Section 1 Earth's Interior

DISCOVER ACTIVITY

How Do Scientists Determine What's Inside Earth?

1. Your teacher will provide you with three closed film canisters. Each canister contains a different material. Your goal is to determine what is inside each canister—even though you can't directly observe what it contains.
2. Stick a label made from a piece of tape on each canister.
3. To gather evidence about the contents of the canisters, you may tap, roll, shake, or weigh them. Record your observations.
4. What differences do you notice between the canisters? Apart from their appearance on the outside, are the canisters similar in any way? How did you obtain this evidence?

Think It Over

Inferring Based on your observations, what can you infer about the contents of the canisters? How do you think scientists gather evidence about Earth's interior?

GUIDE FOR READING

- What are two main forces that change Earth's surface?
- What makes up Earth's interior?

Reading Tip Before you read, rewrite the headings in the section as *what, how,* or *why* questions. As you read, look for answers to these questions.

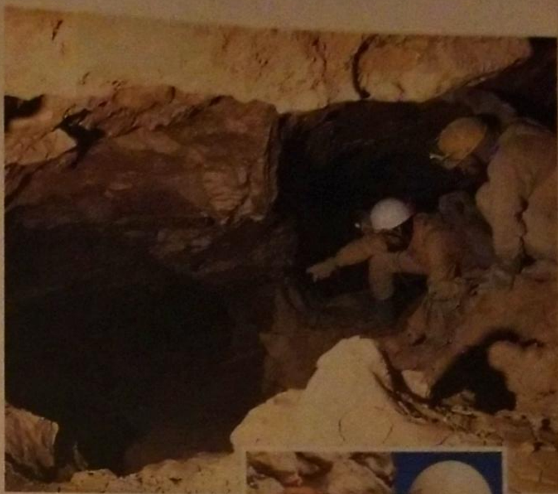
Key Terms geologist • rock • geology • pressure • crust • basalt • granite • mantle • lithosphere • asthenosphere • outer core • inner core

In November 1963, the people of Iceland got to see how new land can be added to Earth's surface. With no warning, the waters south of Iceland began to hiss and bubble. Soon there was a fiery volcanic eruption from beneath the ocean. Steam and ash belched into the sky. Molten rock from inside Earth spurted above the ocean's surface and hardened into a small island. Within the next several years, the new volcano added 2.5 square kilometers of new, raw land to Earth's surface. The Icelanders named the island "Surtsey." In Icelandic mythology, Surtsey is the god of fire.

Figure 1 The island of Surtsey formed in the Atlantic Ocean.

The Science of Geology

Newspapers reported the story of Surtsey's fiery birth. But much of what is known about volcanoes like Surtsey comes from the work of geologists. **Geologists** are scientists who study the forces that make and shape planet Earth. Geologists study the chemical and physical characteristics of **rock,** the material that forms Earth's hard surface. They map where different types of rock are found on and beneath the surface. Geologists describe landforms, the features formed in rock and soil by water, wind, and waves. Geologists study the processes that create Earth's features and search for clues about Earth's history.



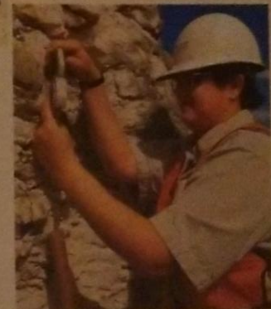


Figure 2 The work of geologists often takes them outdoors—from caves beneath the surface to mountainsides. *Observing What are the geologists in each picture doing?*

The modern science of **geology,** the study of planet Earth, began in the late 1700s. Geologists of that time studied the rocks on the surface. These geologists concluded that Earth's landforms are the work of natural forces that slowly build up and wear down the land.

Studying Surface Changes Forces beneath the surface are constantly changing Earth's appearance. Throughout our planet's long history, its surface has been lifted up, pushed down, bent, and broken. Thus Earth looks different today from the way it did millions of years ago.

Today, geologists divide the forces that change Earth's surface features into two groups: constructive forces and destructive forces. **Constructive forces shape the surface by building up mountains and landmasses. Destructive forces are those that slowly wear away mountains and, eventually, every other feature on the surface.** The formation of the island of Surtsey is an example of constructive forces at work. The ocean waves that will wear away Surtsey's shoreline are an example of Earth's destructive forces.

In the early years of modern geology, only a few facts about Earth's surface were known. Geologists knew that Earth is a sphere with a radius at the equator of more than 6,000 kilometers. They knew that there are seven great landmasses, called continents, that are surrounded by oceans. They knew that the continents are made up of many layers of rock.

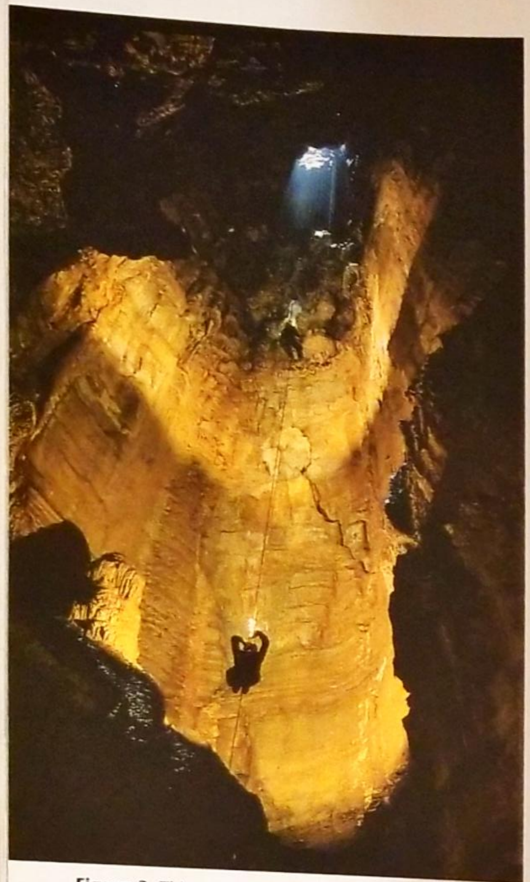


Figure 3 This cave in Georgia may seem deep. But even a deep cave is only a small nick in Earth's surface.

