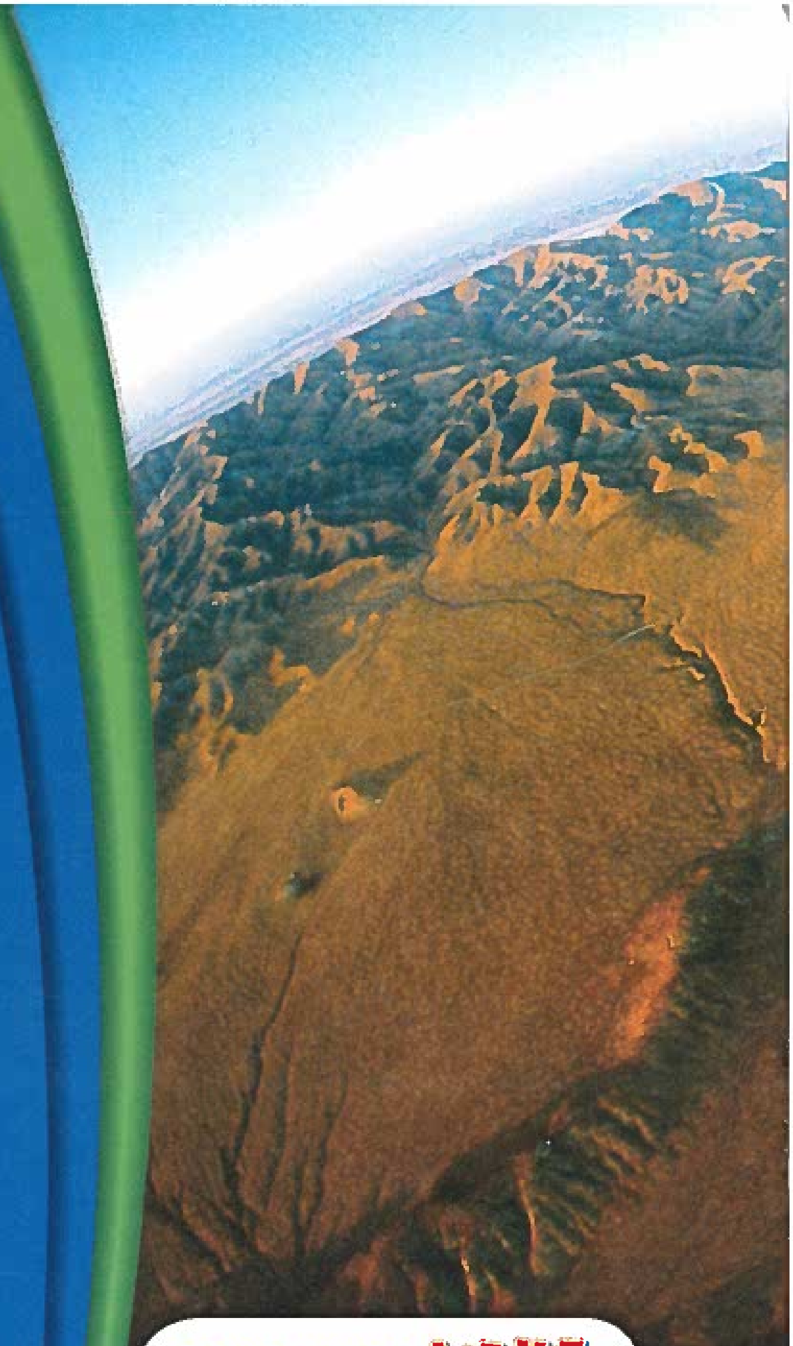
4

Plate Tectonics

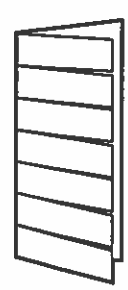


About the PHOTO

The San Andreas fault stretches across the California landscape like a giant wound. The fault, which is 1,000 km long, breaks the Earth's crust from Northern California to Mexico. Because the North American plate and Pacific plate are slipping past one another along the fault, many earthquakes happen.

PRE-READING ACTIVITY

Key-Term Fold Before you read the chapter, create the FoldNote entitled "Key-Term Fold" described in the **Study Skills** section of the Appendix. Write a key term from the chapter on each tab of the key-term fold. Under each tab, write the definition of the key term.



People in Science

Lizzie May

Amateur Paleontologist For Lizzie May, summer vacations have meant trips into the Alaskan wilderness with her stepfather, geologist/paleontologist Kevin May. The purpose of these trips has not been for fun. Instead, Kevin and Lizzie have been exploring the Alaskan wilderness for the remains of ancient life—dinosaurs, in particular.

At age 18, Lizzie May has gained the reputation of being Alaska's most famous teenage paleontologist. It is a reputation that is well deserved. To date, Lizzie has collected hundreds of dinosaur bones and located important sites of dinosaur, bird, and mammal tracks. In her honor and as a result of her hard work in the field, scientists named the skeleton of a dinosaur discovered by the Mays "Lizzie." "Lizzie" is a duckbill dinosaur, or hadrosaur, that lived approximately 90 million years ago. "Lizzie" is the oldest dinosaur ever found in Alaska and one of the earliest known duckbill dinosaurs in North America.

The Mays have made other, equally exciting discoveries. On one summer trip, Kevin and Lizzie located six dinosaur and bird track sites that dated back 97 million to 144 million years. On another trip, the Mays found a fossil marine reptile more than 200 million years old—an ichthyosaur—that had to be removed with the help of a military helicopter. You have to wonder what other exciting adventures are in store for Lizzie and Kevin!

Social Studies ACTIVITY

WRITING SKILL Lizzie May is not the only young person to have made a mark in dinosaur paleontology. Using the Internet or another source, research people such as Bucky Derflinger, Johnny Maurice, Brad Riney, and Wendy Sloboda, who as young people made contributions to the field of dinosaur study. Write a short essay summarizing your findings.

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START-UP ACTIVITY

Continental Collisions

As you can see, continents not only move but can also crash into each other. In this activity, you will model the collision of two continents.

Procedure

1. Obtain **two stacks of paper** that are each about 1 cm thick.
2. Place the two stacks of paper on a **flat surface,** such as a desk.
3. Very slowly, push the stacks of paper together so that they collide. Continue to push the stacks until the paper in one of the stacks folds over.

Analysis

1. What happens to the stacks of paper when they collide with each other?
2. Are all of the pieces of paper pushed upward? If not, what happens to the pieces that are not pushed upward?
3. What type of landform will most likely result from this continental collision?

SECTION 1

Inside the Earth

If you tried to dig to the center of the Earth, what do you think you would find? Would the Earth be solid or hollow? Would it be made of the same material throughout?

READING WARM-UP

Objectives

- Identify the layers of the Earth by their composition.
- Identify the layers of the Earth by their physical properties.
- Describe a tectonic plate.
- Explain how scientists know about the structure of Earth's interior.

Terms to Learn

crust	asthenosphere
mantle	mesosphere
core	tectonic plate
lithosphere	

READING STRATEGY

Reading Organizer As you read this section, create an outline of the section. Use the headings from the section in your outline.

Actually, the Earth is made of several layers. Each layer is made of different materials that have different properties. Scientists think about physical layers in two ways—by their composition and by their physical properties.

The Composition of the Earth

The Earth is divided into three layers—the crust, the mantle, and the core—based on the compounds that make up each layer. A *compound* is a substance composed of two or more elements. The less dense compounds make up the crust and mantle, and the densest compounds make up the core. The layers form because heavier elements are pulled toward the center of the Earth by gravity, and elements of lesser mass are found farther from the center.

The Crust

The outermost layer of the Earth is the **crust.** The crust is 5 to 100 km thick. It is the thinnest layer of the Earth.

As **Figure 1** shows, there are two types of crust—continental and oceanic. Both continental crust and oceanic crust are made mainly of the elements oxygen, silicon, and aluminum. However, the denser oceanic crust has almost twice as much iron, calcium, and magnesium, which form minerals that are denser than those in the continental crust.

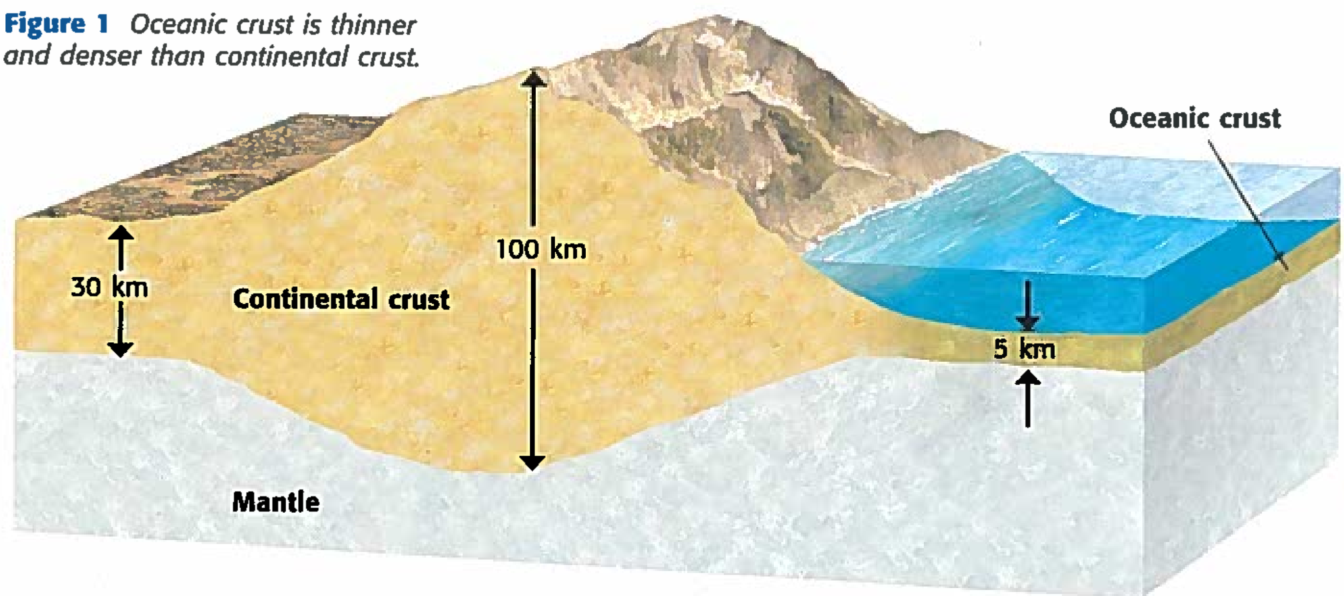


Figure 1 *Oceanic crust is thinner and denser than continental crust.*

The Mantle

The layer of the Earth between the crust and the core is the **mantle.** The mantle is much thicker than the crust and contains most of the Earth's mass.

No one has ever visited the mantle. The crust is too thick to drill through to reach the mantle. Scientists must draw conclusions about the composition and other physical properties of the mantle from observations made on the Earth's surface. In some places, mantle rock pushes to the surface, which allows scientists to study the rock directly.

As you can see in **Figure 2,** another place scientists look for clues about the mantle is the ocean floor. Magma from the mantle flows out of active volcanoes on the ocean floor. These underwater volcanoes have given scientists many clues about the composition of the mantle. Because the mantle has more magnesium and less aluminum and silicon than the crust does, the mantle is denser than the crust.

Figure 2 *Volcanic vents on the ocean floor, such as this vent off the coast of Hawaii, allow magma to rise up through the crust from the mantle.*

The Core

The layer of the Earth that extends from below the mantle to the center of the Earth is the **core.** Scientists think that the Earth's core is made mostly of iron and contains smaller amounts of nickel but almost no oxygen, silicon, aluminum, or magnesium. As shown in **Figure 3,** the core makes up roughly one-third of the Earth's mass.

crust the thin and solid outermost layer of the Earth above the mantle

mantle the layer of rock between the Earth's crust and core

core the central part of the Earth below the mantle

Reading Check **Briefly describe the layers that make up the Earth.** (*See the Appendix for answers to Reading Checks.*)

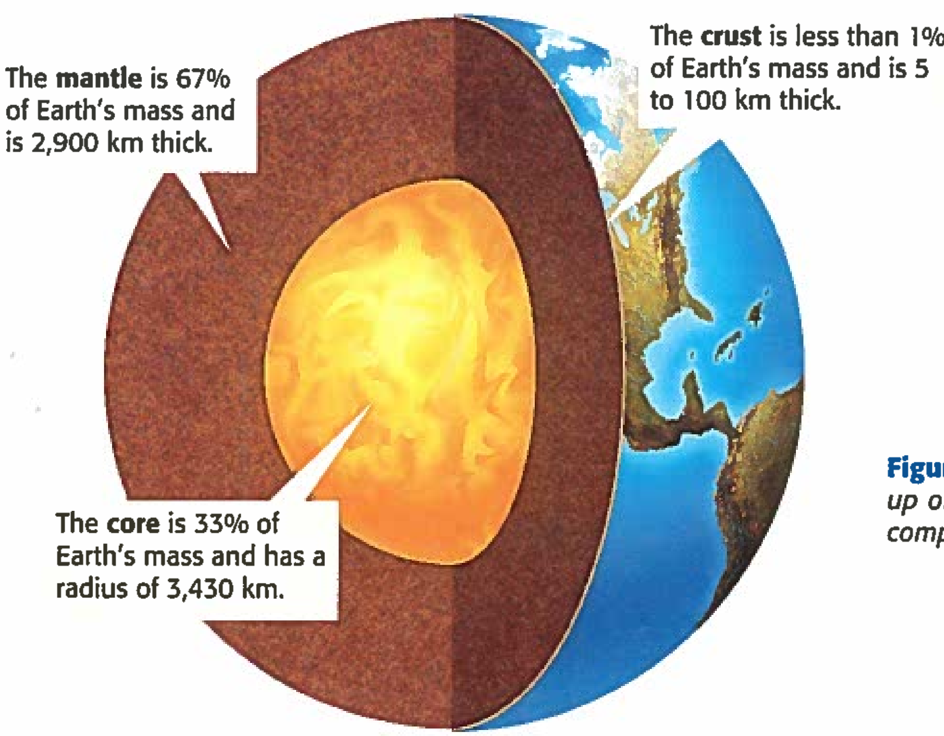


Figure 3 *The Earth is made up of three layers based on the composition of each layer.*

MATH PRACTICE

Using Models

Imagine that you are building a model of the Earth that will have a radius of 1 m. You find out that the average radius of the Earth is 6,380 km and that the thickness of the lithosphere is about 150 km. What percentage of the Earth's radius is the lithosphere? How thick (in centimeters) would you make the lithosphere in your model?

