattern on one side of the ridge is a mirror image of the pattern on the other side of the ridge.

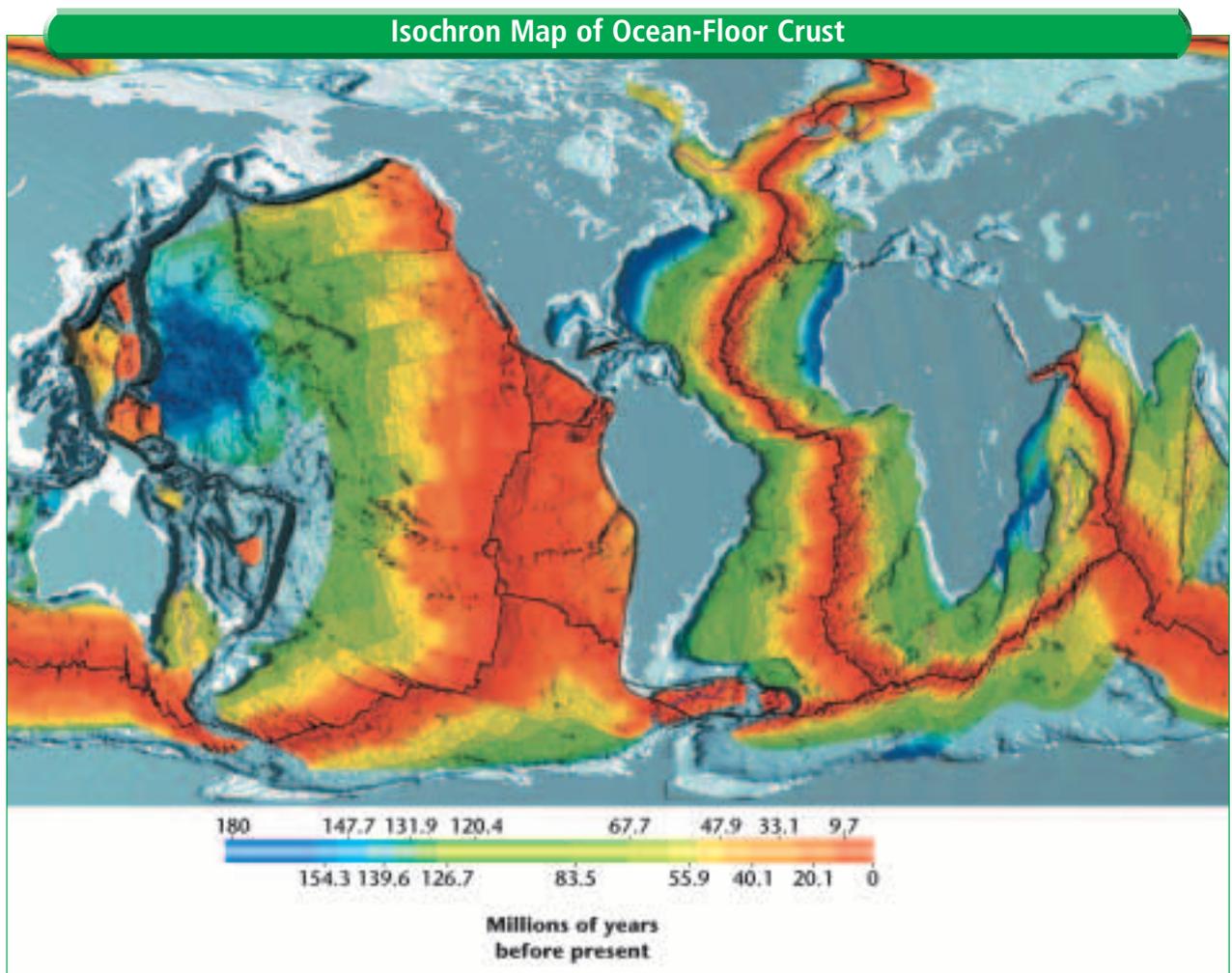
As scientists sought to explain these parallel stripes, they made another important discovery. The magnetic data collected from the ocean floor, shown in *Figure 17-10*, matched the pattern of magnetic reversals that had been found in basalt flows on land, which is shown in *Figure 17-8*. By matching the patterns on the seafloor with the known pattern of reversals on land, scientists were able to determine the age of the ocean floor from a magnetic recording. This method enabled scientists to quickly create isochron maps of the ocean floor. An **isochron** is a line on a map that connects points that have the same age. In the isochron map shown in *Figure 17-11*, note that relatively young ocean-floor crust is near ocean ridges, while older ocean crust is found along deep-sea trenches. You will generate and analyze an isochron map of a part of the seafloor in the *Mapping GeoLab* at the end of this chapter.



SEAFLOOR SPREADING

Once scientists had compiled all the topographic, sedimentary, age, and magnetic data from the seafloor, an American scientist named Harry Hess proposed a theory that could explain their observations. This theory, called **seafloor spreading**, states that new ocean crust is formed at ocean ridges and destroyed at deep-sea trenches. What actually happens during seafloor spreading? Magma, because it is hotter and less dense than surrounding mantle material, is forced toward the crust along an ocean ridge and fills the gap that is created as shown in *Figure 17-12A*, on page 454. When the magma hardens, a small amount of new ocean floor is added to Earth's surface, as illustrated in *Figure 17-12B*. As spreading along a ridge continues, more magma is forced upward and hardens. Each cycle of spreading and the intrusion of magma results in the formation of another small section of ocean floor, which slowly moves away from the ridge, as shown in *Figure 17-12C*.

Figure 17-11 Each colored band on this isochron map of the ocean floor represents the age of that strip of the crust. *What pattern do you observe?*