These layers can sometimes be seen on the walls of canyons and the sides of valleys. However, many riddles remained: How old is Earth? How has Earth's surface changed over time? Why are there oceans, and how did they form? For more than 200 years, geologists have tried to answer these and other questions about the planet.

Indirect Evidence—Seismic Waves One of the most difficult questions that geologists have tried to answer is, What's inside Earth? Much as geologists might like to, they cannot dig a hole to the center of Earth. The extreme conditions in Earth's interior prevent exploration far below the surface. The deepest mine in the world, a gold mine in South Africa, reaches a depth of 3.8 kilometers. But it only scratches the surface. You would have to travel more than 1,600 times that distance—over 6,000 kilometers—to reach Earth's center.

Geologists cannot observe Earth's interior directly. Instead, they must rely on indirect methods of observation. Have you ever hung a heavy picture on a wall? If you have, you know that you can knock on the wall to locate the wooden beam underneath the plaster that will support the picture. When you knock on the wall, you listen carefully for a change in the sound.

When geologists want to study Earth's interior, they also use an indirect method. But instead of knocking on walls, they use seismic waves. Recall from Chapter 4 that when earthquakes occur, they produce seismic waves. Geologists record the seismic waves and study how they travel through the medium of Earth. The speed of these seismic waves and the paths they take reveal how the planet is put together. Using data from seismic waves, geologists have learned that Earth's interior is made up of several layers. Each layer surrounds the layers beneath it, much like the layers of an onion.

☑ ***Checkpoint*** *What kind of indirect evidence do geologists use to study the structure of Earth?*

A Journey to the Center of the Earth

If you really could travel through these layers to the center of Earth, what would your trip be like? To begin, you will need a vehicle that can travel through solid rock. The vehicle will carry scientific instruments to record changes in temperature and pressure as you descend.

Temperature As you start to tunnel beneath the surface, you might expect the rock around you to be cool. At first, the surrounding rock is cool. Then at about 20 meters down your instruments report that the surrounding rock is getting warmer. For every 40 meters that you descend from that point, the temperature rises 1 Celsius degree. This rapid rise in temperature continues for several kilometers. After that, the temperature increases more slowly, but steadily.

Pressure During your journey to the center of Earth, your instruments also record an increase in pressure in the surrounding rock. The deeper you go, the greater the pressure. **Pressure** is the force pushing on a surface or area. Because of the weight of the rock above, pressure inside Earth increases as you go deeper.

As you go toward the center of Earth, you travel through several different layers. **Three main layers make up Earth's interior: the crust, the mantle, and the core. Each layer has its own conditions and materials.** You can see these layers in *Exploring Earth's Interior* on pages 320–321.

Language Arts CONNECTION

Imagine taking a trip to the center of Earth. That's what happens in a novel written by Jules Verne in 1864. At that time, scientists knew almost nothing about Earth's interior. Was it solid or hollow? Hot or cold? People speculated wildly. Verne's novel, called *Journey to the Center of the Earth*, describes the adventures of a scientific expedition to explore a hollow Earth. On the way, the explorers follow caves and tunnels down to a strange sea lit by a miniature sun.

In Your Journal

Write a paragraph that describes the most exciting part of your own imaginary journey to Earth's center.

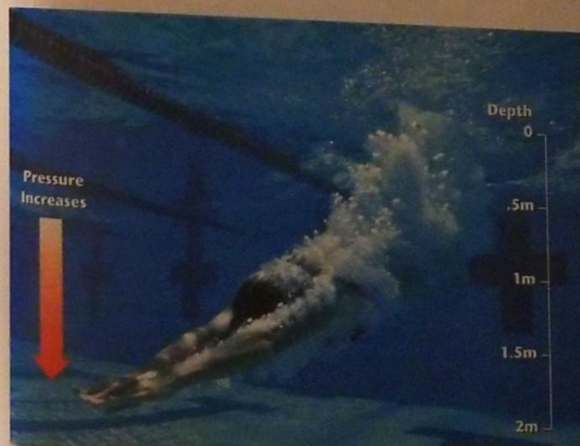


Figure 4 The deeper this swimmer goes, the greater the pressure from the surrounding water. *Comparing and Contrasting* *How is the water in the swimming pool similar to Earth's interior? How is it different?*

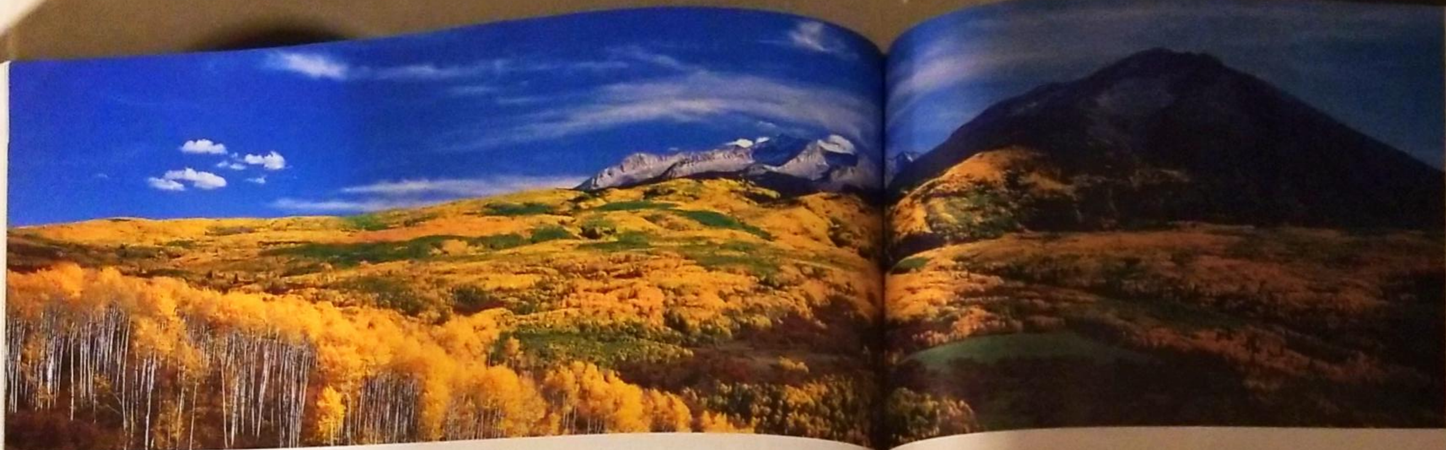


Figure 6 At the surface, Earth's crust forms peaks like these in the Rocky Mountains of Colorado. Soil and plants cover much of the crust. *Comparing and Contrasting How does the thickness of Earth's crust compare to the thickness of the mantle?*

Figure 5 Two of the most common rocks in the crust are basalt and granite. **A.** The dark rock is basalt, which makes up much of the oceanic crust. **B.** The light rock is granite, which makes up much of the continental crust.