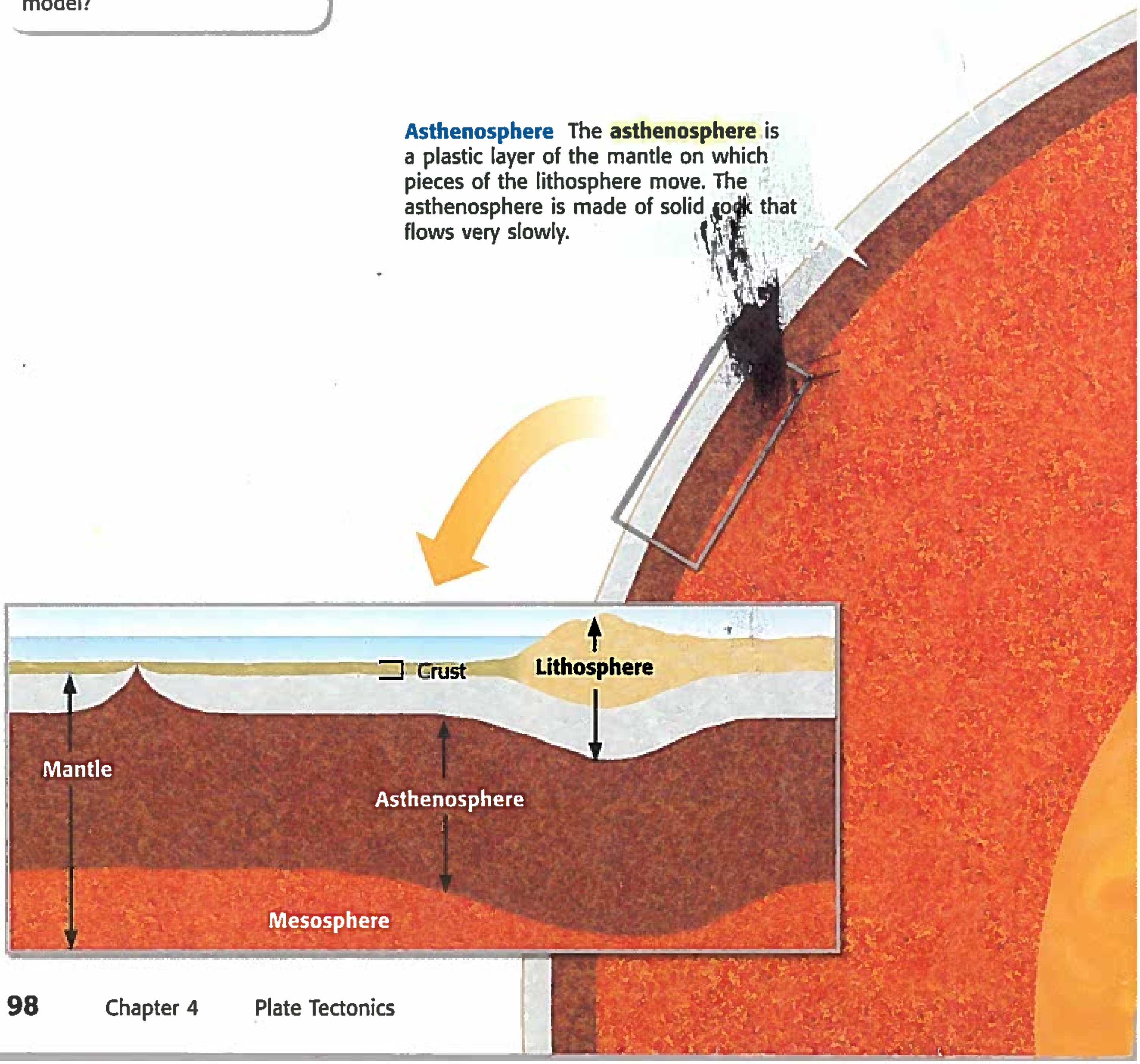
The Physical Structure of the Earth

Another way to look at the Earth is to examine the physical properties of its layers. The Earth is divided into five physical layers—the lithosphere, asthenosphere, mesosphere, outer core, and inner core. As shown in the figure below, each layer has its own set of physical properties.

Reading Check What are the five physical layers of the Earth?

Lithosphere The outermost, rigid layer of the Earth is the **lithosphere.** The lithosphere is made of two parts—the crust and the rigid upper part of the mantle. The lithosphere is divided into pieces called *tectonic plates.*

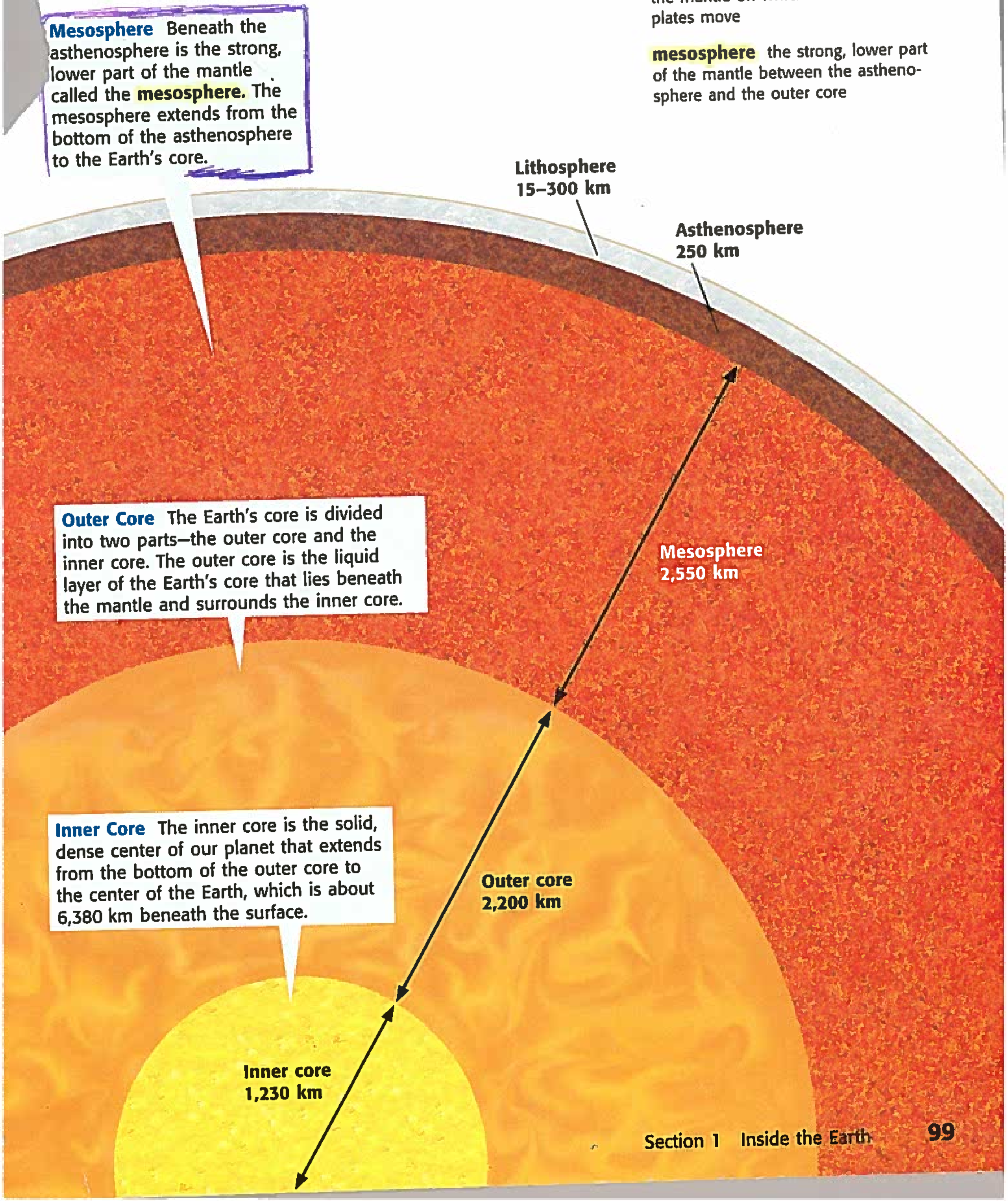
Asthenosphere The **asthenosphere** is a plastic layer of the mantle on which pieces of the lithosphere move. The asthenosphere is made of solid rock that flows very slowly.



lithosphere the solid, outer layer of the Earth that consists of the crust and the rigid upper part of the mantle

asthenosphere the soft layer of the mantle on which the tectonic plates move

mesosphere the strong, lower part of the mantle between the asthenosphere and the outer core



tectonic plate a block of lithosphere that consists of the crust and the rigid, outermost part of the mantle

Tectonic Plates

Pieces of the lithosphere that move around on top of the asthenosphere are called **tectonic plates**. But what exactly does a tectonic plate look like? How big are tectonic plates? How and why do they move around? To answer these questions, begi by thinking of the lithosphere as a giant jigsaw puzzle.

A Giant Jigsaw Puzzle

All of the tectonic plates have names, some of which you may already know. Some of the major tectonic plates are named on the map in **Figure 4.** Notice that each tectonic plate fits together with the tectonic plates that surround it. The lithosphere is like a jigsaw puzzle, and the tectonic plates are like the pieces of a jigsaw puzzle.

Notice that not all tectonic plates are the same. For example, compare the size of the South American plate with that of the Cocos plate. Tectonic plates differ in other ways, too. For example, the South American plate has an entire continent on it and has oceanic crust, but the Cocos plate has only oceanic crust. Some tectonic plates, such as the South American plate, include both continental and oceanic crust.

Major Tectonic Plates

1. Pacific plate
2. North American plate
3. Cocos plate
4. Nazca plate
5. South American plate
6. African plate
7. Eurasian plate
8. Indian plate
9. Australian plate
10. Antarctic plate