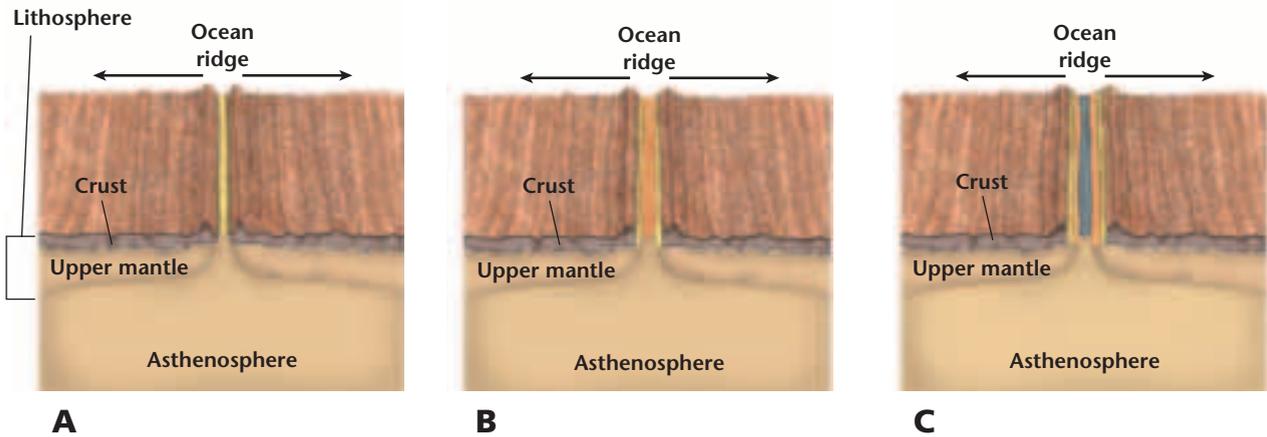


Figure 17-12

Magma that forms in the asthenosphere intrudes into the ocean floor along a ridge and fills the gap that is created **(A)**. When the molten material solidifies, new ocean crust is formed **(B)**. This continuous intrusion and consequent spreading results in the addition of more crust to the ocean floor **(C)**.

The Missing Link Seafloor spreading was the missing link needed by Wegener to complete his model of continental drift. Recall that while Wegener compiled many data to support his idea that the continents are drifting across Earth's surface, he could not explain what caused the landmasses to move or how they moved. Seafloor spreading provides the answer to the *how* question. Continents are not pushing through ocean crust, as Wegener proposed; they are merely passengers that ride with ocean crust as it slowly moves away from ocean ridges. In the next section, you will learn what causes slabs of Earth's crust and rigid upper mantle to move.

SECTION ASSESSMENT

- How do ocean ridges and deep-sea trenches support the theory of seafloor spreading?
- Explain how ocean-floor rocks and sediments are evidence of seafloor spreading.
- Compare and contrast normal magnetic polarity and reversed magnetic polarity.
- Explain how an isochron map of the ocean floor supports the theory of seafloor spreading.
- Thinking Critically** Refer to *Figure 17-11*. Why are the magnetic bands in the eastern Pacific Ocean so far apart compared to the magnetic bands along the Mid-Atlantic Ridge?

SKILL REVIEW

- Concept Mapping** Make an events-chain concept map to show the sequence of steps involved in seafloor spreading. For more help, refer to the *Skill Handbook*.

Initiating event:

Magma forms.

↓ **Event 1:**

↓ **Event 2:**

↓ **Event 3:**

Have you ever wondered why some regions of Earth are dotted with many active volcanoes while other regions have none? Or why earthquakes occur more frequently in certain areas than in others? The answers to these and many other questions are explained by the **theory of plate tectonics**, which states that Earth's crust and rigid upper mantle are broken into enormous slabs called plates. There are a dozen or so major plates and several smaller ones, as shown in **Figure 17-13**. Refer to this figure as you read about tectonic plates. Tectonic plates move in different directions and at different rates over Earth's surface. Rates of movement have been measured with the use of a sophisticated system of receivers and satellites that you'll learn about in the *Science & Technology* feature at the end of this chapter.

PLATE BOUNDARIES

Tectonic plates interact at places called plate boundaries. At some boundaries, plates come together, or converge. At others, plates move away from one another, or diverge. At the third type of boundary, plates move horizontally past one another. Each type of boundary has certain geologic characteristics and processes associated with it.

OBJECTIVES

- **Explain** the theory of plate tectonics.
- **Compare and contrast** the three types of plate boundaries and the features associated with each.

VOCABULARY

theory of plate tectonics
divergent boundary
rift valley
convergent boundary
subduction
transform boundary

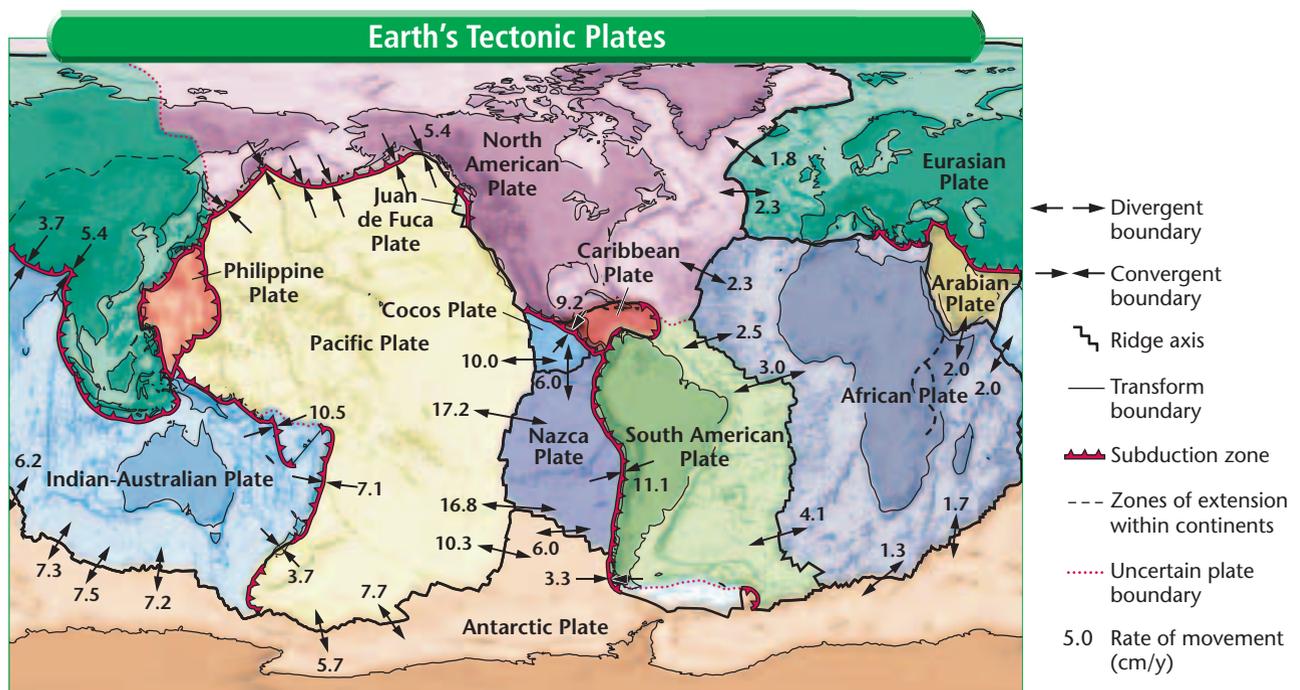


Figure 17-13 Earth's crust and rigid upper mantle are broken into enormous slabs called tectonic plates that interact at places called boundaries.

MiniLab

Model ocean-basin formation

Model the formation of the South Atlantic Ocean.