The Crust

Your journey to the center of Earth begins in the crust. The **crust** is a layer of rock that forms Earth's outer skin. The crust contains rocks and mountains. But the crust also includes the soil and water that cover large parts of Earth's surface.

This outer rind of rock is much thinner than what lies beneath it. In fact, you can think of Earth's crust as being similar to the paper-thin skin of an onion. The crust includes both the dry land and the ocean floor. It is thinnest beneath the ocean and thickest under high mountains. The crust ranges from 5 to 40 kilometers thick.

The crust beneath the ocean is called oceanic crust. Oceanic crust consists mostly of dense rocks such as basalt. **Basalt** (buh SAWLT) is dark, dense rock with a fine texture. Continental crust, the crust that forms the continents, consists mainly of less dense rocks such as granite. **Granite** is a rock that has larger crystals than basalt and is not as dense. It usually is a light color.

The Mantle

Your journey downward continues. At a depth of between 5 and 40 kilometers beneath the surface, you cross a boundary. Above this boundary are the basalt and granite rocks of the crust. Below the boundary is the solid material of the **mantle,** a layer of hot rock.

The crust and the uppermost part of the mantle are very similar. The uppermost part of the mantle and the crust together form a rigid layer called the **lithosphere** (LITH uh sfeer). In Greek, *lithos* means "stone." The average thickness of the lithosphere is about 100 kilometers.

Next you travel farther into the mantle below the lithosphere. Here your vehicle encounters material that is hotter and under increasing pressure. In general, temperature and pressure in the mantle increase with depth. The heat and pressure make the part of the mantle just beneath the lithosphere less rigid than the rock above. Like road tar softened by the heat of the sun, the material that forms this part of the mantle is somewhat soft—it can bend like plastic. This soft layer is called the **asthenosphere** (as THEHN uh sfeer). In Greek, *asthenes* means "weak." Just because *asthenes* means "weak," you can't assume this layer is actually weak. But the asthenosphere is soft. The material in this layer can flow slowly.

The lithosphere floats on top of the asthenosphere. Beneath the asthenosphere, which extends to a depth of 350 kilometers, solid mantle material extends all the way to Earth's core. The mantle is nearly 3,000 kilometers thick.

☑ ***Checkpoint*** *How does the material of the asthenosphere differ from the material of the lithosphere?*

The Core

After traveling through the mantle, you reach the core. Earth's core consists of two parts—a liquid outer core and a solid inner core. The metals iron and nickel make up both parts of the core. The **outer core** is a layer of molten metal that surrounds the inner core. In spite of enormous pressure, the outer core behaves like a thick liquid. The **inner core** is a dense ball of solid metal. In the inner core, extreme pressure squeezes the atoms of iron and nickel so much that they cannot spread out and become liquid.

The outer and inner cores make up about one third of Earth's mass, but only 15 percent of its volume. The inner and outer cores together are just slightly smaller than the moon.

Sharpen your Skills

Creating Data Tables

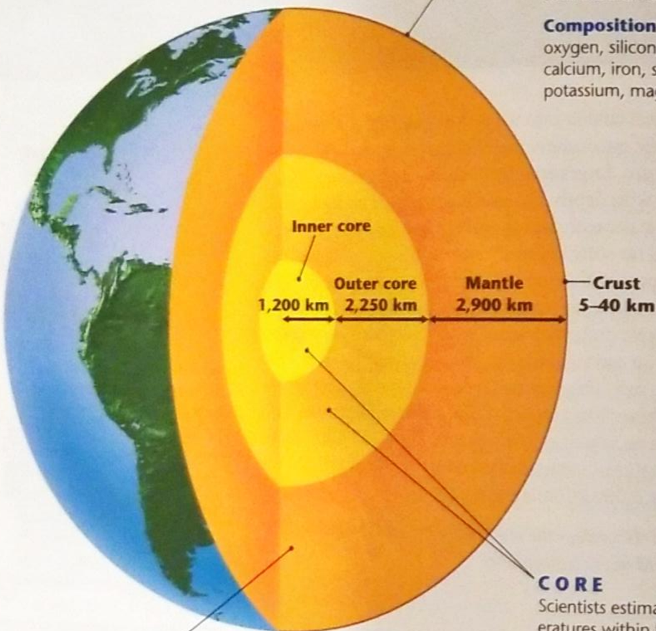
ACTIVITY

Imagine that you have invented a super-strong vehicle that can resist extremely high pressure as it bores a tunnel deep into Earth's interior. You stop several times on your trip to collect data using devices located on your vehicle's outer hull. To see what conditions you would find at various depths on your journey, refer to *Exploring Earth's Interior* on pages 320–321. Copy the table in your notebook or make one on the computer. Then complete the table.

Depth	Name of Layer	What Layer Is Made Of
20 km		
150 km		
2,000 km		
4,000 km		
6,000 km		

EXPLORING *Earth's Interior*

Earth's interior is divided into layers: the crust, mantle, outer core, and inner core. Although Earth's crust seems stable, the extreme heat of Earth's interior causes changes that slowly reshape the surface.



CRUST
The crust is Earth's solid and rocky outer layer, including both the land surface and the ocean floor. The crust averages 32 km thick. At the scale of this drawing, the crust is too thin to show up as more than a thin line.

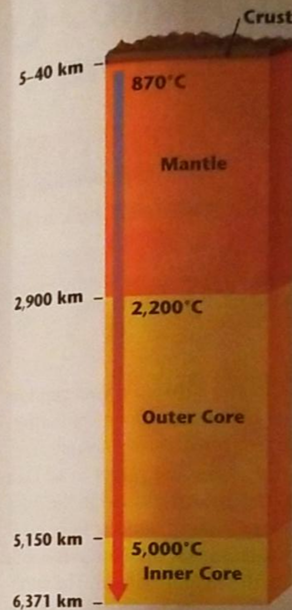
Composition of crust:
oxygen, silicon, aluminum, calcium, iron, sodium, potassium, magnesium

MANTLE
A trip through Earth's mantle goes almost halfway to the center of Earth. The chemical composition of the mantle does not change much from one part of the mantle to another. However, physical conditions in the mantle change because pressure and temperature increase with depth.