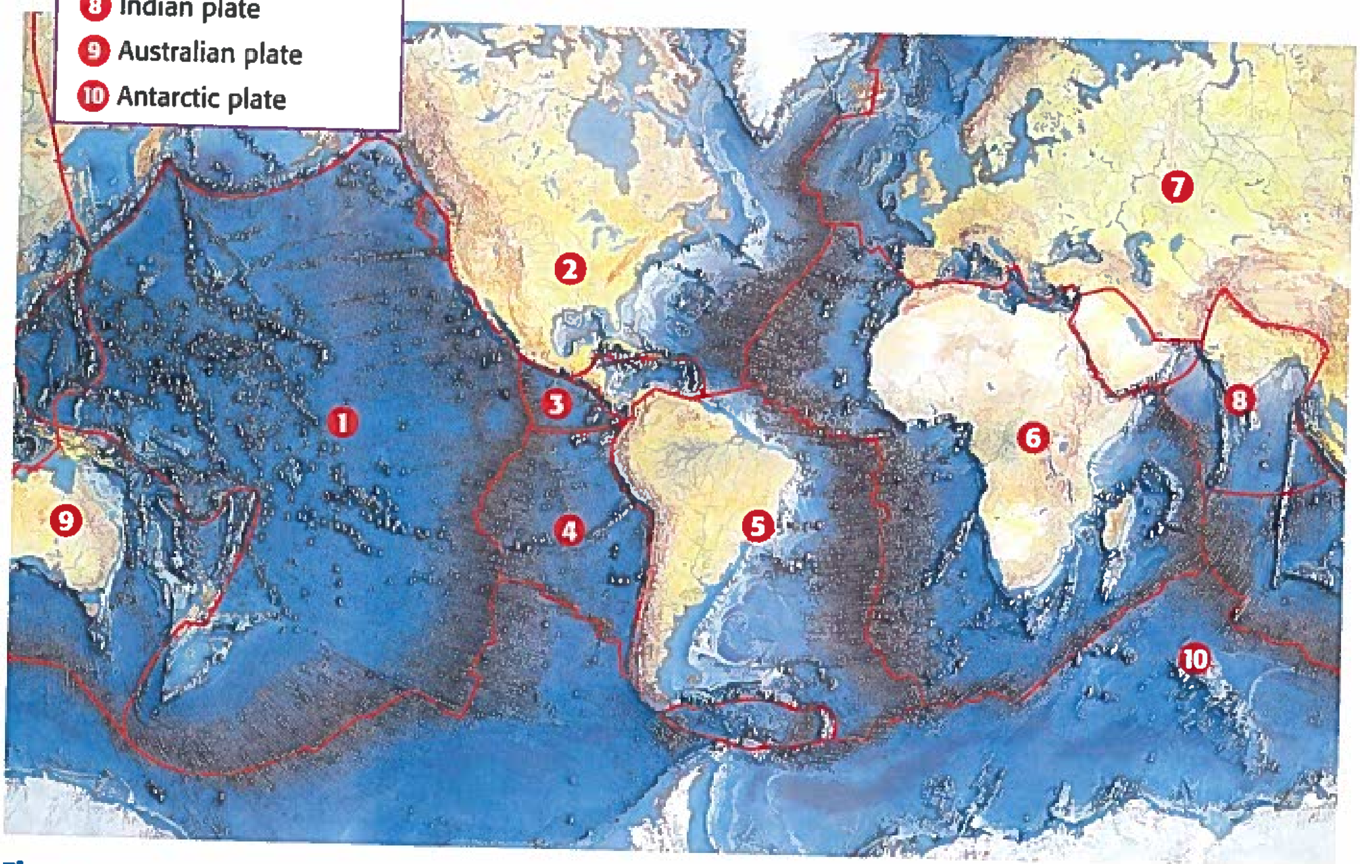
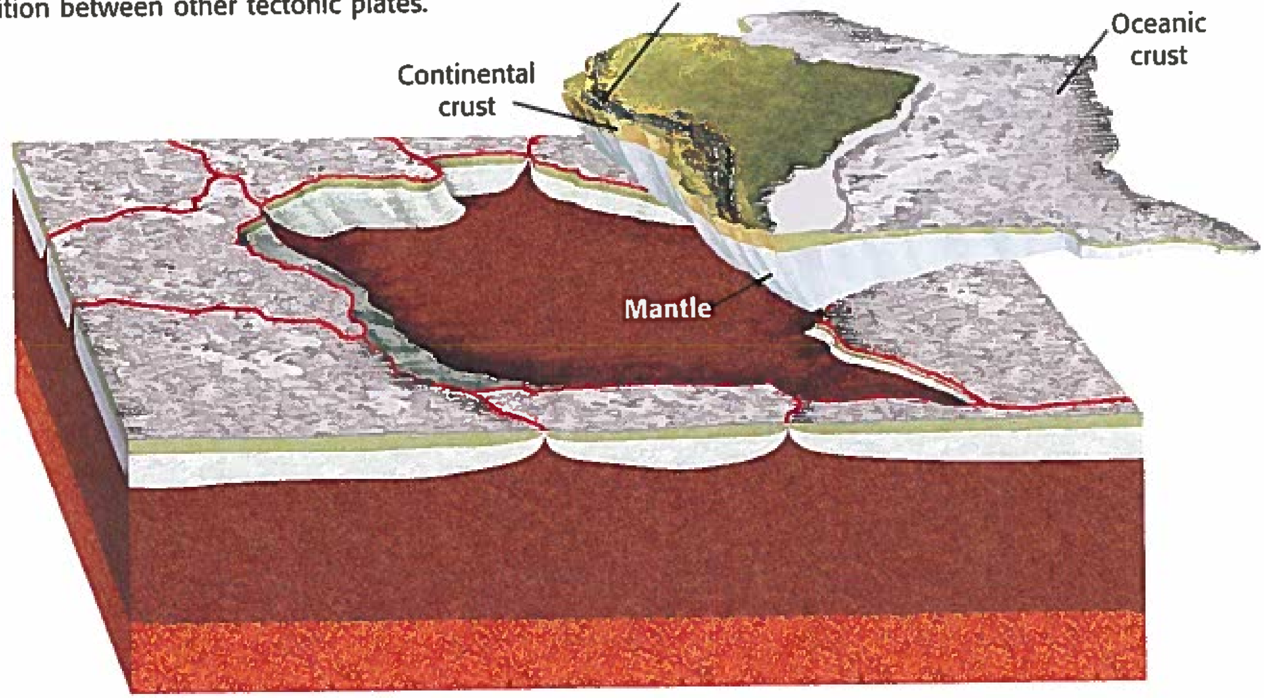


Figure 4 *Tectonic plates fit together like the pieces of a giant jigsaw puzzle.*

Figure 5 The South American Plate

This image shows what you might see if you could lift the South American plate out of its position between other tectonic plates.



A Tectonic Plate Close-Up

What would a tectonic plate look like if you could lift it out of its place? **Figure 5** shows what the South American plate might look like if you could. Notice that this tectonic plate not only consists of the upper part of the mantle but also consists of both oceanic crust and continental crust. The thickest part of the South American plate is the continental crust. The thinnest part of this plate is in the mid-Atlantic Ocean.

Like Ice Cubes in a Bowl of Punch

Think about ice cubes floating in a bowl of punch. If there are enough cubes, they will cover the surface of the punch and bump into one another. Parts of the ice cubes are below the surface of the punch and displace the punch. Large pieces of ice displace more punch than small pieces of ice. Tectonic plates "float" on the asthenosphere in a similar way. The plates cover the surface of the asthenosphere, and they touch one another and move around. The lithosphere displaces the asthenosphere. Thick tectonic plates, such as those made of continental crust, displace more asthenosphere than do thin plates, such as those made of oceanic lithosphere.

Reading Check **Why do tectonic plates made of continental lithosphere displace more asthenosphere than tectonic plates made of oceanic lithosphere do?**

Quick Lab

Tectonic Ice Cubes

1. Take the bottom half of a clear, **2 L soda bottle** that has been cut in half. Make sure that the label has been removed.
2. Fill the bottle with **water** to about 1 cm below the top edge of the bottle.
3. Get **three pieces of irregularly shaped ice** that are small, medium, and large.
4. Float the ice in the water, and note how much of each piece is below the surface of the water.
5. Do all pieces of ice float mostly below the surface? Which piece is mostly below the surface? Why?

SCHOOL to HOME

Build a Seismograph

Seismographs are instruments that seismologists, scientists who study earthquakes, use to detect seismic waves. Research seismograph designs with your parent. For example, a simple seismograph can be built by using a weight suspended by a spring next to a ruler. With your parent, attempt to construct a home seismograph based on a design you have selected. Outline each of the steps used to build your seismograph, and present the written outline to your teacher.

ACTIVITY

Mapping the Earth's Interior

How do scientists know things about the deepest parts of the Earth, where no one has ever been? Scientists have never even drilled through the crust, which is only a thin skin on the surface of the Earth. So, how do we know so much about the mantle and the core?

Would you be surprised to know that some of the answers come from earthquakes? When an earthquake happens, vibrations called *seismic waves* are produced. Seismic waves travel at different speeds through the Earth. Their speed depends on the density and composition of material that they pass through. For example, a seismic wave traveling through a solid will go faster than a seismic wave traveling through a liquid.

When an earthquake happens, machines called *seismographs* measure the times at which seismic waves arrive at different distances from an earthquake. Seismologists can then use these distances and travel times to calculate the density and thickness of each physical layer of the Earth. **Figure 6** shows how seismic waves travel through the Earth.

Reading Check What are some properties of seismic waves?

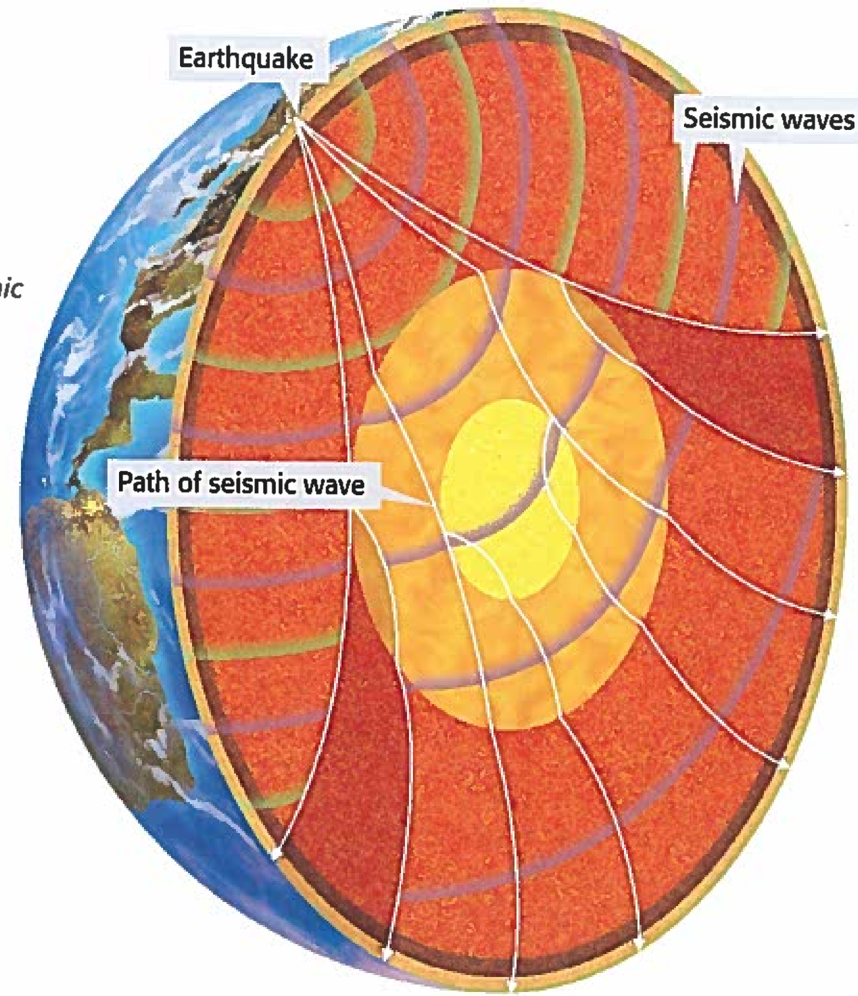


Figure 6 *By measuring changes in the speed of seismic waves that travel through Earth's interior, seismologists have learned that the Earth is made of different layers.*

SECTION Review

Summary

- The Earth is made up of three layers—the crust, the mantle, and the core—based on chemical composition. Less dense compounds make up the crust and mantle. Denser compounds make up the core.
- The Earth is made up of five main physical layers: the lithosphere, the asthenosphere, the mesosphere, the outer core, and the inner core.
- Tectonic plates are large pieces of the lithosphere that move around on the Earth's surface.
- The crust in some tectonic plates is mainly continental. Other plates have only oceanic crust. Still other plates include both continental and oceanic crust.
- Thick tectonic plates, such as those in which the crust is mainly continental, displace more asthenosphere than do thin plates, such as those in which the crust is mainly oceanic.
- Knowledge about the layers of the Earth comes from the study of seismic waves caused by earthquakes.

Using Key Terms

For each pair of terms, explain how the meanings of the terms differ.

1. *crust* and *mantle*
2. *lithosphere* and *asthenosphere*

Understanding Key Ideas

3. The part of the Earth that is molten is the
   a. crust.
   b. mantle.
   c. outer core.
   d. inner core.
4. The part of the Earth on which the tectonic plates move is the
   a. lithosphere.
   b. asthenosphere.
   c. mesosphere.
   d. crust.
5. Identify the layers of the Earth by their chemical composition.
6. Identify the layers of the Earth by their physical properties.
7. Describe a tectonic plate.
8. Explain how scientists know about the structure of the Earth's interior.

Interpreting Graphics

9. According to the wave speeds shown in the table below, which two physical layers of the Earth are densest?

Speed of Seismic Waves in Earth's Interior

Physical layer	Wave speed
Lithosphere	7 to 8 km/s
Asthenosphere	7 to 11 km/s
Mesosphere	11 to 13 km/s
Outer core	8 to 10 km/s
Inner core	11 to 12 km/s

Critical Thinking

10. **Making Comparisons** Explain the difference between the crust and the lithosphere.
11. **Analyzing Ideas** Why does a seismic wave travel faster through solid rock than through water?

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For a variety of links related to this chapter, go to www.scilinks.org
Topic: Composition of the Earth; Structure of the Earth
SciLinks code: HSM0329; HSM1468

SECTION 2

Restless Continents

READING WARM-UP

Objectives

- Describe Wegener's hypothesis of continental drift.
- Explain how sea-floor spreading provides a way for continents to move.
- Describe how new oceanic lithosphere forms at mid-ocean ridges.
- Explain how magnetic reversals provide evidence for sea-floor spreading.

Terms to Learn

continental drift
sea-floor spreading

READING STRATEGY

Paired Summarizing Read this section silently. In pairs, take turns summarizing the material. Stop to discuss ideas that seem confusing.

Have you ever looked at a map of the world and noticed how the coastlines of continents on opposite sides of the oceans appear to fit together like the pieces of a puzzle? Is it just coincidence that the coastlines fit together well? Is it possible that the continents were actually together sometime in the past?

Wegener's Continental Drift Hypothesis

One scientist who looked at the pieces of this puzzle was Alfred Wegener (VAY guh nuhr). In the early 1900s, he wrote about his hypothesis of *continental drift*. **Continental drift** is the hypothesis that states that the continents once formed a single landmass, broke up, and drifted to their present locations. This hypothesis seemed to explain a lot of puzzling observations, including the observation of how well continents fit together.

Continental drift also explained why fossils of the same plant and animal species are found on continents that are on different sides of the Atlantic Ocean. Many of these ancient species could not have crossed the Atlantic Ocean. As you can see in **Figure 1,** without continental drift, this pattern of fossils would be hard to explain. In addition to fossils, similar types of rock and evidence of the same ancient climatic conditions were found on several continents.