Procedure

1. Use a world map to create paper templates of South America and Africa.
2. Place the two continental templates in the center of a piece of 11" × 17" paper and fit them together along their Atlantic coastlines.
3. Carefully trace around the templates with a pencil. Remove the templates and label the diagram "150 million years ago."
4. Use an average spreading rate of 4 cm/y and a map scale of 1 cm = 500 km to create a series of maps that accurately show the development of the Atlantic Ocean at 30-million-year intervals, beginning 150 million years ago.

Analyze and Conclude

1. Compare your last map with a world map. Is the actual width of the South Atlantic Ocean the same on both maps?
2. What might have caused any difference between the width in your model and the actual width of the present South Atlantic Ocean?

Divergent Boundaries Places where two tectonic plates are moving apart are called **divergent boundaries**. Most divergent boundaries are found on the seafloor, where they form ocean ridges, as shown in *Figure 17-14*. The actual plate boundary is located in a rift, or fault-bounded valley, which forms along the axis of a ridge. It is in this central rift that the process of seafloor spreading begins. The formation of new ocean crust at most divergent boundaries accounts for the high heat flow, volcanism, and earthquakes associated with these boundaries.

Over millions of years, the process of seafloor spreading along a divergent boundary may cause an ocean basin to grow wider. Scientists have measured the rate of growth of the Atlantic Ocean at about 2 to 3 cm/y. How does this compare to the rate used in the *MiniLab* on this page? Can you explain the difference between the actual size of the Atlantic Ocean Basin and the size of the basin in your model?

Although most divergent boundaries form ridges on the ocean floor, some divergent boundaries form on continents. When continental crust begins to separate, the stretched crust forms a long, narrow depression called a **rift valley**. A rift valley is currently forming in East Africa. The rifting might eventually lead to the formation of a new ocean basin.

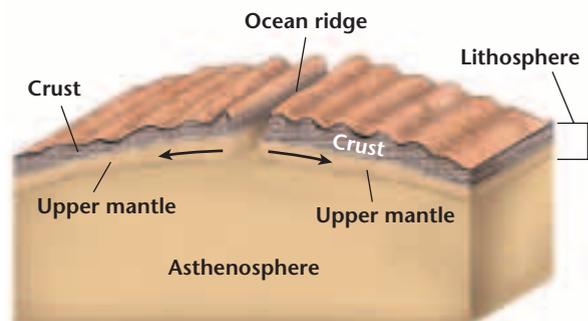


Figure 17-14 Divergent boundaries are places where plates separate. An ocean ridge is a divergent boundary on the ocean floor.

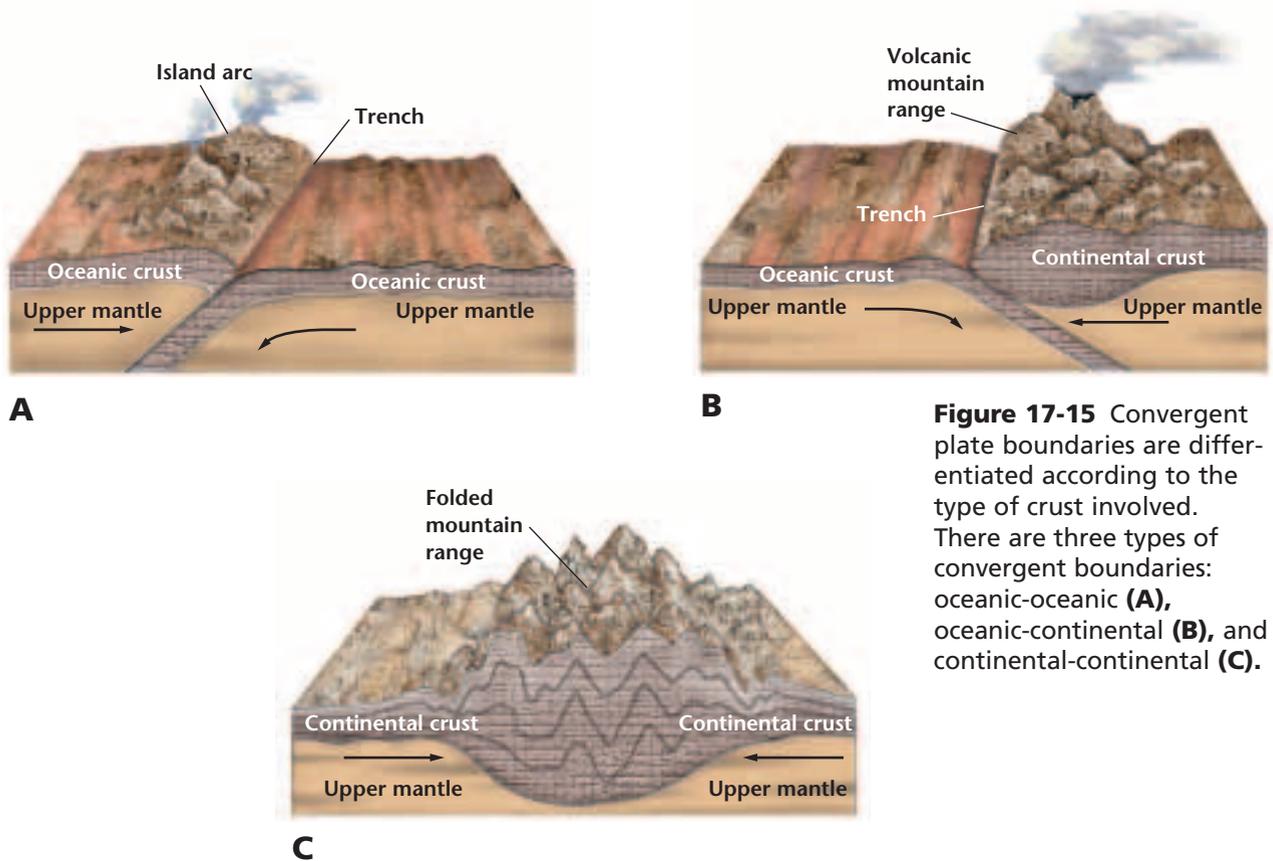


Figure 17-15 Convergent plate boundaries are differentiated according to the type of crust involved. There are three types of convergent boundaries: oceanic-oceanic (**A**), oceanic-continental (**B**), and continental-continental (**C**).

Convergent Boundaries Places where two tectonic plates are moving toward each other are **convergent boundaries**. There are three types of convergent boundaries, which are classified according to the type of crust involved. Recall from Chapter 1 that oceanic crust is made mostly of basalt. Continental crust is composed mostly of granite and sedimentary rocks, both of which are less dense than basalt. The three types of convergent boundaries are oceanic crust converging with oceanic crust, oceanic crust converging with continental crust, and continental crust converging and colliding with continental crust. These three types of tectonic boundaries are shown in *Figure 17-15*.