Composition of mantle:
silicon, oxygen, iron, magnesium

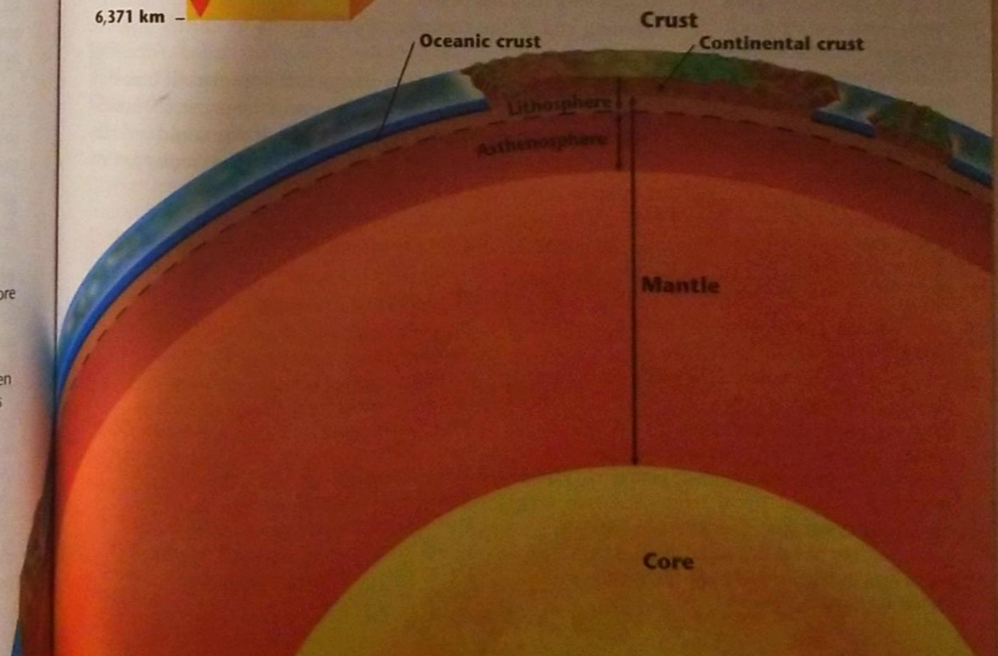
CORE
Scientists estimate that temperatures within Earth's outer core and inner core, both made of iron and nickel, range from about 2,000°C to 5,000°C. If these estimates are correct, then Earth's center may be as hot as the sun's surface.

Composition of core:
iron, nickel



◀ CROSS SECTION FROM SURFACE TO CENTER
From Earth's surface to its center, the layers of Earth's interior differ in their composition, temperature, and pressure. Notice how temperature increases toward the inner core.

CRUST-TO-MANTLE
The rigid crust and lithosphere float on the hot, soft material of the asthenosphere. Notice that continental crust, made mostly of granite, is several times thicker than oceanic crust, made mostly of basalt. ▼



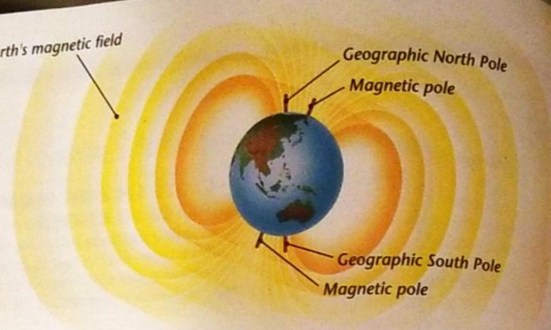


Figure 7 Like a magnet, Earth's magnetic field has north and south poles.

Sharpen your Skills

Interpreting Data — ACTIVITY

Set a compass on a white piece of paper on your desk. Turn the compass until the needle lines up with north. Mark the directions North, South, East, and West on the paper. Move a magnet up and down close to the compass. What happens to the compass needle? Explain your observations.

Earth's Magnetic Field

INTEGRATING PHYSICS Recall from Chapter 3 that in convection, heat is transferred by the movement of currents within a liquid. These currents are called convection currents. Earth's magnetic field—a force that causes the planet to act like a giant bar magnet—is created by convection currents in the liquid outer core. As you can see in Figure 7, the magnetic field affects the whole Earth. When you use a compass, the compass needle aligns with the lines of force in Earth's magnetic field. The north-seeking end of the compass needle points to Earth's magnetic north pole.

Consider an ordinary bar magnet. If you place it beneath a piece of paper and sprinkle iron filings on the paper, the iron filings line up with the bar's magnetic field. If you could cover the entire planet with iron filings, they would form a similar pattern.

Section 1 Review

1. Describe how constructive and destructive forces shape the surface of Earth.
2. What are the layers that make up Earth? Write a sentence about each one.
3. What happens in Earth's interior to produce Earth's magnetic field? Describe the layers of the interior where the magnetic field is produced.
4. **Thinking Critically Comparing and Contrasting** What are some of the differences and similarities between the mantle and the core? Explain.

Check Your Progress — CHAPTER PROJECT

Begin by sketching a cross section of Earth's crust and the different layers of the upper mantle. How can your model show these layers along with Earth's plates and other surface features? How can you show the thickness of the different layers at the correct scale? Think about materials you can use for your model. Using the map on page 341, pick a plate to investigate. Research this plate's movements and how it interacts with neighboring plates.

SECTION 2 Convection Currents and the Mantle

DISCOVER — ACTIVITY

How Can Heat Cause Motion in a Liquid?

1. ⚠ Carefully pour some hot water into a small, shallow pan. Fill a clear, plastic cup about half-full with cold water. Place the cup in the pan.
2. Allow the water to stand for two minutes until all motion stops.
3. Fill a plastic dropper with some food coloring. Then, holding the dropper under the water surface and slightly away from the edge of the cup, gently squeeze a small droplet of the food coloring into the water.
4. Observe the water for one minute.
5. Add another droplet at the water surface in the middle of the cup and observe again.