Reading Check **How did fossils provide evidence for Wegener's hypothesis of continental drift?** (*See the Appendix for answers to Reading Checks.*)

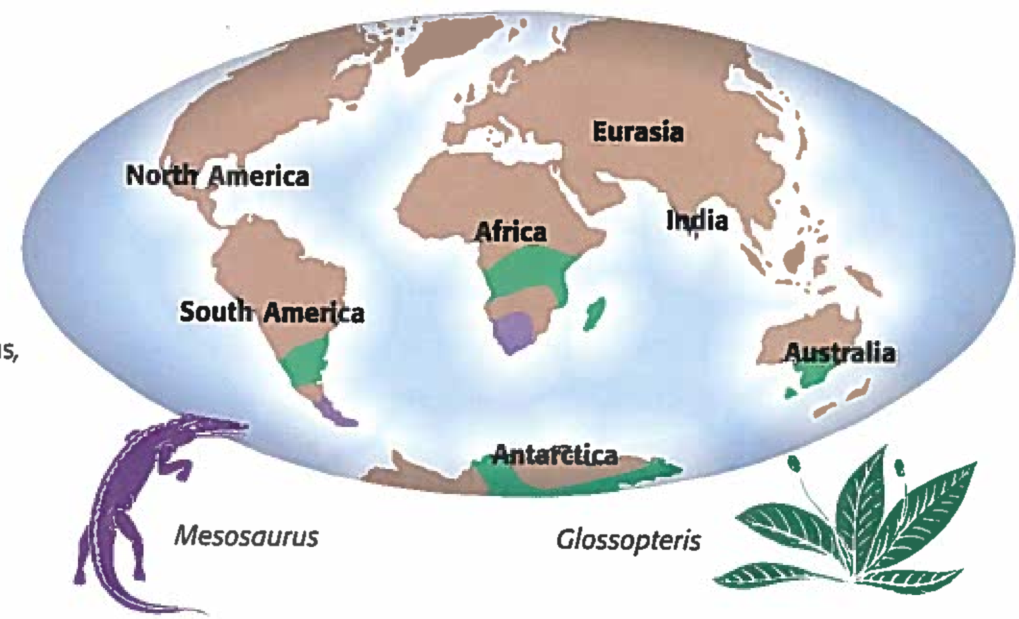


Figure 1 *Fossils of* Mesosaurus, *a small, aquatic reptile, and* Glossopteris, *an ancient plant species, have been found on several continents.*

Figure 2 The Drifting Continents

245 Million Years Ago
Pangaea existed when some of the earliest dinosaurs were roaming the Earth. The continent was surrounded by a sea called *Panthalassa*, which means "all sea."

180 Million Years Ago
Gradually, Pangaea broke into two big pieces. The northern piece is called *Laurasia*. The southern piece is called *Gondwana*.

65 Million Years Ago
By the time the dinosaurs became extinct, Laurasia and Gondwana had split into smaller pieces.

The Breakup of Pangaea

Wegener made many observations before proposing his hypothesis of continental drift. He thought that all of the present continents were once joined in a single, huge continent. Wegener called this continent *Pangaea* (pan JEE uh), which is Greek for "all earth." We now know from the hypothesis of plate tectonics that Pangaea existed about 245 million years ago. We also know that Pangaea further split into two huge continents—Laurasia and Gondwana—about 180 million years ago. As shown in **Figure 2,** these two continents split again and formed the continents we know today.

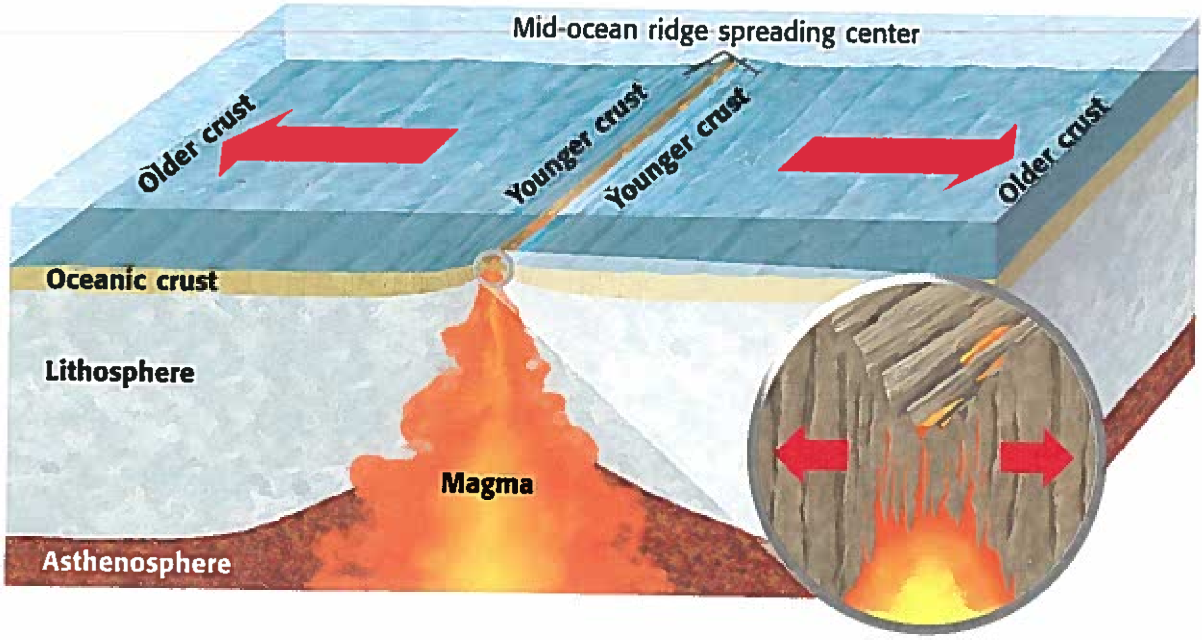
continental drift the hypothesis that states that the continents once formed a single landmass, broke up, and drifted to their present locations

Sea-Floor Spreading

When Wegener put forth his hypothesis of continental drift, many scientists would not accept his hypothesis. From the calculated strength of the rocks, it did not seem possible for the crust to move in this way. During Wegener's life, no one knew the answer. It wasn't until many years later that evidence provided some clues to the forces that moved the continents.

Figure 3 **Sea-Floor Spreading**

Sea-floor spreading creates new oceanic lithosphere at mid-ocean ridges.



sea-floor spreading the process by which new oceanic lithosphere forms as magma rises toward the surface and solidifies

Mid-Ocean Ridges and Sea-Floor Spreading

A chain of submerged mountains runs through the center of the Atlantic Ocean. The chain is part of a worldwide system of mid-ocean ridges. Mid-ocean ridges are underwater mountain chains that run through Earth's ocean basins.

Mid-ocean ridges are places where sea-floor spreading takes place. **Sea-floor spreading** is the process by which new oceanic lithosphere forms as magma rises toward the surface and solidifies. As the tectonic plates move away from each other, the sea floor spreads apart and magma fills in the gap. As this new crust forms, the older crust gets pushed away from the mid-ocean ridge. As **Figure 3** shows, the older crust is farther away from the mid-ocean ridge than the younger crust is.

Evidence for Sea-Floor Spreading: Magnetic Reversals

Some of the most important evidence of sea-floor spreading comes from magnetic reversals recorded in the ocean floor. Throughout Earth's history, the north and south magnetic poles have changed places many times. When the poles change places, the polarity of Earth's magnetic poles changes, as shown in **Figure 4.** When Earth's magnetic poles change places, this change is called a *magnetic reversal.*

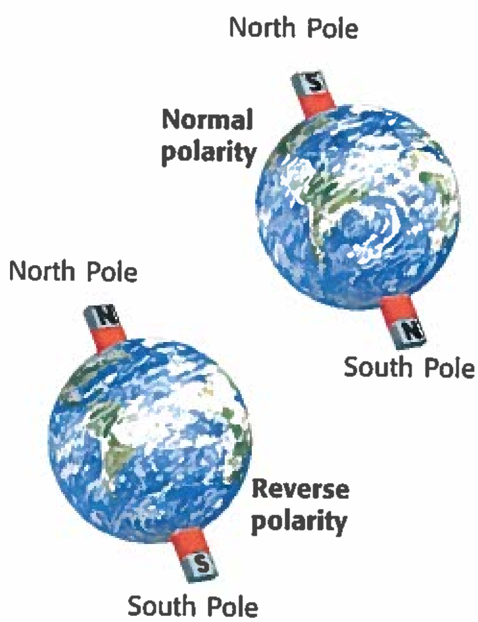


Figure 4 *The polarity of Earth's magnetic field changes over time.*

Magnetic Reversals and Sea-Floor Spreading

The molten rock at the mid-ocean ridges contains tiny grains of magnetic minerals. These mineral grains contain iron and are like compasses. They align with the magnetic field of the Earth. When the molten rock cools, the record of these tiny compasses remains in the rock. This record is then carried slowly away from the spreading center of the ridge as sea-floor spreading occurs.

As you can see in **Figure 5,** when the Earth's magnetic field reverses, the magnetic mineral grains align in the opposite direction. The new rock records the direction of the Earth's magnetic field. As the sea floor spreads away from a mid-ocean ridge, it carries with it a record of magnetic reversals. This record of magnetic reversals was the final proof that sea-floor spreading does occur.

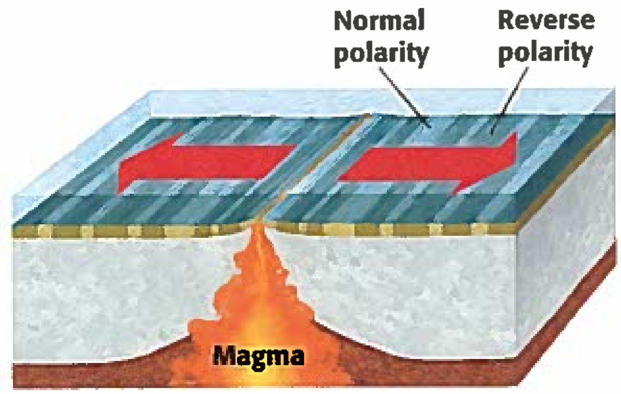


Figure 5 *Magnetic reversals in oceanic crust are shown as bands of light blue and dark blue oceanic crust. Light blue bands indicate normal polarity, and dark blue bands indicate reverse polarity.*

Reading Check How is a record of magnetic reversals recorded in molten rock at mid-ocean ridges?

SECTION Review

Summary

- Wegener hypothesized that continents drift apart from one another and have done so in the past.
- The process by which new oceanic lithosphere forms at mid-ocean ridges is called sea-floor spreading.
- As tectonic plates separate, the sea floor spreads apart and magma fills in the gap.
- Magnetic reversals are recorded over time in oceanic crust.

Using Key Terms

1. In your own words, write a definition for each of the following terms: *continental drift* and *sea-floor spreading*.

Understanding Key Ideas

2. At mid-ocean ridges,
   a. the crust is older.
   b. sea-floor spreading occurs.
   c. oceanic lithosphere is destroyed.
   d. tectonic plates are colliding.
3. Explain how oceanic lithosphere forms at mid-ocean ridges.
4. What is magnetic reversal?

Math Skills

5. If a piece of sea floor has moved 50 km in 5 million years, what is the yearly rate of sea-floor motion?

Critical Thinking

6. **Identifying Relationships** Explain how magnetic reversals provide evidence for sea-floor spreading.
7. **Applying Concepts** Why do bands indicating magnetic reversals appear to be of similar width on both sides of a mid-ocean ridge?
8. **Applying Concepts** Why do you think that old rocks are rare on the ocean floor?

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For a variety of links related to this chapter, go to www.scilinks.org

Topic: Tectonic Plates
SciLinks code: HSM1497

SECTION 3

The Theory of Plate Tectonics

READING WARM-UP

Objectives

- Describe the three types of tectonic plate boundaries.
- Describe the three forces thought to move tectonic plates.
- Explain how scientists measure the rate at which tectonic plates move.

Terms to Learn

plate tectonics
convergent boundary
divergent boundary
transform boundary

READING STRATEGY

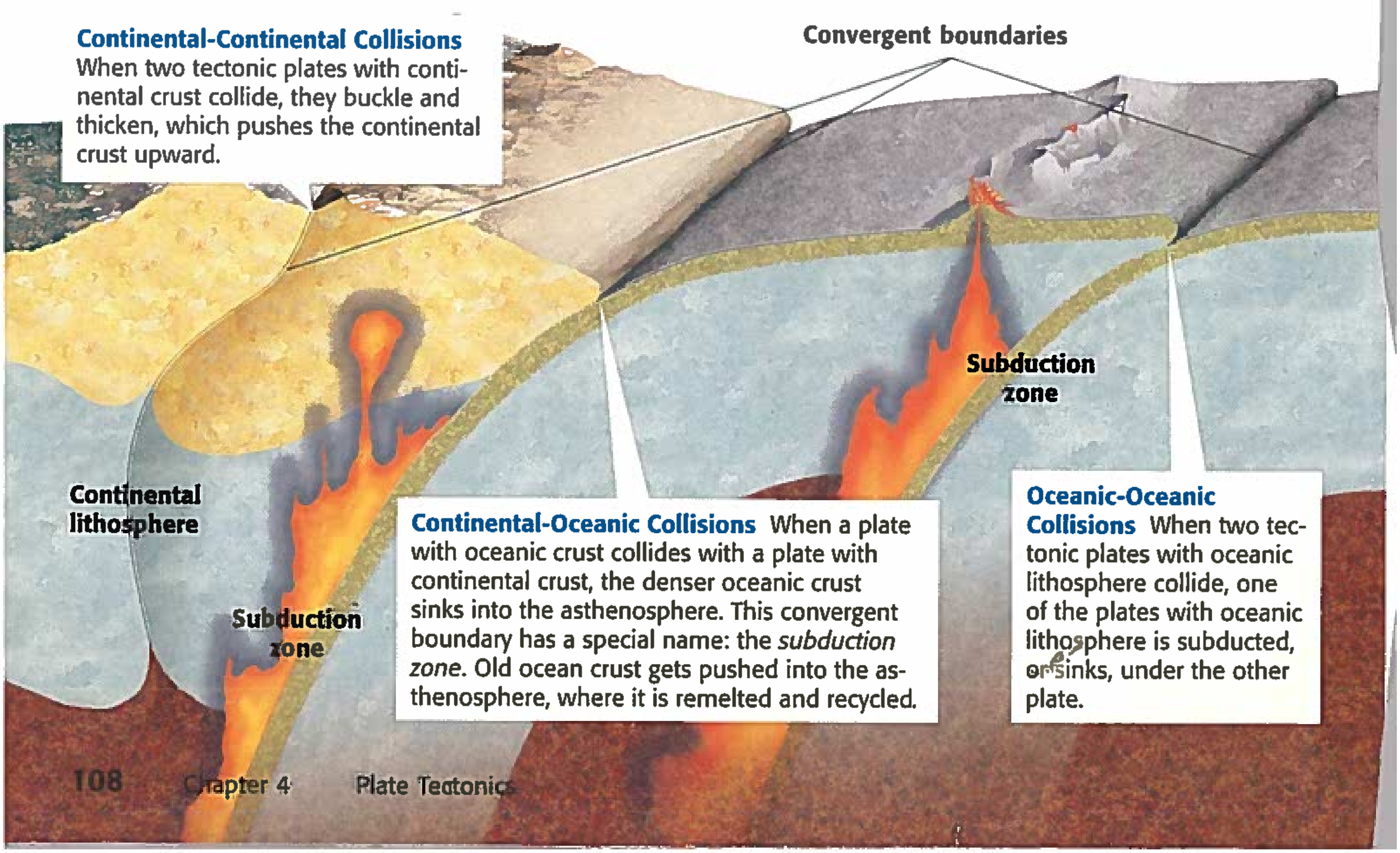
Brainstorming The key idea of this section is plate tectonics. Brainstorm words and phrases related to plate tectonics.