What is happening at the oceanic-oceanic boundary shown in *Figure 17-15A*? One of the two plates is descending beneath the other in a process called **subduction**. A subduction zone forms when one oceanic plate, which has become denser as a result of cooling, descends below another plate. The process of subduction creates a deep-sea trench. The subducted plate descends into the mantle and melts, thereby recycling the oceanic crust formed at the ridge. Some of the magma that forms is forced back to the surface, erupts, and forms an arc of volcanic islands that parallel the trench.



Figure 17-16 Mt. Cleveland is a volcano in Alaska that formed as the result of convergence along an oceanic-oceanic boundary.

Some examples of trenches and island arcs are the Mariana Trench and Mariana Islands in the West Pacific Ocean and the Aleutian Trench and Aleutian Islands in the North Pacific Ocean. A volcanic peak in the Aleutian Islands is shown in **Figure 17-16**.

Subduction also occurs when an oceanic plate converges with a continental plate, as you can see in **Figure 17-15B**. Note that the denser oceanic plate is subducted. Oceanic-continental convergence also produces a trench and volcanic arc. However, instead of an arc of volcanic islands forming, as in oceanic-oceanic plate convergence, a series of volcanoes erupt along the edge of the continental plate. The result of this type of subduction is a mountain

range with many volcanoes. The Peru-Chile Trench and the Andes Mountains, which are located along the western coast of South America, formed in this way.

The third type of convergent boundary forms when two continental plates collide. This convergent boundary forms when an ocean basin between converging oceanic and continental plates is

Problem-Solving Lab

Interpreting Scientific Illustrations

Determine how plate motions change along a transform boundary The figure at right shows the Gibbs Fracture Zone, which is a segment of the Mid-Atlantic Ridge located south of Iceland and west of the British Isles. Copy this figure.

Analysis

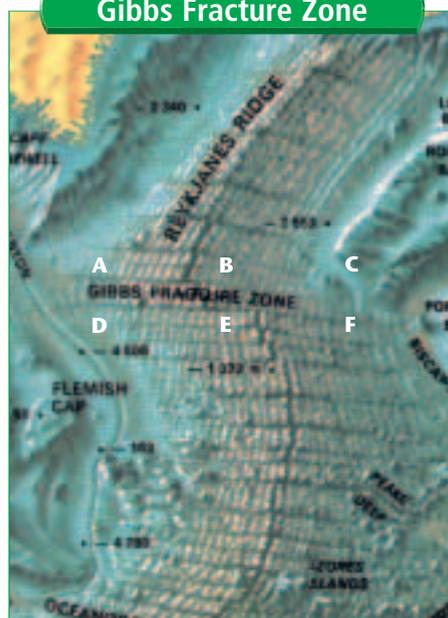
1. In what direction is the seafloor moving at each location? Draw arrows on your copy to indicate these directions at each location.
2. Compare the direction of motion for the following pairs

of locations: A and D, B and E, and C and F.

Thinking Critically

3. Which locations are on the North American Plate?
4. Which portion of the fracture zone is the boundary between North America and Europe?
5. At which location is the oldest crust located?

Gibbs Fracture Zone



entirely subducted. One continent is pulled into the subduction zone, but it can't be subducted because continental rocks are too buoyant to be forced into the mantle. As a result, the colliding edges of the continents are crumpled and uplifted to form a mountain range, as shown in *Figure 17-15C*. The Himalayas formed in this way.

Transform Boundaries A place where two plates slide horizontally past each other, as shown in *Figure 17-17*, is a **transform boundary**. How does this type of boundary compare to divergent and convergent boundaries? Along divergent boundaries, new crust is formed at ridges, and at convergent boundaries, old crust is destroyed by subduction. At transform boundaries, however, crust is only deformed or fractured. Transform boundaries are characterized by long faults, sometimes hundreds of kilometers in length, and by shallow earthquakes. Most transform boundaries offset sections of ocean ridges, as you observed in the *Problem-Solving Lab* on the previous page. Rarely do transform boundaries occur on continents. The San Andreas Fault is probably the best-known exception. Recall from the *Discovery Lab* at the beginning of this chapter that the San Andreas Fault system separates southwestern California from the rest of the state. Movements along this transform fault system are responsible for most of the earthquakes that strike California every year.

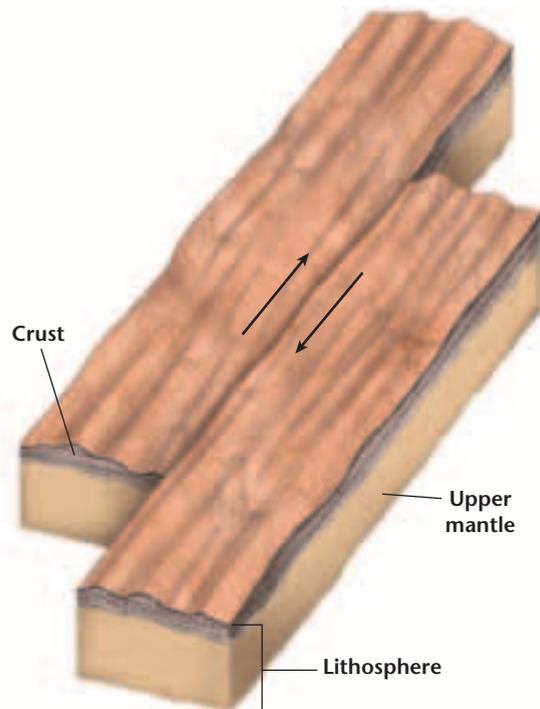


Figure 17-17 Plates move horizontally past each other along a transform plate boundary.

SECTION ASSESSMENT

1. Explain the theory of plate tectonics.
2. Explain what happens at the three types of plate boundaries.
3. What geologic features are associated with each type of convergent boundary?
4. Where do transform boundaries most commonly occur?
5. **Thinking Critically** Transform boundaries change, or transform, the relative movement of the plates involved. Describe how

newly formed crust moves between parts of a ridge that are offset by a transform boundary.

SKILL REVIEW

6. **Making and Using Tables** Make a table that summarizes the features associated with each type of plate boundary. For more help, refer to the *Skill Handbook*.

OBJECTIVES

- **Explain** the process of convection.
- **Summarize** how convection in the mantle is related to the movements of tectonic plates.
- **Compare and contrast** the processes of ridge push and slab pull.