Think It Over

Inferring How do you explain what happened to the droplets of food coloring? Why do you think the second droplet moved in a way that was different from the way the first droplet moved?

GUIDE FOR READING

- How is heat transferred?
- What causes convection currents in Earth's mantle?

Reading Tip As you read, draw a concept map of the three types of heat transfer. Include supporting ideas about convection.

Key Term density

Earth's molten outer core is nearly as hot as the surface of the sun. To explain how heat from the core affects the mantle, you need to recall how heat is transferred in solids and liquids. If you have ever touched a hot pot accidentally, you have discovered for yourself (in a painful way) that heat moves. In this case, it moved from the hot pot to your hand. The movement of energy from a warmer object to a cooler object is called heat transfer.

Heat is always transferred from a warmer substance to a cooler substance. For example, holding an ice cube will make your hand begin to feel cold in a few seconds. But is the coldness in the ice cube moving to your hand? Since cold is the absence of heat, it's the heat in your hand that moves to the ice cube! **Heat is transferred through radiation, conduction, and convection.**

Radiation

Recall from Chapter 3 that radiation is the transfer of energy by electromagnetic waves. Radiation does not require matter to transfer heat, or thermal energy. Sunlight is radiation that warms Earth's surface. The process takes place with no direct contact between the sun and Earth's surface. Other familiar forms of radiation include the heat you feel around a flame or open fire.

Figure 8 In conduction, the heated particles of a substance transfer heat to other particles through direct contact. That's how the spoon and the pot itself heat up.

Conduction

Remember that heat transfer by direct contact of particles of matter is called conduction. What happens as a spoon heats up in a pot of soup? Heat is transferred from the hot soup and the pot to the particles that make up the spoon. The particles near the bottom of the spoon vibrate faster as they are heated, so they bump into other particles and heat them, too. Gradually the entire spoon heats up. When your hand touches the spoon, conduction transfers heat from the spoon directly to your skin. Then you feel the heat. Look at Figure 8 to see how heat flows in this system.

Convection

Conduction heats the spoon, but how does the soup inside the pot heat up? Recall from Chapter 3 that heat transfer involving the movement of fluids—liquids and gases—is called convection. Convection is heat transfer by the movement of a heated fluid. During convection, heated particles of fluid begin to flow, transferring heat energy from one part of the fluid to another.

Heat transfer by convection is caused by differences of temperature and density within a fluid. **Density** is a measure of how much mass there is in a volume of a substance. For example, rock is more dense than water because a given volume of rock has more mass than the same volume of water.

When a liquid or gas is heated, the particles move faster. As the particles move faster, they spread apart. Because the particles of the heated fluid are farther apart, they occupy more space. The density decreases. But when a fluid cools, its particles move more slowly and settle together more closely. As the fluid becomes cooler, its density increases.

Figure 9 In this pot, the soup close to the heat source is hotter and less dense than the soup near the surface. These differences in temperature and density cause convection currents.

Convection occurs when you heat soup on a stove. As the soup at the bottom of the pot gets hot, it expands and therefore becomes less dense. The warm, less dense soup moves upward and floats over the cooler, denser soup. At the surface, the warm soup spreads out and cools, becoming denser. Then, gravity pulls this cooler, denser soup back down to the bottom of the pot, where it is heated again. Figure 9 shows this pattern of movement.

A constant flow begins as the cooler soup continually sinks to the bottom of the pot and the warmer soup rises. A convection current is the flow that transfers heat within a fluid.

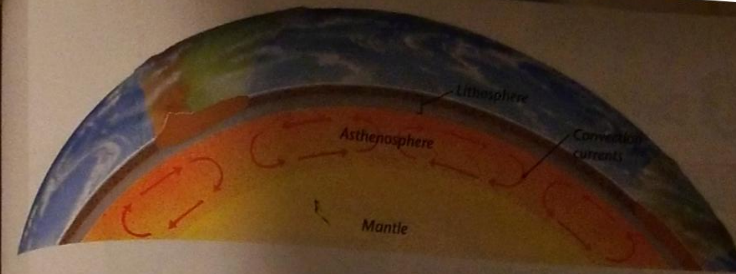


Figure 10 Heat from Earth's mantle and core causes convection currents to form in the asthenosphere. Some geologists think convection currents extend throughout the mantle. *Applying Concepts What part of Earth's interior is like the soup in the pot? What part is like the burner on the stove?*

The heating and cooling of a fluid, changes in the fluid's density, and the force of gravity combine to set convection currents in motion. Convection currents continue as long as heat is added. What happens after the heat source is removed? Without heat, the convection currents will eventually stop when all of the material has reached the same temperature.

Checkpoint *What is convection?*

Convection in Earth's Mantle

Like soup simmering in a pot, Earth's mantle responds to heat. You can see in Figure 10 how some geologists think convection currents flow in the asthenosphere. **Heat from Earth's core and from the mantle itself causes the convection currents in the mantle.** Hot columns of mantle material rise slowly through the asthenosphere. At the top of the asthenosphere, the hot material spreads out and pushes the cooler material out of the way. This cooler material sinks back into the asthenosphere. Over and over, the cycle of rising and sinking takes place. Convection currents like these have been moving inside Earth for more than four billion years!

Section 2 Review

1. What are the three types of heat transfer?
2. Describe how convection currents form.
3. In general, what happens to the density of a fluid when it becomes hotter?
4. What happens to convection currents when a fluid reaches a constant temperature?
5. **Thinking Critically** **Predicting** What will happen to the flow of hot rock in Earth's mantle if the planet's core eventually cools down? Explain your answer.

Science at Home

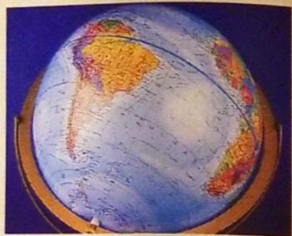
Convection and Home Heating
Convection currents may keep the air inside your home at a comfortable temperature. Air is made up of gases, so it is a fluid. Regardless of the type of home heating system, heated air circulates through a room by convection. You may have tried to adjust the flow of air in a stuffy room by opening a window. When you did so, you were making use of convection currents. With an adult family member, study how your home is heated. Look for evidence of convection currents.