It takes an incredible amount of force to move a tectonic plate! But where does this force come from?

As scientists' understanding of mid-ocean ridges and magnetic reversals grew, scientists formed a theory to explain how tectonic plates move. **Plate tectonics** is the theory that the Earth's lithosphere is divided into tectonic plates that move around on top of the asthenosphere. In this section, you will learn what causes tectonic plates to move. But first you will learn about the different types of tectonic plate boundaries.

Tectonic Plate Boundaries

A boundary is a place where tectonic plates touch. All tectonic plates share boundaries with other tectonic plates. These boundaries are divided into three types: convergent, divergent, and transform. The type of boundary depends on how the tectonic plates move relative to one another. Tectonic plates can collide, separate, or slide past each other. Earthquakes can occur at all three types of plate boundaries. The figure below shows examples of tectonic plate boundaries.



Continental-Continental Collisions When two tectonic plates with continental crust collide, they buckle and thicken, which pushes the continental crust upward.

Continental-Oceanic Collisions When a plate with oceanic crust collides with a plate with continental crust, the denser oceanic crust sinks into the asthenosphere. This convergent boundary has a special name: the *subduction zone*. Old ocean crust gets pushed into the asthenosphere, where it is remelted and recycled.

Oceanic-Oceanic Collisions When two tectonic plates with oceanic lithosphere collide, one of the plates with oceanic lithosphere is subducted, or sinks, under the other plate.

Convergent Boundaries

When two tectonic plates collide, the boundary between them is a **convergent boundary.** What happens at a convergent boundary depends on the kind of crust at the leading edge of each tectonic plate. The three types of convergent boundaries are continental-continental boundaries, continental-oceanic boundaries, and oceanic-oceanic boundaries.

Divergent Boundaries

When two tectonic plates separate, the boundary between them is called a **divergent boundary.** New sea floor forms at divergent boundaries. Mid-ocean ridges are the most common type of divergent boundary.

Transform Boundaries

When two tectonic plates slide past each other horizontally, the boundary between them is a **transform boundary.** The San Andreas Fault in California is a good example of a transform boundary. This fault marks the place where the Pacific and North American plates are sliding past each other.

Reading Check **Define the term *transform boundary*.** (*See the Appendix for answers to Reading Checks.*)

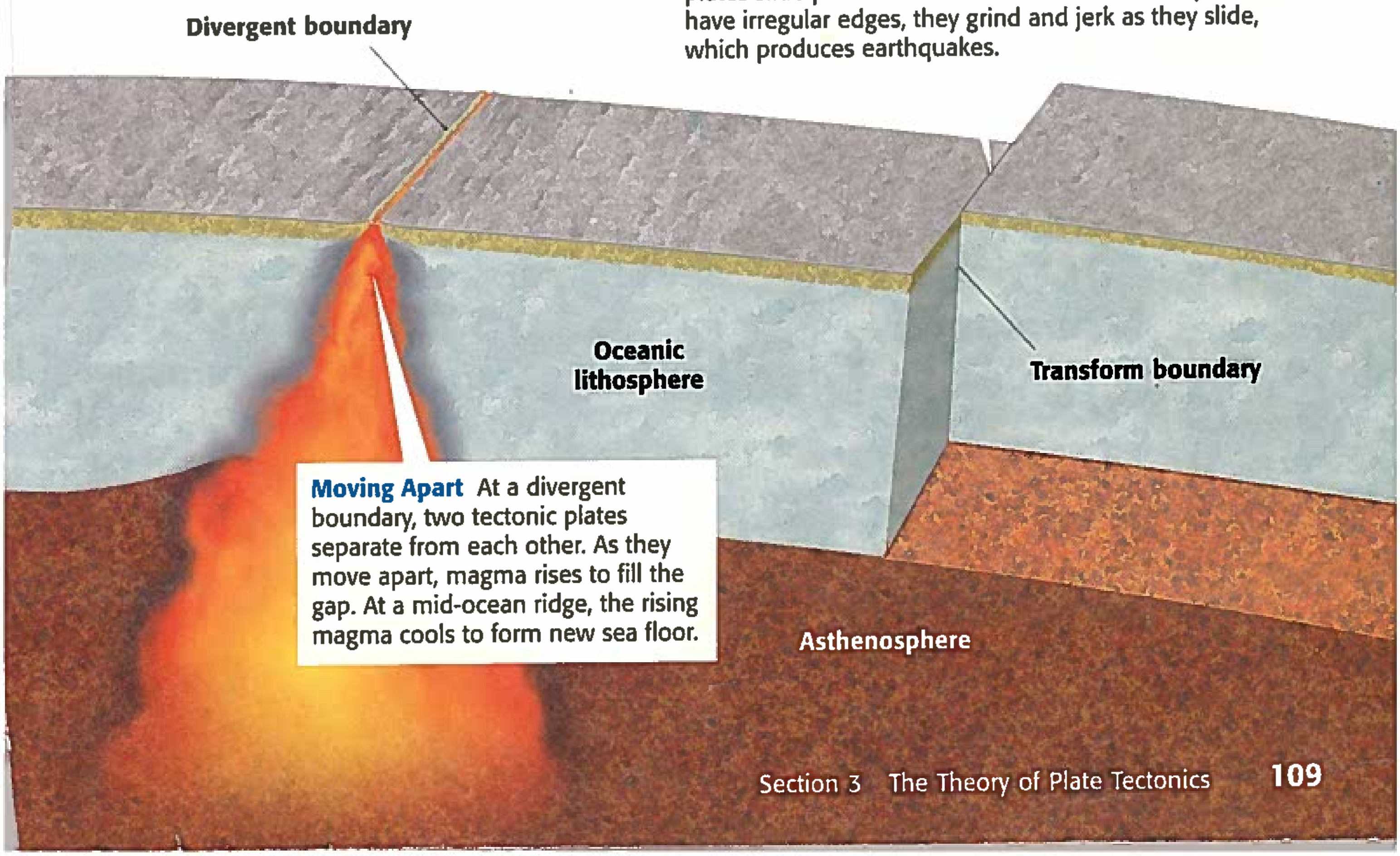
plate tectonics the theory that explains how large pieces of the Earth's outermost layer, called *tectonic plates,* move and change shape

convergent boundary the boundary formed by the collision of two lithospheric plates

divergent boundary the boundary between two tectonic plates that are moving away from each other

transform boundary the boundary between tectonic plates that are sliding past each other horizontally

Sliding Past At a transform boundary, two tectonic plates slide past one another. Because tectonic plates have irregular edges, they grind and jerk as they slide, which produces earthquakes.



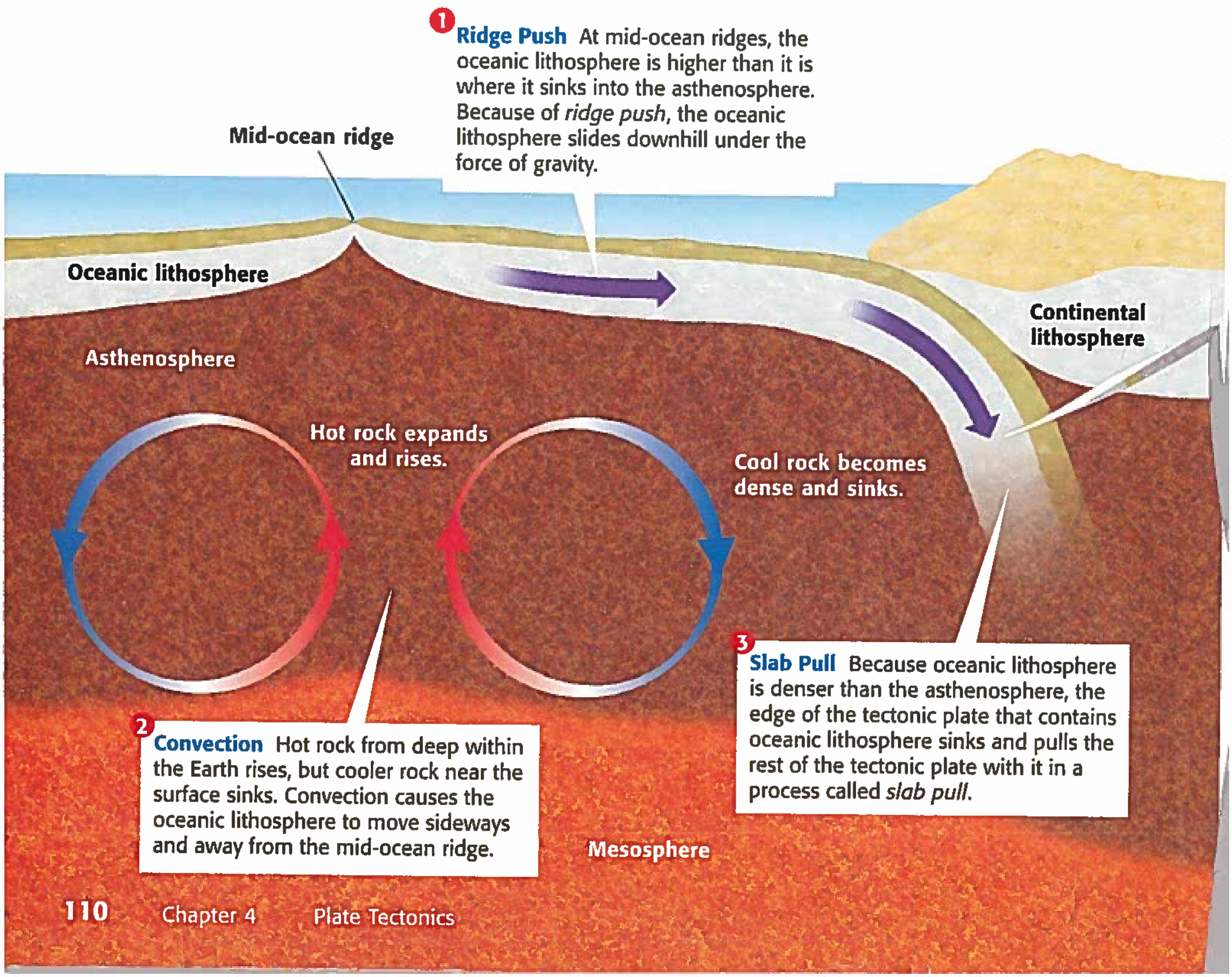
Moving Apart At a divergent boundary, two tectonic plates separate from each other. As they move apart, magma rises to fill the gap. At a mid-ocean ridge, the rising magma cools to form new sea floor.

Possible Causes of Tectonic Plate Motion

You have learned that plate tectonics is the theory that the lithosphere is divided into tectonic plates that move around on top of the asthenosphere. What causes the motion of tectonic plates? Remember that the solid rock of the asthenosphere flows very slowly. This movement occurs because of changes in density within the asthenosphere. These density changes are caused by the outward flow of thermal energy from deep within the Earth. When rock is heated, it expands, becomes less dense, and tends to rise to the surface of the Earth. As the rock gets near the surface, the rock cools, becomes more dense, and tends to sink. **Figure 1** shows three possible causes of tectonic plate motion.

Reading Check **What causes changes in density in the asthenosphere?**

Figure 1 **Three Possible Driving Forces of Plate Tectonics**



Tracking Tectonic Plate Motion

How fast do tectonic plates move? The answer to this question depends on many factors, such as the type and shape of the tectonic plate and the way that the tectonic plate interacts with the tectonic plates that surround it. Tectonic plate movements are so slow and gradual that you can't see or feel them—the movement is measured in centimeters per year.

The Global Positioning System

Scientists use a system of satellites called the *global positioning system* (GPS), shown in **Figure 2**, to measure the rate of tectonic plate movement. Radio signals are continuously beamed from satellites to GPS ground stations, which record the exact distance between the satellites and the ground station. Over time, these distances change slightly. By recording the time it takes for the GPS ground stations to move a given distance, scientists can measure the speed at which each tectonic plate moves.