VOCABULARY

ridge push
slab pull

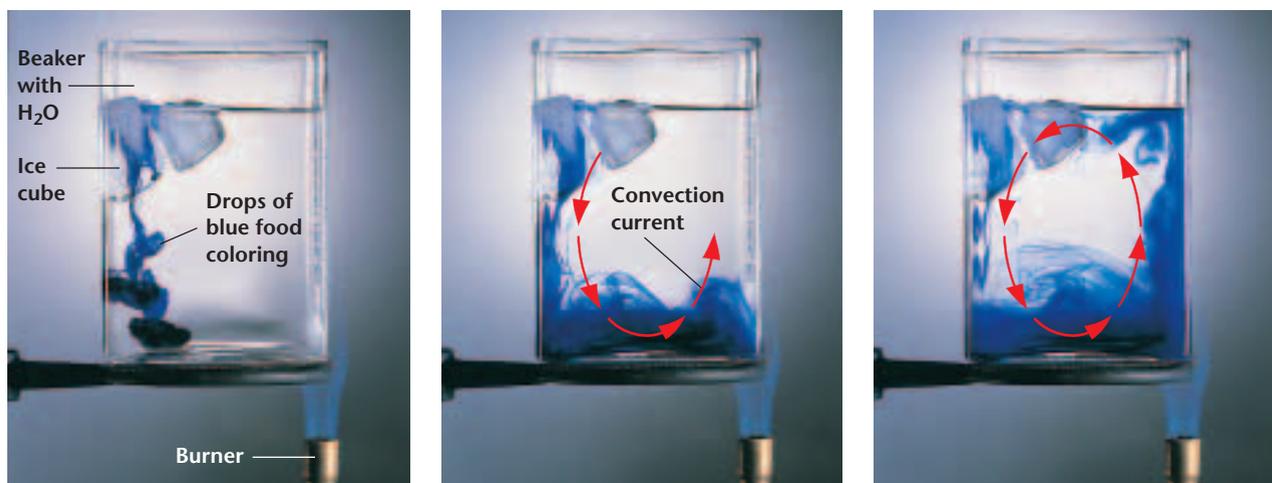
Today, plate tectonics is no longer in question. The directions and rates of plate movements have been measured. One of the main questions about the theory of plate tectonics, however, has remained unanswered ever since Alfred Wegener first proposed continental drift. What force or forces cause tectonic plates to move? Even today, what actually causes the plates to move is not well understood. One of the leading hypotheses proposes that large-scale motion in the mantle is the mechanism that drives the movement of tectonic plates.

MANTLE CONVECTION

Recall from Chapter 11 that the transfer of thermal energy by the movement of heated matter is called convection. The heating of matter causes it to expand and to decrease in density. The warmed matter then rises as a result of buoyancy. The cooler part of the matter sinks as a result of gravity. This up-and-down flow produces a pattern of motion called a convection current. Convection currents aid in the transfer of thermal energy from the warmer regions of matter to cooler regions. A convection current can be observed in the series of photographs shown in *Figure 17-18*.

Convection currents in the mantle are thought to be the driving mechanism of plate movements. Recall that even though the mantle is a solid, part of it, the asthenosphere, can flow like a soft, pliable plastic. Convection currents in this part of the mantle are set in motion by the transfer of energy between Earth's hot interior and its cooler exterior. Hot mantle material is less dense than cooler mantle

Figure 17-18 Convection currents transfer thermal energy in unequally heated matter.



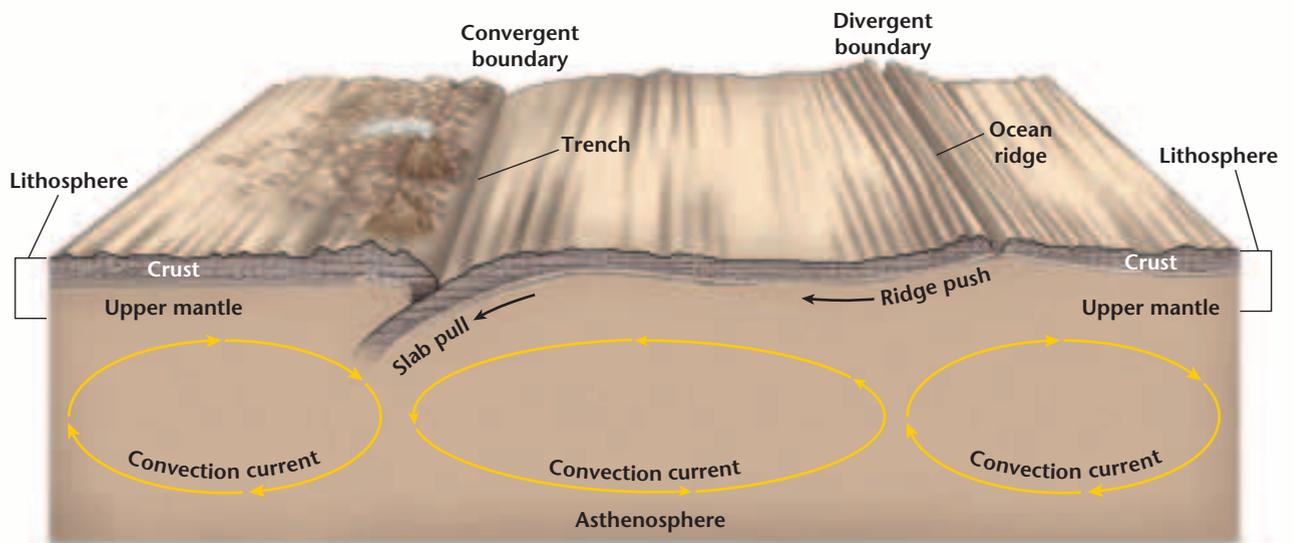


Figure 17-19 Ridge push and slab pull are tectonic processes associated with convection currents in the mantle.

material and, thus, the hot material is slowly forced toward the crust. Cooler parts of this material sink back toward the core. The convection currents that result can be thousands of kilometers across but flow at rates of only a few centimeters per year. Scientists hypothesize that these convection currents are probably set in motion by subducting slabs, thus causing plates to move.

How are convergent and divergent movements related to the flow direction of mantle convection? The rising part of a convection current spreads out as it reaches the upper mantle and causes both upward and lateral forces. These forces lift and split the lithosphere at divergent plate boundaries. As the plates separate, material rising from the mantle supplies the magma that hardens to form new ocean crust. The downward part of a convection current occurs where a sinking force pulls tectonic plates downward at convergent boundaries.

Push and Pull Exactly how is mantle convection related to the movements of tectonic plates? Scientists hypothesize that there are several processes involved. Study *Figure 17-19*. During the formation of an ocean ridge, forces in the mantle cause the asthenosphere to rise. The weight of the uplifted ridge is thought to push an oceanic plate toward the trench formed at the subduction zone in a process called **ridge push** as shown in *Figure 17-19*. In addition to ridge push, the horizontal flow at the top of a convection current could create drag on the lithosphere and thereby contribute to plate motion.