SECTION
3 Drifting Continents

DISCOVER ACTIVITY

How Are Earth's Continents Linked Together?

1. Find the oceans and the seven continents on a globe showing Earth's physical features.
2. How much of the globe is occupied by the Pacific Ocean? Does most of Earth's "dry" land lie in the Northern or Southern hemisphere?
3. Find the points or areas where most of the continents are connected. Find the points at which several of the continents almost touch, but are not connected.
4. Examine the globe more closely. Find the great belt of mountains running from north to south along the western side of North and South America. Look for another great belt of mountains on the globe.



Think It Over

Posing Questions What questions can you pose about how oceans, continents, and mountains are distributed on Earth's surface?

GUIDE FOR READING

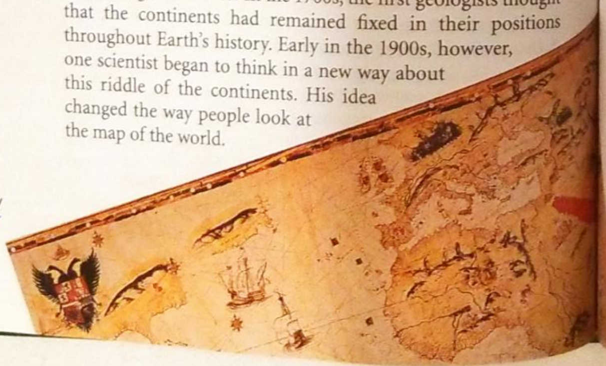
- What was Wegener's hypothesis of continental drift?
- Why was Alfred Wegener's hypothesis rejected by most scientists of his day?

Reading Tip As you read, look for evidence that supports the hypothesis of continental drift.

Key Terms Pangaea • continental drift • fossil

Five hundred years ago, the sea voyages of Columbus and other explorers changed the map of the world. The continents of Europe, Asia, and Africa were already known to mapmakers. Soon mapmakers were also showing the outlines of the continents of North and South America. Looking at these world maps, many people wondered why the coasts of several continents matched so neatly.

Look at the modern world map in Figure 11. Notice how the coasts of Africa and South America look as if they could fit together like jigsaw-puzzle pieces. Could the continents have once been a single landmass? In the 1700s, the first geologists thought that the continents had remained fixed in their positions throughout Earth's history. Early in the 1900s, however, one scientist began to think in a new way about this riddle of the continents. His idea changed the way people look at the map of the world.



World map drawn by Juan Vespucci in 1526 ▶

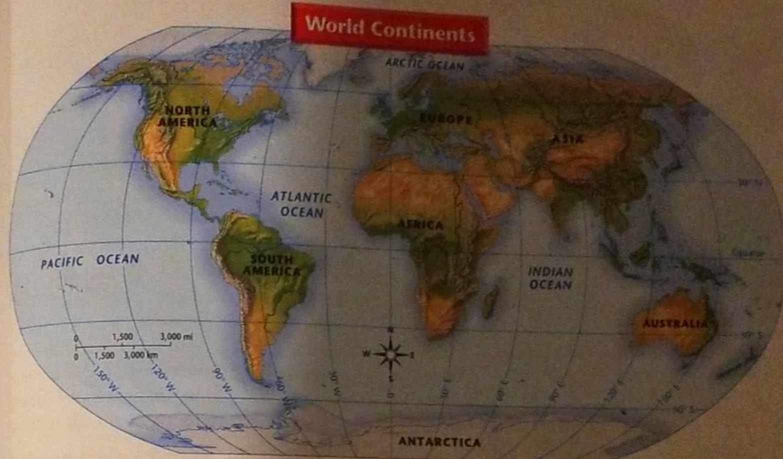


Figure 11 Today's continents provide clues about Earth's history. ***Observing*** *Which coastlines of continents seem to match up like jigsaw-puzzle pieces?*

Continental Drift

In 1910, a young German scientist named Alfred Wegener (VAY guh nur) became curious about the relationship of the continents. He formed a hypothesis that Earth's continents had moved! **Wegener's hypothesis was that all the continents had once been joined together in a single landmass and have since drifted apart.**

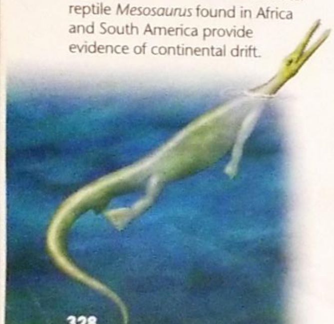
Wegener named this supercontinent **Pangaea** (pan JEE uh), meaning "all lands." According to Wegener, Pangaea existed about 300 million years ago. This was the time when the fossil record contains the first evidence that reptiles and winged insects lived on Earth. Also, tropical forests, which later formed coal deposits, covered much of Earth.

Wegener hypothesized that over tens of millions of years, Pangaea began to break apart. The pieces of Pangaea slowly moved toward their present-day locations, becoming the continents as they are today. Wegener's idea that the continents slowly moved over Earth's surface became known as **continental drift.**

Have you ever tried to persuade a friend to accept a new idea? You probably had to provide some convincing evidence. Wegener gathered evidence from different scientific fields to support his ideas about continental drift. In particular, he studied landforms, fossils, and evidence that showed how Earth's climate had changed over many millions of years. Wegener published all his evidence for continental drift in a book called *The Origin of Continents and Oceans*, first published in 1915.

Figure 12 Wegener and modern geologists point to several types of evidence to support the idea that the continents were once joined in a single landmass called Pangaea. *Inferring According to Wegener's hypothesis, what does the presence of similar mountain ranges in Africa and South America indicate?*

Figure 13 Fossils of the freshwater reptile *Mesosaurus* found in Africa and South America provide evidence of continental drift.



Evidence From Landforms Wegener thought that mountain ranges and other features on the continents provided evidence for continental drift. When he pieced together maps of Africa and South America, he saw a mountain range running from east to west in South Africa that lined up with a mountain range in Argentina. European coal fields matched up with similar coal fields in North America. Wegener compared matching these features to reassembling a torn-up newspaper. If the pieces could be put back together, the "words" would match.