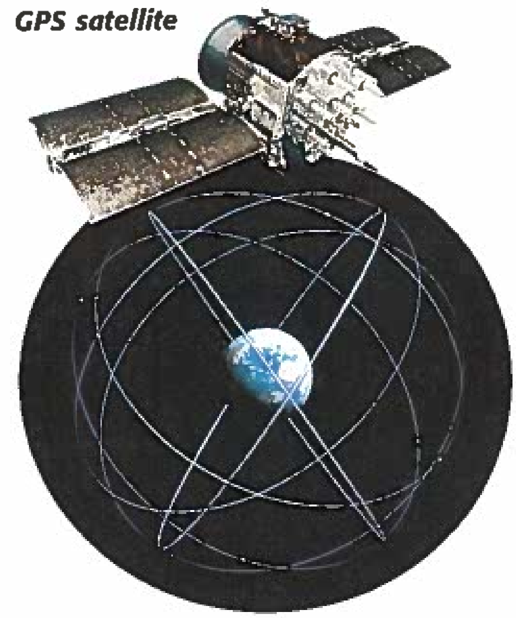


Figure 2 *The image above shows the orbits of the GPS satellites.*

SECTION Review

Summary

- Boundaries between tectonic plates are classified as convergent, divergent, or transform.
- Ridge push, convection, and slab pull are three possible driving forces of plate tectonics.
- Scientists use data from a system of satellites called the global positioning system to measure the rate of motion of tectonic plates.

Using Key Terms

1. In your own words, write a definition for the term *plate tectonics*.

Understanding Key Ideas

2. The speed a tectonic plate moves per year is best measured in
   a. kilometers per year.
   b. centimeters per year.
   c. meters per year.
   d. millimeters per year.
3. Briefly describe three possible driving forces of tectonic plate movement.
4. Explain how scientists use GPS to measure the rate of tectonic plate movement.

Math Skills

5. If an orbiting satellite has a diameter of 60 cm, what is the total surface area of the satellite? (Hint: *surface area* = $4\pi r^2$)

Critical Thinking

6. **Identifying Relationships** When convection takes place in the mantle, why does cool rock material sink and warm rock material rise?
7. **Analyzing Processes** Why does oceanic crust sink beneath continental crust at convergent boundaries?

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For a variety of links related to this chapter, go to www.scilinks.org

Topic: Plate Tectonics
SciLinks code: HSM1171

SECTION 4

Deforming the Earth's Crust

READING WARM-UP

Objectives

- Describe two types of stress that deform rocks.
- Describe three major types of folds.
- Explain the differences between the three major types of faults.
- Identify the most common types of mountains.
- Explain the difference between uplift and subsidence.

Terms to Learn

compression
tension
folding
fault
uplift
subsidence

READING STRATEGY

Discussion Read this section silently. Write down questions that you have about this section. Discuss your questions in a small group.

Have you ever tried to bend something, only to have it break? Take long, uncooked pieces of spaghetti, and bend them very slowly but only a little. Now, bend them again, but this time, bend them much farther and faster. What happened?

How can a material bend at one time and break at another time? The answer is that the stress you put on the material was different each time. *Stress* is the amount of force per unit area on a given material. The same principle applies to the rocks in the Earth's crust. Different things happen to rock when different types of stress are applied.

Deformation

The process by which the shape of a rock changes because of stress is called *deformation*. In the example above, the spaghetti deformed in two different ways—by bending and by breaking. **Figure 1** illustrates this concept. The same thing happens in rock layers. Rock layers bend when stress is placed on them. But when enough stress is placed on rocks, they can reach their elastic limit and break.

Compression and Tension

The type of stress that occurs when an object is squeezed, such as when two tectonic plates collide, is called **compression.** When compression occurs at a convergent boundary, large mountain ranges can form.

Another form of stress is *tension*. **Tension** is stress that occurs when forces act to stretch an object. As you might guess, tension occurs at divergent plate boundaries, such as mid-ocean ridges, when two tectonic plates pull away from each other.

Reading Check **How do the forces of plate tectonics cause rock to deform?** (*See the Appendix for answers to Reading Checks.*)

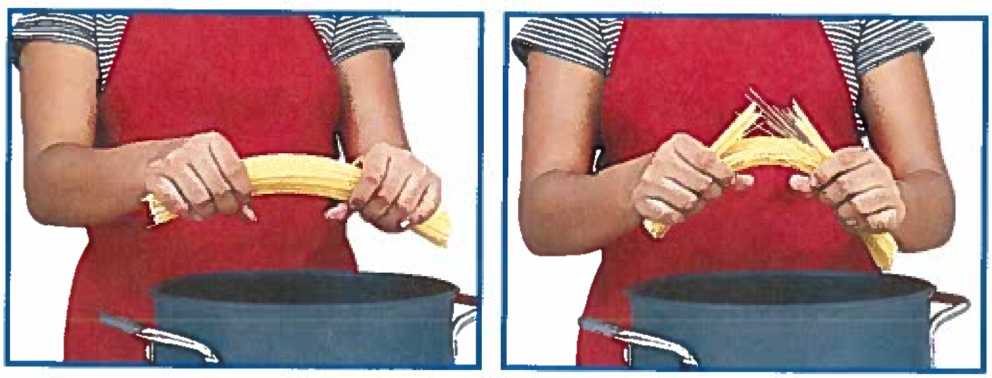
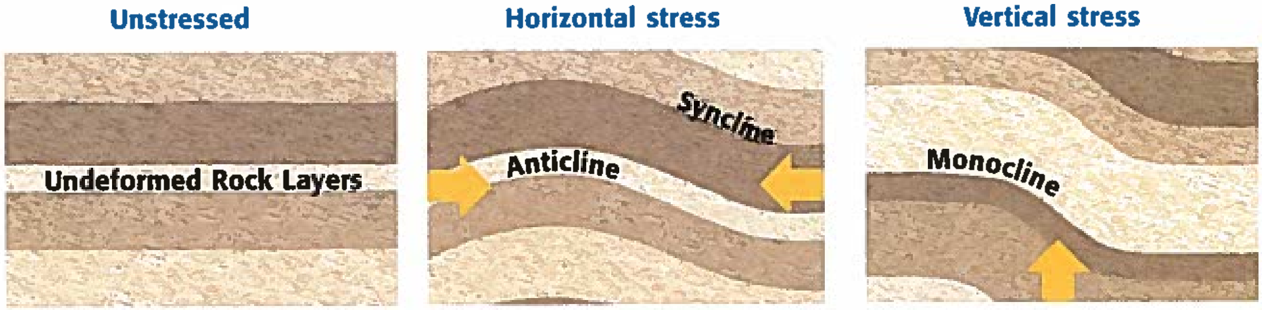


Figure 1 *When a small amount of stress is placed on uncooked spaghetti, the spaghetti bends. Additional stress causes the spaghetti to break.*

Figure 2 Folding: When Rock Layers Bend Because of Stress



Folding

The bending of rock layers because of stress in the Earth's crust is called **folding.** Scientists assume that all rock layers started as horizontal layers. So, when scientists see a fold, they know that deformation has taken place.

compression stress that occurs when forces act to squeeze an object

tension stress that occurs when forces act to stretch an object

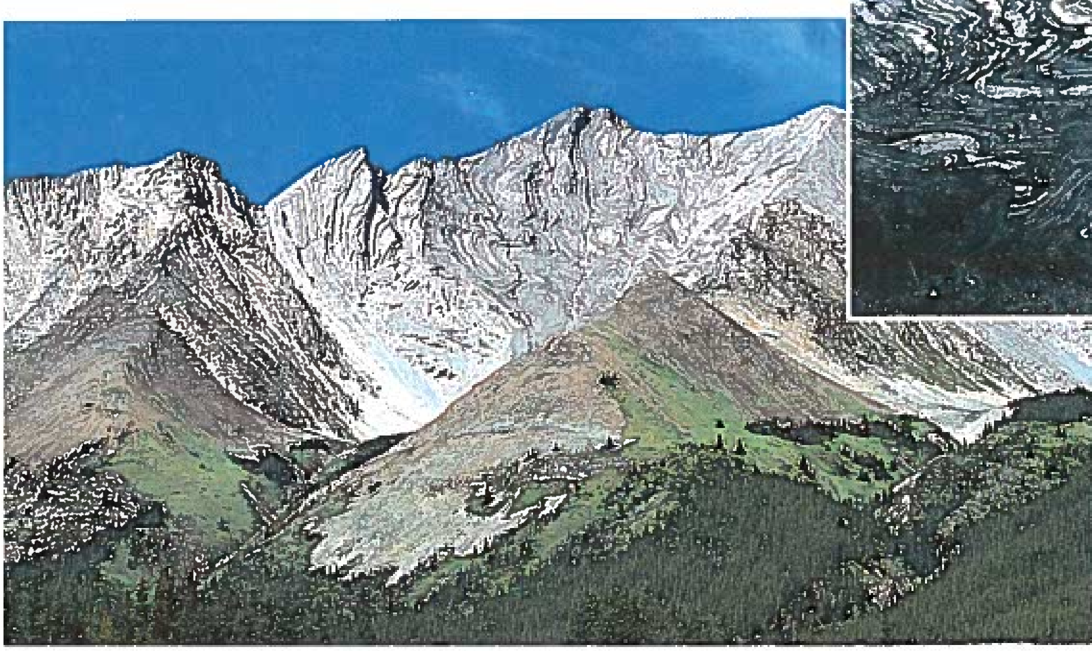
folding the bending of rock layers due to stress

Types of Folds

Depending on how the rock layers deform, different types of folds are made. **Figure 2** shows the two most common types of folds—*anticlines*, or upward-arching folds, and *synclines*, downward, troughlike folds. Another type of fold is a *monocline*. In a monocline, rock layers are folded so that both ends of the fold are horizontal. Imagine taking a stack of paper and laying it on a table. Think of the sheets of paper as different rock layers. Now put a book under one end of the stack. You can see that both ends of the sheets are horizontal, but all of the sheets are bent in the middle.

Folds can be large or small. The largest folds are measured in kilometers. Other folds are also obvious but are much smaller. These small folds can be measured in centimeters. **Figure 3** shows examples of large and small folds.

Figure 3 *The large photo shows mountain-sized folds in the Rocky Mountains. The small photo shows a rock that has folds smaller than a penknife.*



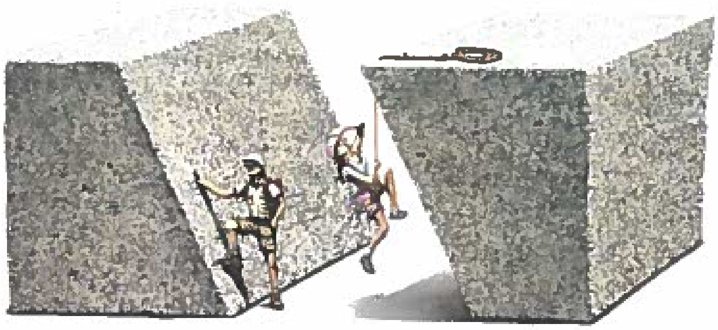


Figure 4 *The position of a fault block determines whether it is a hanging wall or a footwall.*

Faulting

Some rock layers break when stress is applied to them. The surface along which rocks break and slide past each other is called a **fault.** The blocks of crust on each side of the fault are called *fault blocks*.

When a fault is not vertical, understanding the difference between its two sides—the *hanging wall* and the *footwall*—is useful. **Figure 4** shows the difference between a hanging wall and a footwall. Two main types of faults can form. The type of fault that forms depends on how the hanging wall and footwall move in relationship to each other.

fault a break in a body of rock along which one block slides relative to another

Normal Faults

A *normal fault* is shown in **Figure 5.** When a normal fault moves, it causes the hanging wall to move down relative to the footwall. Normal faults usually occur when tectonic forces cause tension that pulls rocks apart.

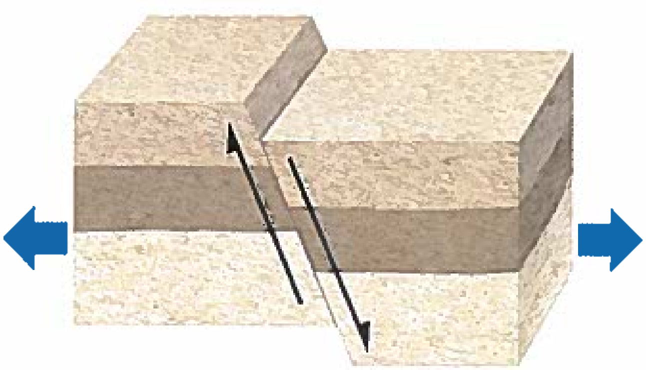
Reverse Faults

A *reverse fault* is shown in **Figure 5.** When a reverse fault moves, it causes the hanging wall to move up relative to the footwall. This movement is the reverse of a normal fault. Reverse faults usually happen when tectonic forces cause compression that pushes rocks together.

Reading Check **How does the hanging wall in a normal fault move in relation to a reverse fault?**

Figure 5 Normal and Reverse Faults

Normal Fault When rocks are pulled apart because of tension, normal faults often form.



Reverse Fault When rocks are pushed together by compression, reverse faults often form.

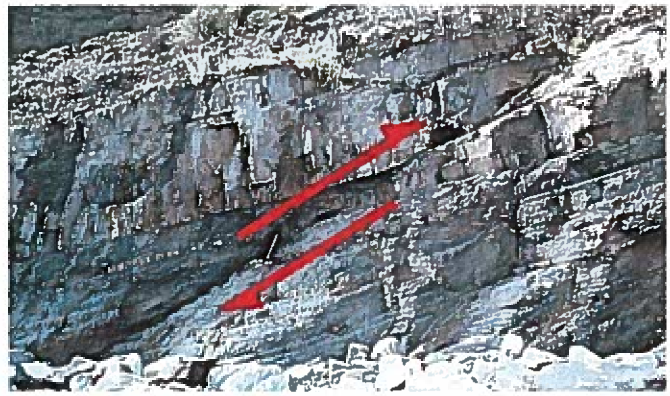


Figure 6 *The photo at left is a normal fault. The photo at right is a reverse fault.*

Telling the Difference Between Faults

It's easy to tell the difference between a normal fault and a reverse fault in drawings with arrows. But what types of faults are shown in **Figure 6**? You can certainly see the faults, but which one is a normal fault, and which one is a reverse fault? In the top left photo in **Figure 6,** one side has obviously moved relative to the other side. You can tell this fault is a normal fault by looking at the order of sedimentary rock layers. If you compare the two dark layers near the surface, you can see that the hanging wall has moved down relative to the footwall.