A combination of mechanisms may be involved in plate motions at subduction zones as well. A sinking region of a mantle convection current could suck an oceanic plate downward into a subduction zone. The weight of a subducting plate helps pull the trailing lithosphere into the subduction zone in a process called **slab pull**, as shown in *Figure 17-19*.

Unanswered Questions While most scientists agree that convection currents in the mantle are related to the movement of tectonic plates, there are still unanswered questions about how these currents originate and what their actual sizes are. Are mantle convection currents permanent features? Do they shift their positions through geologic time? How does a convection current start? What causes the movement of a convection current to stop? Is convection taking place only in the upper mantle? Or, do these enormous convection currents include the lower mantle? *Figure 17-20* shows an image of the mantle 2700 km below Earth's surface that was generated from earthquake data. This image suggests that the convection currents associated with plate movements might include the lower mantle. Some geologists working in this branch of Earth science have even suggested that subducted slabs, over time, might eventually reach Earth's outer core.

Other remaining questions concern relationships between convection currents and the overlying plates. For example, does downward convection cause a subduction zone, or does the process of subduction create the convection current? Most studies show that the process of slab pull is the most important force driving tectonic plate motions.

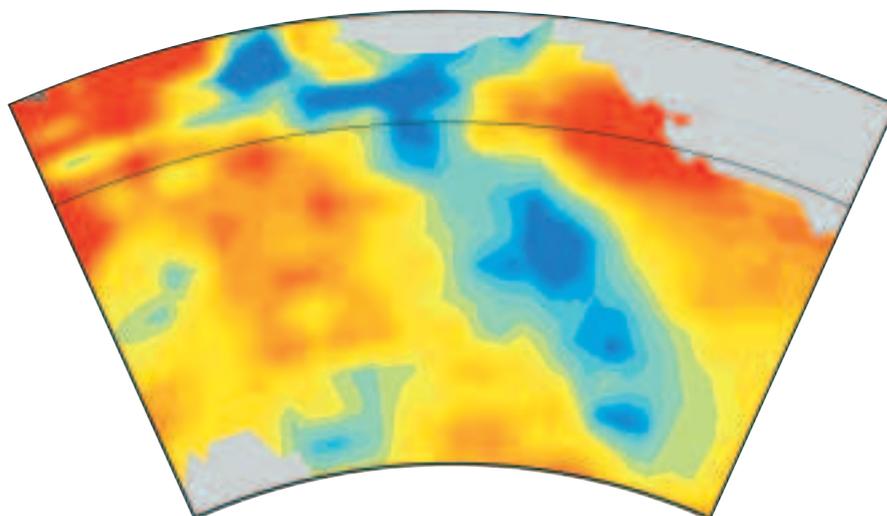


Figure 17-20 This is an image of Earth's mantle under the southern United States. The image was generated using the travel times of earthquake waves. The elongated blue feature is an area of the mantle where subduction is thought to have occurred in the past.



Figure 17-21 Spreading in the Great Rift Valley of East Africa, shown here, is related to convection currents in Earth's mantle.

A similar set of questions surround the formation of divergent plate boundaries. The Great Rift Valley, in Africa, part of which is shown in *Figure 17-21*, is evidence that a divergent boundary can develop on a continent. But what causes an upward convection current to form beneath a continent? One hypothesis is that large continental masses ultimately cause their own breakup by acting as insulating blankets. The underlying mantle then becomes warmer and causes the upward leg of a convection current to develop, which eventually causes the continent to split.

The questions presented here are just some of those that geologists hope to answer in the future. What questions do you have about what causes Earth's crust and rigid upper mantle to slowly but continuously change over geologic time?

SECTION ASSESSMENT

1. Make and label a diagram that explains the process of convection.
2. What are the relationships among mantle convection, ocean ridges, and subduction zones?
3. Hypothesize what might happen to mantle convection currents beneath a continental-continental convergent boundary.
4. How have earthquake data been used to explore the size of convection currents in the mantle?
5. **Thinking Critically** If a subducting slab is pulling the lithosphere into the mantle and a continent is pulled into the subduction zone, what do you think might happen?

SKILL REVIEW

6. **Making Diagrams** Make a diagram that contrasts the tectonic processes of ridge push and slab pull. Include captions in your diagram. For more help, refer to the *Skill Handbook*.

Making a Paleomagnetic Map

Iron-bearing minerals in rocks record the orientation of Earth's magnetic field at the time of their formation. These preserved magnetic alignments in ocean-floor rocks can be used to date different parts of the seafloor and to determine rates of spreading along divergent plate margins.

Preparation

Problem

How can you use paleomagnetic data to interpret information about ocean-floor rocks?

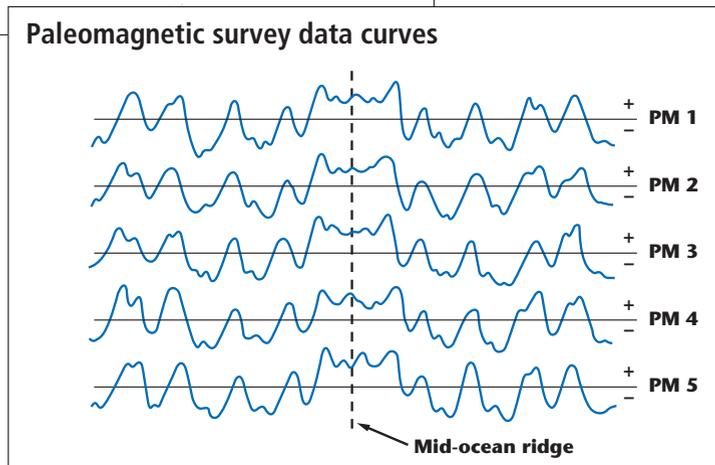
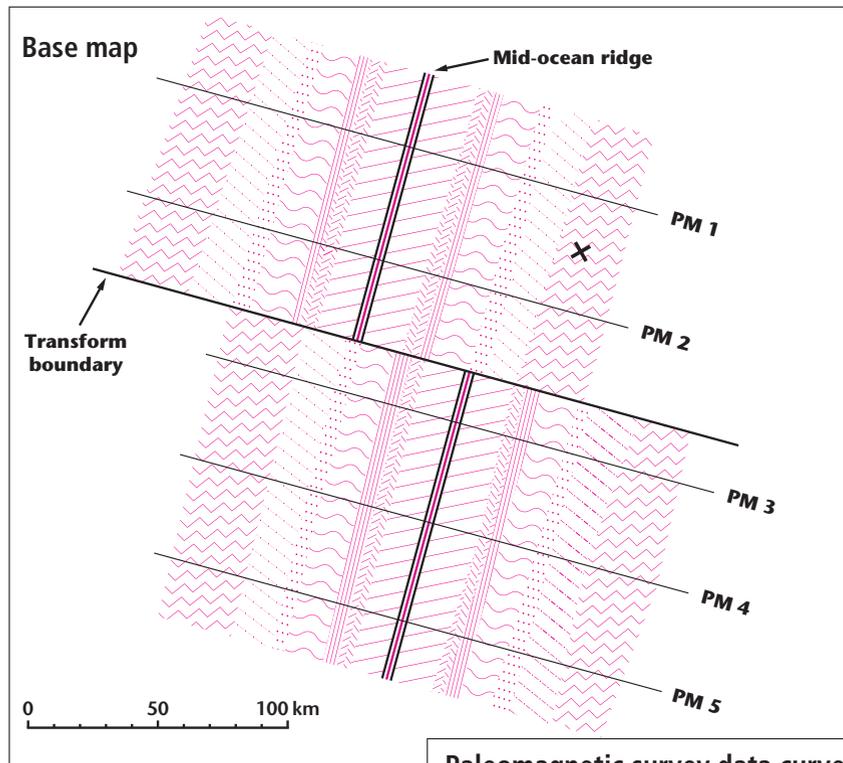
Materials