Evidence From Fossils Wegener also used fossil evidence as support for continental drift. A **fossil** is a trace of an organism that has been preserved in rock. For example, fossils of the reptiles *Mesosaurus* and *Lystrosaurus* had been found in places now separated by oceans. Neither reptile could have swum long distances across salt water. Therefore, Wegener concluded that these reptiles once lived on a single landmass. Another example was *Glossopteris* (glaw SAHP tuh ris), a fernlike plant that lived 250 million years ago. *Glossopteris* fossils had been found in rocks in Africa, South America, Australia, India, and Antarctica. The occurrence of *Glossopteris* on these widely separated landmasses convinced Wegener that the continents had once been united.

Figure 14 Fossils of *Glossopteris* are found on continents in the Southern Hemisphere and in India.

INTEGRATING LIFE SCIENCE The seedlike structures of *Glossopteris* could not have traveled across the distances that separate the continents today. The "seeds" were too large for the wind to carry and too fragile to have survived an ocean trip. How did *Glossopteris* come to live on such widely separated continents? Wegener inferred that the continents at that time were joined as the supercontinent Pangaea.

Evidence From Climate Wegener also used evidence of climate change to support his hypothesis of continental drift. Spitsbergen is an island in the Arctic Ocean north of Norway. This island is ice-covered and has a harsh polar climate. But fossils of tropical plants had been found on Spitsbergen. When these plants lived about 300 million years ago, the island must have had a warm and mild climate. Wegener concluded that Spitsbergen must have been located closer to the equator at that time.

Thousands of kilometers to the south, geologists had found evidence that at the same time it was warm in Spitsbergen, the climate was much colder in South Africa. This evidence included deep scratches in rocks that showed that continental glaciers once covered South Africa. Continental glaciers are thick layers of ice that cover hundreds of thousands of square kilometers. But the climate of South Africa is too mild today for continental glaciers to form. Wegener concluded that, when Pangaea existed, South Africa was much closer to the South Pole.

According to Wegener, these clues provide evidence that continental drift happened. The climates of Spitsbergen and South Africa changed because the positions of these places on Earth's surface changed. As a continent moves toward the equator, its climate becomes warmer. As a continent moves toward the poles, its climate becomes colder. But the continent carries with it the fossils and rocks that formed at its previous location.

☑ ***Checkpoint*** *What were the three types of evidence Wegener used to support his hypothesis of continental drift?*

TRY THIS

Reassembling the Pieces ACTIVITY

Assembling a puzzle can reveal a hidden meaning.

1. Working with a partner, obtain one sheet of newspaper per person.
2. Tear your sheet of newspaper into six to eight large pieces. Trade your pieces with your partner.
3. Try to fit the pieces of newspaper together.

Making Models What evidence did you use to put the pieces together? How do your pieces of newspaper serve as a model of the theory of continental drift?

Figure 15 Although scientists rejected his hypothesis, Wegener continued to collect evidence for continental drift and to update his book. He died in 1930 on an expedition to explore Greenland's continental glacier.

Scientists Reject Wegener's Hypothesis

Wegener did more than provide a hypothesis about continental drift. He attempted to explain how drift took place. He even offered a new explanation for how mountains form. Wegener thought that when drifting continents collide, their edges crumple and fold. The folding continents slowly push up huge chunks of rock to form great mountains.

However, Wegener could not provide a satisfactory explanation for the force that pushes or pulls the continents. Because Wegener could not identify the cause of continental drift, most geologists rejected his idea. In addition, for geologists to accept Wegener's idea, they would need to change their own explanations of what caused continents and mountains to form.

Many geologists in the early 1900s thought that Earth was slowly cooling and shrinking. According to this idea, mountains formed when the crust wrinkled like the skin of a dried-up apple. Wegener said that if the apple hypothesis were correct, then mountains should be found all over Earth's surface. But mountains usually occur in narrow bands along the edges of continents. Wegener thought that his own hypothesis better explained where mountains occur and how they form.

For nearly half a century, from the 1920s to the 1960s, most scientists paid little attention to the idea of continental drift. Then new evidence about Earth's structure led scientists to reconsider Wegener's bold hypothesis.

Section 3 Review

1. What was Wegener's hypothesis of continental drift?
2. How did Wegener use evidence based on fossils to support his hypothesis that the continents had moved?
3. What was the main reason scientists rejected Wegener's hypothesis of continental drift?
4. **Thinking Critically** **Inferring** Coal deposits have also been found beneath the ice of Antarctica. But coal only forms in warm swamps. Use Wegener's hypothesis to explain how coal could be found so near the poles.

Science at Home

Moving the Continents You can demonstrate Wegener's idea of continental drift. Use the world map in Figure 11. On a sheet of tracing paper, trace the outlines of the continents bordering the Atlantic Ocean. Label the continents. Then use scissors to carefully cut the map along the eastern edge of South America, North America, and Greenland. Next, cut along the western edge of Africa and Europe (including the British Isles). Throw away the Atlantic Ocean. Place the two cut-out pieces on a dark surface and ask family members to try to fit the two halves together. Explain to them about the supercontinent Pangaea and its history.

Section 4 Sea-Floor Spreading

Discover Activity

What Is the Effect of a Change in Density?

1. Partially fill a sink or dishpan with water.
2. Open up a dry washcloth in your hand. Does the washcloth feel light or heavy?
3. Moisten one edge of the washcloth in the water. Then gently place the washcloth so that it floats on the water's surface. Observe the washcloth carefully (especially at its edges) as it starts to sink.
4. Remove the washcloth from the water and open it up in your hand. Is the mass of the washcloth the same as, less than, or greater than when it was dry?

Think It Over

Observing How did the washcloth's density change? What effect did this change in density have on the washcloth?

Deep in the ocean, the temperature is near freezing. There is no light, and living things are generally scarce. Yet some areas of the deep-ocean floor are teeming with life. One of these areas is the East Pacific Rise, a region of the Pacific Ocean floor off the coasts of Mexico and South America. Here, ocean water sinks through cracks, or vents, in the crust. The water is heated by contact with hot material from the mantle and then spurts back into the ocean.

Around these hot-water vents live some of the most bizarre creatures ever discovered. Giant, red-tipped tube worms sway in the water. Nearby sit giant clams nearly a meter across. Strange spiderlike crabs scuttle by. Surprisingly, the geological features of this strange environment provided scientists with evidence that strongly supports Wegener's hypothesis of continental drift.

Guide for Reading

- What is the process of sea-floor spreading?
- What happens to the ocean floor at deep ocean trenches?