Strike-Slip Faults

A third major type of fault is called a *strike-slip fault.* An illustration of a strike-slip fault is shown in **Figure 7.** *Strike-slip faults* form when opposing forces cause rock to break and move horizontally. If you were standing on one side of a strike-slip fault looking across the fault when it moved, the ground on the other side would appear to move to your left or right. The San Andreas Fault in California is a spectacular example of a strike-slip fault.

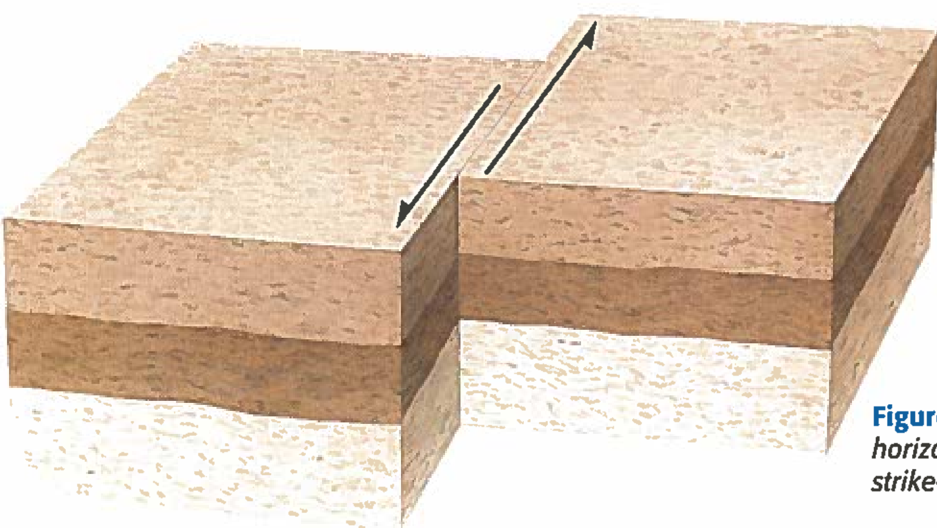


Figure 7 *When rocks are moved horizontally by opposing forces, strike-slip faults often form.*

QuickLab

Modeling Strike-Slip Faults

1. Use **modeling clay** to construct a box that is 6 in. × 6 in. × 4 in. Use different colors of clay to represent different horizontal layers.
2. Using **scissors,** cut the box down the middle. Place **two 4 in. × 6 in. index cards** inside the cut so that the two sides of the box slide freely.
3. Using gentle pressure, slide the two sides horizontally past one another.
4. How does this model illustrate the motion that occurs along a strike-slip fault?

Figure 8 *The Andes Mountains formed on the edge of the South American plate where it converges with the Nazca plate.*

Plate Tectonics and Mountain Building

You have just learned about several ways the Earth's crust changes because of the forces of plate tectonics. When tectonic plates collide, land features that start as folds and faults can eventually become large mountain ranges. Mountains exist because tectonic plates are continually moving around and colliding with one another. As shown in **Figure 8,** the Andes Mountains formed above the subduction zone where two tectonic plates converge.

When tectonic plates undergo compression or tension, they can form mountains in several ways. Take a look at three of the most common types of mountains—folded mountains, fault-block mountains, and volcanic mountains.

Folded Mountains

The highest mountain ranges in the world are made up of folded mountains. These ranges form at convergent boundaries where continents have collided. *Folded mountains* form when rock layers are squeezed together and pushed upward. If you place a pile of paper on a table and push on opposite edges of the pile, you will see how folded mountains form.

An example of a folded mountain range that formed at a convergent boundary is shown in **Figure 9.** About 390 million years ago, the Appalachian Mountains formed when the landmasses that are now North America and Africa collided. Other examples of mountain ranges that consist of very large and complex folds are the Alps in central Europe, the Ural Mountains in Russia, and the Himalayas in Asia.

Reading Check **Explain how folded mountains form.**

Figure 9 *The Appalachian Mountains were once as tall as the Himalaya Mountains but have been worn down by hundreds of millions of years of weathering and erosion.*

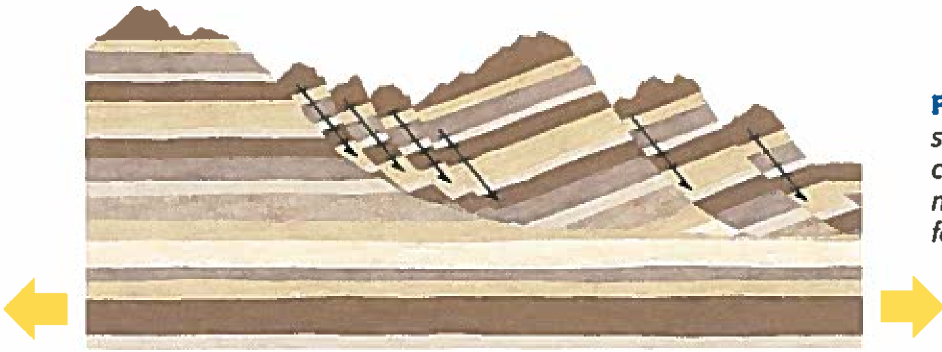


Figure 10 *When the crust is subjected to tension, the rock can break along a series of normal faults, which creates fault-block mountains.*

Fault-Block Mountains

When tectonic forces put enough tension on the Earth's crust, a large number of normal faults can result. *Fault-block mountains* form when this tension causes large blocks of the Earth's crust to drop down relative to other blocks. **Figure 10** shows one way that fault-block mountains form.

When sedimentary rock layers are tilted up by faulting, they can produce mountains that have sharp, jagged peaks. As shown in **Figure 11,** the Tetons in western Wyoming are a spectacular example of fault-block mountains.

Volcanic Mountains

Most of the world's major volcanic mountains are located at convergent boundaries where oceanic crust sinks into the asthenosphere at subduction zones. The rock that is melted in subduction zones forms magma, which rises to the Earth's surface and erupts to form *volcanic mountains*. Volcanic mountains can also form under the sea. Sometimes these mountains can rise above the ocean surface to become islands. The majority of tectonically active volcanic mountains on the Earth have formed around the tectonically active rim of the Pacific Ocean. The rim has become known as the *Ring of Fire*.

CONNECTION TO Social Studies

WRITING SKILL **The Naming of the Appalachian Mountains** How did the Appalachian Mountains get their name? It is believed that the Appalachian Mountains were named by Spanish explorers in North America during the 16th century. It is thought that the name was taken from a Native American tribe called *Appalachee*, who lived in northern Florida. Research other geological features in the United States, including mountains and rivers, whose names are of Native American origin. Write the results of your research in a short essay.

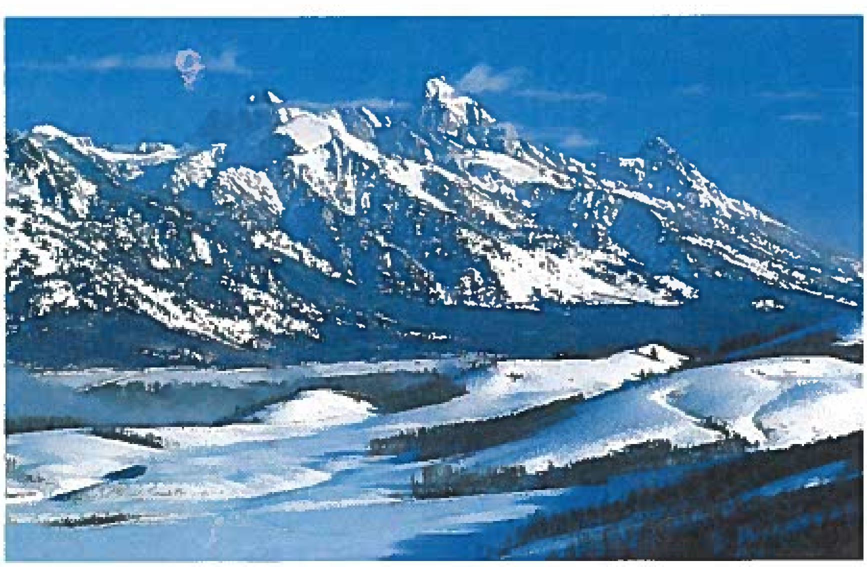


Figure 11 *The Tetons formed as a result of tectonic forces that stretched the Earth's crust and caused it to break in a series of normal faults.*

Uplift and Subsidence

INTERNET ACTIVITY

For another activity related to this chapter, go to **go.hrw.com** and type in the keyword **HZ5TECW.**

Vertical movements in the crust are divided into two types—uplift and subsidence. The rising of regions of Earth's crust to higher elevations is called **uplift.** Rocks that are uplifted may or may not be highly deformed. The sinking of regions of Earth's crust to lower elevations is known as **subsidence** (suhb SIED'ns). Unlike some uplifted rocks, rocks that subside do not undergo much deformation.

uplift the rising of regions of the Earth's crust to higher elevations

subsidence the sinking of regions of the Earth's crust to lower elevations

Uplifting of Depressed Rocks

The formation of mountains is one type of uplift. Uplift can also occur when large areas of land rise without deforming. One way areas rise without deforming is a process known as *rebound*. When the crust rebounds, it slowly springs back to its previous elevation. Uplift often happens when a weight is removed from the crust.

Subsidence of Cooler Rocks

Rocks that are hot take up more space than cooler rocks. For example, the lithosphere is relatively hot at mid-ocean ridges. The farther the lithosphere is from the ridge, the cooler and denser the lithosphere becomes. Because the oceanic lithosphere now takes up less volume, the ocean floor subsides.

Tectonic Letdown

Subsidence can also occur when the lithosphere becomes stretched in rift zones. A *rift zone* is a set of deep cracks that forms between two tectonic plates that are pulling away from each other. As tectonic plates pull apart, stress between the plates causes a series of faults to form along the rift zone. As shown in **Figure 12,** the blocks of crust in the center of the rift zone subside.

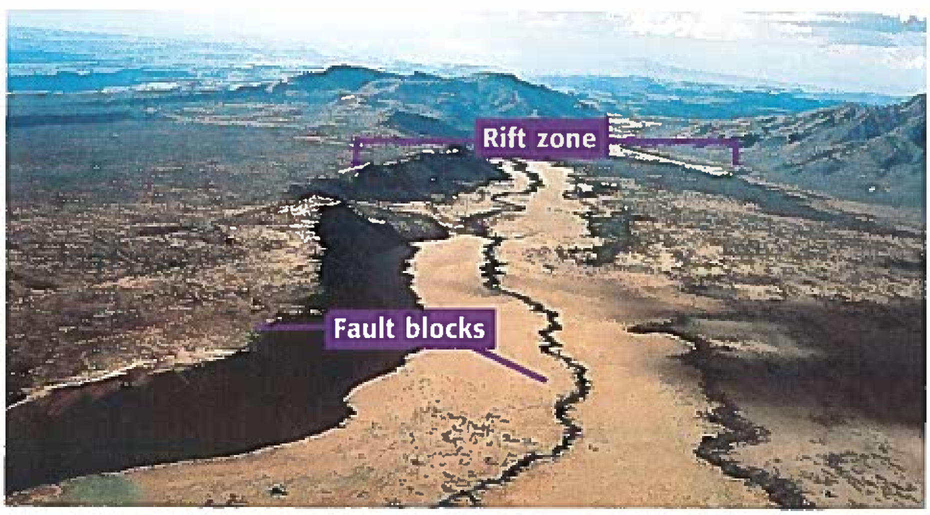


Figure 12 *The East African Rift, from Ethiopia to Kenya, is part of a divergent boundary, but you can see how the crust has subsided relative to the blocks at the edge of the rift zone.*

SECTION Review

Summary

- Compression and tension are two forces of plate tectonics that can cause rock to deform.
- Folding occurs when rock layers bend because of stress.
- Faulting occurs when rock layers break because of stress and then move on either side of the break.
- Mountains are classified as either folded, fault-block, or volcanic depending on how they form.
- Mountain building is caused by the movement of tectonic plates. Folded mountains and volcanic mountains form at convergent boundaries. Fault-block mountains form at divergent boundaries.
- Uplift and subsidence are the two types of vertical movement in the Earth's crust. Uplift occurs when regions of the crust rise to higher elevations. Subsidence occurs when regions of the crust sink to lower elevations.

Using Key Terms

For each pair of key terms, explain how the meanings of the terms differ.

1. *compression* and *tension*
2. *uplift* and *subsidence*

Understanding Key Ideas

3. The type of fault in which the hanging wall moves up relative to the footwall is called a
   - a. strike-slip fault.
   - b. fault-block fault.
   - c. normal fault.
   - d. reverse fault.
4. Describe three types of folds.
5. Describe three types of faults.
6. Identify the most common types of mountains.
7. What is rebound?
8. What are rift zones, and how do they form?

Critical Thinking

9. **Predicting Consequences** If a fault occurs in an area where rock layers have been folded, which type of fault is it likely to be? Why?
10. **Identifying Relationships** Would you expect to see a folded mountain range at a mid-ocean ridge? Explain your answer.