tracing paper
metric ruler
No. 2 pencil

colored pencils
Figure 17-8

Procedure

1. Use the tracing paper and the No. 2 pencil to carefully copy the base map on the following page. Be sure to include the magnetic survey lines, the map scale, and the location indicated by the letter *X* on your tracing.
2. Transfer the magnetic survey data from PM1 to your tracing by placing the survey line on your map over the PM1 data curve on the following page. Be sure to align the mid-ocean ridge with the dashed line before you begin transferring the line. Label the line.
3. Repeat step 2 for the other four lines.
4. Next, use your ruler to draw a series of parallel lines between PM1 and PM2 to connect the corresponding positive and negative magnetic reversals. Draw the lines past PM2, but stop the lines at the transform boundary.
5. Draw another series of lines between survey lines PM3 and PM4 and between PM4 and PM5. Again, end these lines at the transform boundary.
6. The positive magnetic reading along the mid-ocean ridge represents the Brunhes Magnetic Epoch. The first negative anomaly on either side of the ridge marks the beginning of the Matuyama Magnetic Epoch. Use *Figure 17-8* to identify the magnetic reversals.
7. Assign a color for each magnetic reversal. Then, color the corresponding stripe on each side of the ridge.



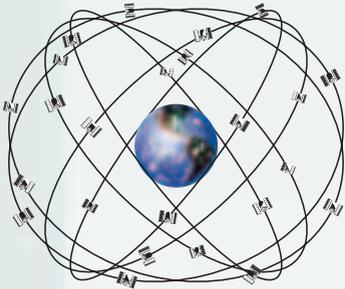
Analyze

1. Why was it necessary to color corresponding stripes on each side of the ridge in step 7?
2. Use *Figure 17-8* to determine the age of the seafloor at location X.

Conclude & Apply

1. What might cause an individual magnetic stripe of ocean-floor crust to vary in width?
2. What is the average spreading rate along this section of the mid-ocean ridge?

The Global Positioning System



An ambulance driver speeds toward the location of someone having a heart attack. A hiker in unfamiliar territory successfully returns to her campsite. The driver of an armored vehicle transports hundreds of thousands of dollars from businesses to a local bank. What do these people have in common? Each of them is likely to be navigating using a system of satellites currently in orbit around Earth, a system that most people aren't even aware exists.

The Global Positioning System, or GPS, was developed by the United States Department of Defense to track tanks, planes, and ships. Twenty-four satellites, roughly 20 000 km above Earth, are part of this system, each circling on a different orbital path about once every 12 hours. The number of satellites, their distances from Earth, and their orbital periods make the GPS incredibly accurate and essentially give every square meter on our planet a unique address.

How does this system work? A receiver on Earth picks up signals coming from at least three or four satellites in space. The time it takes for the signals to travel from the satellites to the receiver can be used to calculate the latitude, longitude, and elevation of the location of the receiver.

Everyday Uses

The development of the GPS forever changed navigation and mapping. While this system is still operated by the military, there are thousands of civilian users all over the world. Fire, police, and rescue departments, public transportation systems, long-haul trucking companies, taxi services, and fishing fleets all use the GPS to keep drivers and passengers safe, to navigate in unfamiliar territory, and to protect expensive cargo from theft or loss. Hand-held GPS receivers are also used by hikers, hunters, drivers, and boaters.

Scientific Uses

In addition to its everyday uses, the GPS is a valuable tool for collecting information about Earth's surface. Scientists use the GPS to map volcanic regions, where temperature extremes and steep, rocky slopes make it very difficult to use traditional mapping systems. The GPS is also useful in determining sites for nuclear power plants and radioactive waste disposal sites, facilities that must be constructed in areas that are relatively inactive geologically.

The pinpoint accuracy of the GPS has also allowed geophysicists to measure how tectonic plates move in relation to each other over time. For example, the expansion of Iceland, which sits astride the Mid-Atlantic Ridge, is taking place at about 12 mm/year. This rate of movement would have been impossible to measure without the use of the GPS.

Internet

Go to the Earth Science Web Site at earthgeu.com to find out how the GPS has been used to help predict earthquakes that occur along the transform boundary called the San Andreas Fault.

CHAPTER 17 Study Guide

Summary

SECTION 17.1

Drifting Continents



Main Ideas

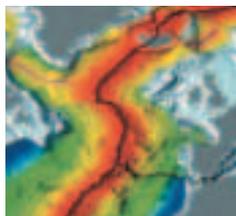
- The matching coastlines of continents on opposite sides of the Atlantic Ocean suggest that the continents were once joined.
- Continental drift states that Earth's continents were joined as a single landmass that broke apart and sent the continents adrift.
- Wegener supported his hypothesis of continental drift with rock types, fossils, and ancient climatic data. His hypothesis was not accepted at first because he couldn't explain how the continents moved or what caused their motion.

Vocabulary

continental drift (p. 444)
Pangaea (p. 444)

SECTION 17.2

Seafloor Spreading



Main Ideas

- Sonar and magnetic studies of ocean rocks and sediments led to the proposal of the theory of seafloor spreading.
- Magnetic patterns on the seafloor are symmetric in relation to ocean ridges, indicating that ocean crust on either side of the ridge is moving away from the ridge at essentially the same rate.
- During seafloor spreading, magma rises and hardens to form new crust, which becomes part of the ocean floor. Each cycle of spreading and intrusion results in the formation of another small section of ocean floor, which slowly moves away from the ridge.