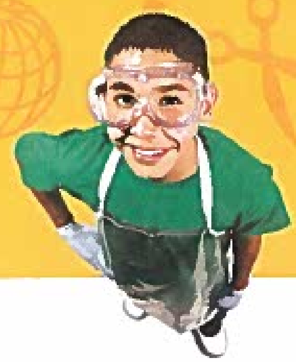
Interpreting Graphics

Use the diagram below to answer the questions that follow.

11. What type of fault is shown in the diagram?
12. At what kind of tectonic boundary would you most likely find this fault?

Using Scientific Methods

Model-Making Lab



Convection Connection

Some scientists think that convection currents within the Earth's mantle cause tectonic plates to move. Because these convection currents cannot be observed directly, scientists use models to simulate the process. In this activity, you will make your own model to simulate tectonic plate movement.

OBJECTIVES

Model convection currents to simulate plate tectonic movement.

Draw conclusions about the role of convection in plate tectonics.

MATERIALS

- craft sticks (2)
- food coloring
- gloves, heat-resistant
- hot plates, small (2)
- pan, aluminum, rectangular
- pencil
- ruler, metric
- thermometers (3)
- water, cold
- wooden blocks

SAFETY

Ask a Question

1. How can I make a model of convection currents in the Earth's mantle?

Form a Hypothesis

2. Turn the question above into a statement in which you give your best guess about what factors will have the greatest effect on your convection model.

Test the Hypothesis

3. Place two hot plates side by side in the center of your lab table. Be sure that they are away from the edge of the table.
4. Place the pan on top of the hot plates. Slide the wooden blocks under the pan to support the ends. Make sure that the pan is level and secure.
5. Fill the pan with cold water. The water should be at least 4 cm deep. Turn on the hot plates, and put on your gloves.
6. After a minute or two, tiny bubbles will begin to rise in the water above the hot plates. Gently place two craft sticks on the water's surface.
7. Use the pencil to align the sticks parallel to the short ends of the pan. The sticks should be about 3 cm apart and near the center of the pan.
8. As soon as the sticks begin to move, place a drop of food coloring in the center of the pan. Observe what happens to the food coloring.

9 With the help of a partner, hold one thermometer bulb just under the water at the center of the pan. Hold the other two thermometers just under the water near the ends of the pan. Record the temperatures.

10 When you are finished, turn off the hot plates. After the water has cooled, carefully empty the water into a sink.

Analyze the Results

1 **Explaining Events** Based on your observations of the motion of the food coloring, how does the temperature of the water affect the direction in which the craft sticks move?

Draw Conclusions

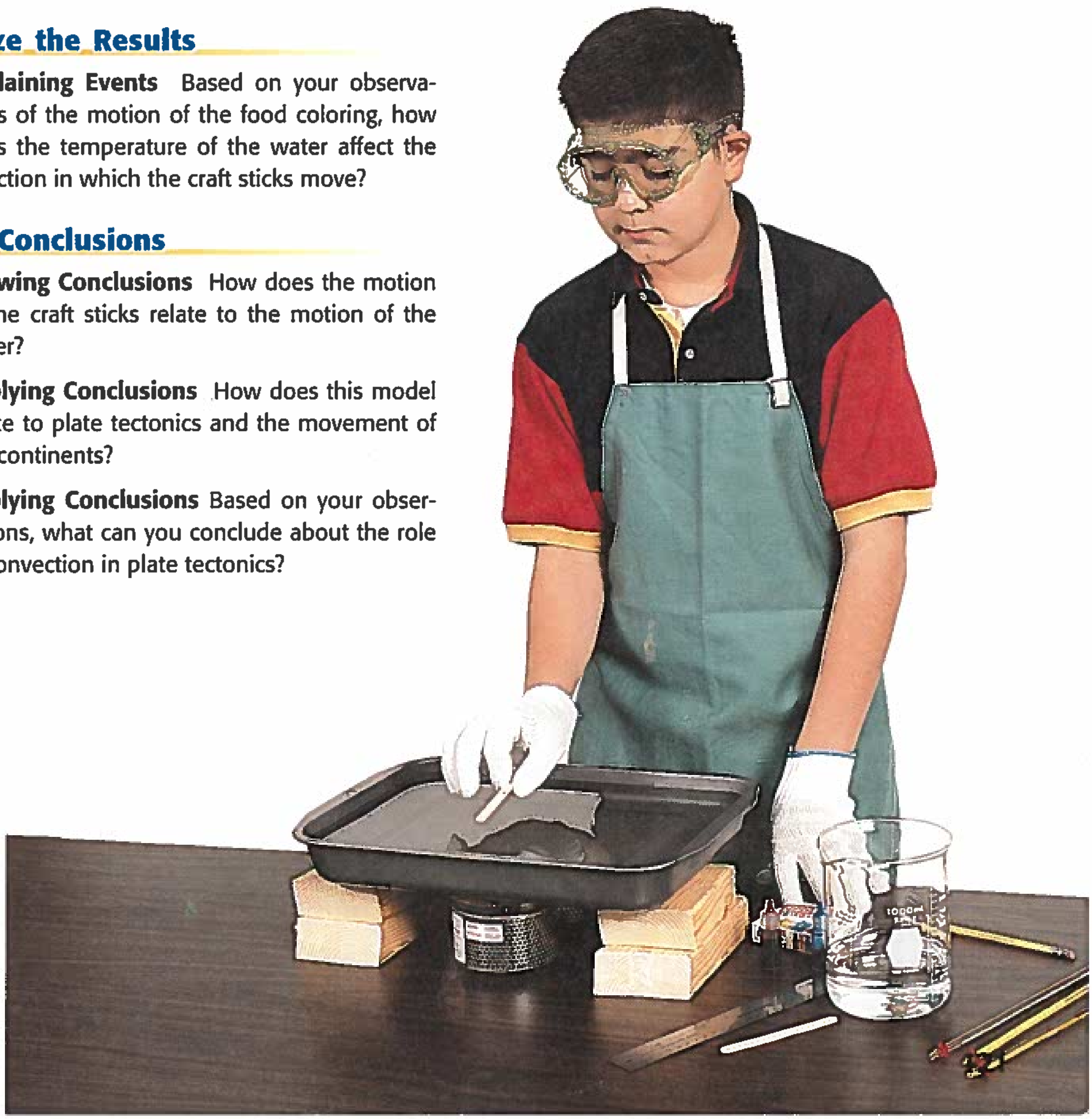
2 **Drawing Conclusions** How does the motion of the craft sticks relate to the motion of the water?

3 **Applying Conclusions** How does this model relate to plate tectonics and the movement of the continents?

4 **Applying Conclusions** Based on your observations, what can you conclude about the role of convection in plate tectonics?

Applying Your Data

Suggest a substance other than water that might be used to model convection in the mantle. Consider using a substance that flows more slowly than water.



Chapter Review

USING KEY TERMS

1 Use the following terms in the same sentence: *crust*, *mantle*, and *core*.

Complete each of the following sentences by choosing the correct term from the word bank.

asthenosphere	uplift
tension	continental drift

2 The hypothesis that continents can drift apart and have done so in the past is known as ___.

3 The ___ is the soft layer of the mantle on which the tectonic plates move.

4 ___ is stress that occurs when forces act to stretch an object.

5 The rising of regions of the Earth's crust to higher elevations is called ___.

UNDERSTANDING KEY IDEAS

Multiple Choice

6 The strong, lower part of the mantle is a physical layer called the
- **a.** lithosphere.
- **b.** mesosphere.
- **c.** asthenosphere.
- **d.** outer core.

7 The type of tectonic plate boundary that forms from a collision between two tectonic plates is a
- **a.** divergent plate boundary.
- **b.** transform plate boundary.
- **c.** convergent plate boundary.
- **d.** normal plate boundary.

8 The bending of rock layers due to stress in the Earth's crust is known as
- **a.** uplift.
- **b.** folding.
- **c.** faulting.
- **d.** subsidence.

9 The type of fault in which the hanging wall moves up relative to the footwall is called a
- **a.** strike-slip fault.
- **b.** fault-block fault.
- **c.** normal fault.
- **d.** reverse fault.

10 The type of mountain that forms when rock layers are squeezed together and pushed upward is the
- **a.** folded mountain.
- **b.** fault-block mountain.
- **c.** volcanic mountain.
- **d.** strike-slip mountain.

11 Scientists' knowledge of the Earth's interior has come primarily from
- **a.** studying magnetic reversals in oceanic crust.
- **b.** using a system of satellites called the *global positioning system*.
- **c.** studying seismic waves generated by earthquakes.
- **d.** studying the pattern of fossils on different continents.

Short Answer

12 Explain how scientists use seismic waves to map the Earth's interior.

13 How do magnetic reversals provide evidence of sea-floor spreading?

14 Explain how sea-floor spreading provides a way for continents to move.

15 Describe two types of stress that deform rock.

16 What is the global positioning system (GPS), and how does GPS allow scientists to measure the rate of motion of tectonic plates?

CRITICAL THINKING

17 **Concept Mapping** Use the following terms to create a concept map: *sea-floor spreading, convergent boundary, divergent boundary, subduction zone, transform boundary,* and *tectonic plates.*

18 **Applying Concepts** Why does oceanic lithosphere sink at subduction zones but not at mid-ocean ridges?

19 **Identifying Relationships** New tectonic material continually forms at divergent boundaries. Tectonic plate material is also continually destroyed in subduction zones at convergent boundaries. Do you think that the total amount of lithosphere formed on the Earth is about equal to the amount destroyed? Why?

20 **Applying Concepts** Folded mountains usually form at the edge of a tectonic plate. How can you explain folded mountain ranges located in the middle of a tectonic plate?

INTERPRETING GRAPHICS

Imagine that you could travel to the center of the Earth. Use the diagram below to answer the questions that follow.

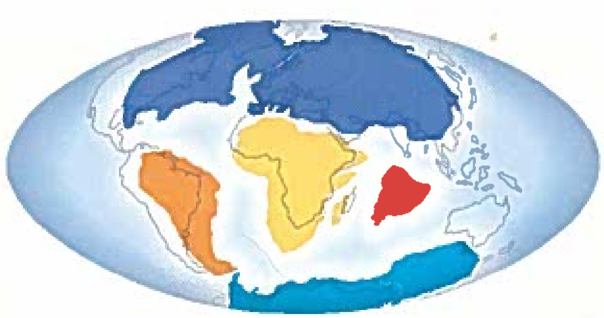
<table>
<tr><th>Composition</th><th>Structure</th></tr>
<tr><td>Crust (50 km)</td><td rowspan="2">Lithosphere (150 km)</td></tr>
<tr><td rowspan="3">Mantle (2,900 km)</td></tr>
<tr><td>Asthenosphere (250 km)</td></tr>
<tr><td>Mesosphere (2,550 km)</td></tr>
<tr><td rowspan="2">Core (3,430 km)</td><td>Outer core (2,200 km)</td></tr>
<tr><td>Inner core (1,228 km)</td></tr>
</table>

21 How far beneath the Earth's surface would you have to go before you were no longer passing through rock that had the composition of granite?

22 How far beneath the Earth's surface would you have to go to find liquid material in the Earth's core?

23 At what depth would you find mantle material but still be within the lithosphere?

24 How far beneath the Earth's surface would you have to go to find solid iron and nickel in the Earth's core?



Standardized Test Preparation

READING

Read each of the passages below. Then, answer the questions that follow each passage.

Passage 1 The Deep Sea Drilling Project was a program to retrieve and research rocks below the ocean to test the hypothesis of sea-floor spreading. For 15 years, scientists studying sea-floor spreading conducted research aboard the ship *Glomar Challenger*. Holes were drilled in the sea floor from the ship. Long, cylindrical lengths of rock, called *cores*, were obtained from the drill holes. By examining fossils in the cores, scientists discovered that rock closest to mid-ocean ridges was the youngest. The farther from the ridge the holes were drilled, the older the rock in the cores was. This evidence supported the idea that sea-floor spreading creates new lithosphere at mid-ocean ridges.

1. In the passage, what does *conducted* mean?
- **A** directed
- **B** led
- **C** carried on
- **D** guided

2. Why were cores drilled in the sea floor from the *Glomar Challenger*?
- **F** to determine the depth of the crust
- **G** to find minerals in the sea-floor rock
- **H** to examine fossils in the sea-floor rock
- **I** to find oil and gas in the sea-floor rock

3. Which of the following statements is a fact according to the passage?
- **A** Rock closest to mid-ocean ridges is older than rock at a distance from mid-ocean ridges.
- **B** One purpose of scientific research on the *Glomar Challenger* was to gather evidence for sea-floor spreading.
- **C** Fossils examined by scientists came directly from the sea floor.
- **D** Evidence gathered by scientists did not support sea-floor spreading.

Passage 2 The Himalayas are a range of mountains that is 2,400 km long and that arcs across Pakistan, India, Tibet, Nepal, Sikkim, and Bhutan. The Himalayas are the highest mountains on Earth. Nine mountains, including Mount Everest, the highest mountain on Earth, are more than 8,000 m tall. The formation of the Himalaya Mountains began about 80 million years ago. A tectonic plate carrying the Indian subcontinent collided with the Eurasian plate. The Indian plate was driven beneath the Eurasian plate. This collision caused the uplift of the Eurasian plate and the formation of the Himalayas. This process is continuing today.

1. In the passage, what does the word *arcs* mean?
- **A** forms a circle
- **B** forms a plane
- **C** forms a curve
- **D** forms a straight line

2. According to the passage, which geologic process formed the Himalaya Mountains?
- **F** divergence
- **G** subsidence
- **H** strike-slip faulting
- **I** convergence

3. Which of the following statements is a fact according to the passage?
- **A** The nine tallest mountains on Earth are located in the Himalaya Mountains.
- **B** The Himalaya Mountains are located within six countries.
- **C** The Himalaya Mountains are the longest mountain range on Earth.
- **D** The Himalaya Mountains formed more than 80 million years ago.