Vocabulary

isochron (p. 452)
magnetic reversal (p. 451)
magnetometer (p. 448)
paleomagnetism (p. 451)
seafloor spreading (p. 453)

SECTION 17.3

Theory of Plate Tectonics



Main Ideas

- Plate tectonics states that Earth's crust and rigid upper mantle are broken into large slabs of rock called plates, which move in different directions and at different rates over Earth's surface.
- At divergent plate boundaries, plates move apart. At convergent boundaries, plates come together. At transform boundaries, plates slide horizontally past each other.
- High heat flow, volcanism, and earthquakes are associated with divergent boundaries; trenches, island arcs, and folded mountains with convergent boundaries; and faults and earthquakes with transform boundaries.

Vocabulary

convergent boundary (p. 457)
divergent boundary (p. 456)
rift valley (p. 456)
subduction (p. 457)
theory of plate tectonics (p. 455)
transform boundary (p. 459)

SECTION 17.4

Causes of Plate Motions



Main Ideas

- Convection is the transfer of energy via the movement of heated matter. Convection currents in the mantle are the result of energy transfer between Earth's hot interior and cooler exterior.
- Ridge push occurs when the elevation of a ridge pushes a plate toward a subduction zone. Slab pull occurs as the weight of the subducting plate pulls a plate into a subduction zone.

Vocabulary

ridge push (p. 461)
slab pull (p. 462)



CHAPTER 17 Assessment

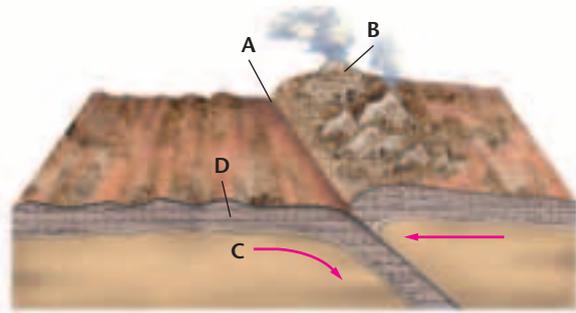
Understanding Main Ideas

1. What was Wegener's hypothesis called?
 - a. seafloor spreading
 - b. plate tectonics
 - c. continental drift
 - d. slab pull
2. The fit of the coastlines of which of the following continents led people to suggest that the continents had drifted over time?
 - a. North and South America
 - b. North America and Africa
 - c. South America and Africa
 - d. Europe and North America
3. Which of the following evidence was used by Wegener to support his hypothesis that the continents had once been joined?
 - a. rock types and ages
 - b. plate tectonics
 - c. slab pull and ridge push
 - d. fossils of ocean plants
4. Which of the following was NOT used by Wegener to support his hypothesis of continental drift?
 - a. fossils of land-dwelling animals
 - b. paleomagnetic data
 - c. coal beds in Antarctica
 - d. glacial deposits
5. Why was the hypothesis of continental drift rejected when it was proposed by Wegener?
 - a. Wegener thought that the south pole had changed location.
 - b. Wegener thought that Earth's rotation was the driving force.
 - c. Wegener couldn't explain how or why continents moved.
 - d. Wegener died in Greenland in 1930.
6. How did the use of sonar change scientists' ideas about ocean-floor topography?

7. Explain how sediments on the ocean floor vary in relation to an ocean ridge.
8. Differentiate among the following terms: *magnetic reversal*, *reversed field*, and *normal field*.
9. Explain the theory of plate tectonics.
10. Compare and contrast the three types of convergent plate boundaries.

Applying Main Ideas

Use the diagram below to answer questions 11, 12, and 13.



11. What type of boundary is shown?
12. Copy the figure and identify the features labeled A, B, C, and D.
13. Use arrows to label the directions of plate movements.
14. The Andes Mountains are tectonically active. What type of plate boundary is involved in their continued formation?

Test-Taking Tip

READ QUESTIONS CAREFULLY Watch the little words. Underline words like *least*, *not*, *except*, and *but* when you see them in test questions. They change the meaning of the question!

CHAPTER 17

Assessment

15. Explain the relationship among an ocean ridge, a rift, and a divergent plate boundary.
16. Explain how movements at divergent and convergent plate boundaries are related to flow direction of mantle convection currents.

Use **Figure 17-8** on page 451 to answer questions 17, 18, and 19.

17. Which is longer, an event or an epoch?
18. How long did the Gauss Epoch last?
19. How many reversals occurred in the Gilbert Epoch? How many normal events occurred during this epoch?
20. Why did the idea of continental drift become more accepted after seafloor spreading was proposed?
21. Explain what causes the paleomagnetic patterns on the seafloor.
22. Refer to **Figure 17-13** on page 455. Find and identify a place where the Mid-Atlantic Ridge surfaces.
23. Study the rates of plate motions shown in **Figure 17-13** on page 455. How far has the island of Hawaii moved since you were born?

Thinking Critically

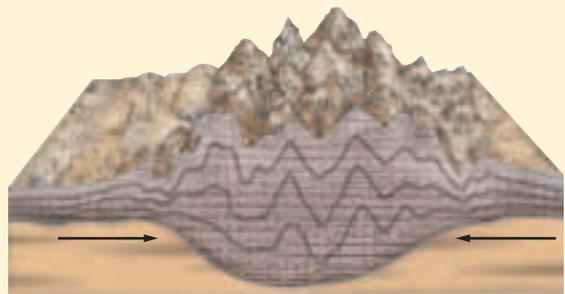
24. Locate Africa in **Figure 17-13** on page 455. Identify the major plate boundaries affecting this continent. In which direction is Africa moving in relation to these boundaries?
25. What might cause corresponding magnetic stripes of ocean-floor crust to have different widths?
26. Why do you think earthquakes are common along plate boundaries?
27. Most earthquakes associated with convergent boundaries originate much deeper than earthquakes associated with divergent boundaries. Explain.

Standardized Test Practice

1. Which piece of evidence did NOT advance the hypothesis of continental drift?
 - a. similar rock types on different continents
 - b. crustal rock on the ocean floor
 - c. similar fossils on different continents
 - d. coal beds in Antarctica

INTERPRETING SCIENTIFIC ILLUSTRATIONS

Use the diagram to answer questions 2–3.



2. What type of plate boundary is shown?
 - a. an ocean ridge
 - b. a continental-continental boundary
 - c. a transform boundary
 - d. an oceanic-continental boundary
3. Which of the following features forms along this type of boundary?
 - a. subduction zones
 - b. oceanic trenches
 - c. island arcs
 - d. folded mountains
4. The weight of a subducting plate helps pull the trailing lithosphere into a subduction zone in which of the following processes?
 - a. slab pull
 - b. ridge pull
 - c. slab push
 - d. ridge push