Reading Tip Before you read, preview the art and captions looking for new terms. As you read, find the meanings of these terms.

Key Terms mid-ocean ridge
- sea-floor spreading
- deep-ocean trench
- subduction

Figure 16 Tube worms cluster near hot water vents in the ocean floor.

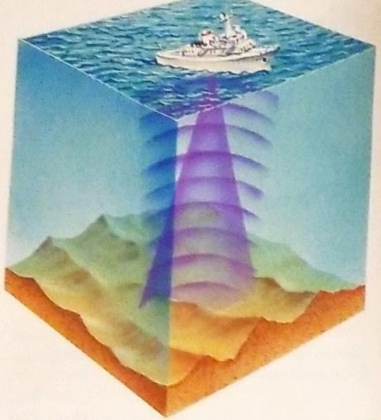


Figure 17 Scientists use sonar to map the ocean floor.

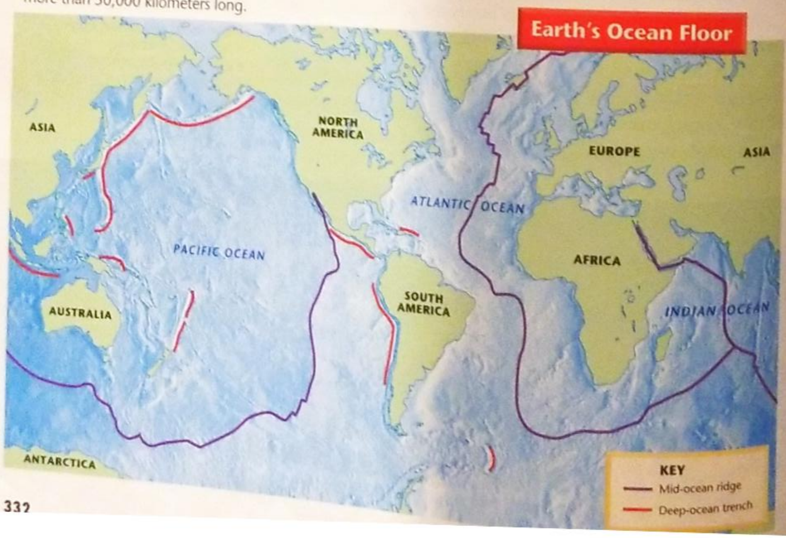
Mapping the Mid-Ocean Ridge

The East Pacific Rise is just one part of the **mid-ocean ridge,** the longest chain of mountains in the world. In the mid-1900s, scientists mapped the mid-ocean ridge using sonar. Recall from Chapter 5 that a sonar device bounces sound waves off underwater objects and then records the echoes of these sound waves. The time it takes for the echo to arrive indicates the distance to the object.

The mid-ocean ridge curves like the seam of a baseball along the sea floor, extending into all of Earth's oceans. Most of the mountains in the mid-ocean ridge lie hidden under hundreds of meters of water. However, there are places where the ridge pokes above the surface. For example, the island of Iceland is a part of the mid-ocean ridge that rises above the surface in the North Atlantic Ocean. A steep-sided valley splits the top of the mid-ocean ridge for most of its length. The valley is almost twice as deep as the Grand Canyon. The mapping of the mid-ocean ridge made scientists curious to know what the ridge was and how it got there.

☑ *Checkpoint What device is used to map the ocean floor?*

Figure 18 The mid-ocean ridge is more than 50,000 kilometers long.



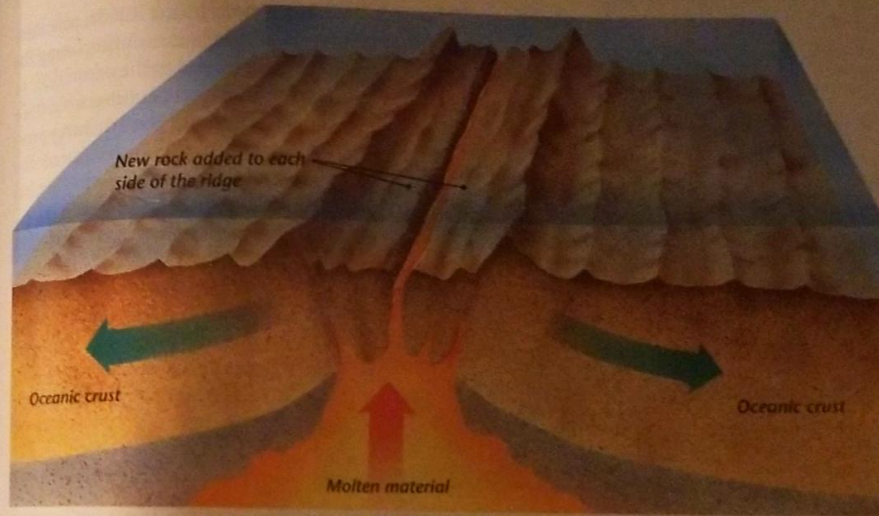


Figure 19 Molten material erupts though the valley that runs along the center of the mid-ocean ridge. This material hardens to form the rock of the ocean floor. *Applying Concepts What happens to the rock along the ridge when new molten material erupts?*

Evidence for Sea-Floor Spreading

Harry Hess, an American geologist, was one of the scientists who studied the mid-ocean ridge. Hess carefully examined maps of the mid-ocean ridge. Then he began to think about the ocean floor in relation to the problem of continental drift. Finally, he reconsidered an idea that he previously had thought impossible: Maybe Wegener was right! Perhaps the continents do move.

In 1960, Hess proposed a radical idea. He suggested that the ocean floors move like conveyor belts, carrying the continents along with them. This movement begins at the mid-ocean ridge. The mid-ocean ridge forms along a crack in the oceanic crust. **At the mid-ocean ridge, molten material rises from the mantle and erupts. The molten material then spreads out, pushing older rock to both sides of the ridge.** As the molten material cools, it forms a strip of solid rock in the center of the ridge. Then more molten material flows into the crack. This material splits apart the strip of solid rock that formed before, pushing it aside.

Hess called the process that continually adds new material to the ocean floor **sea-floor spreading.** He realized that the sea floor spreads apart along both sides of the mid-ocean ridge as new crust is added. Look at Figure 19 to see the process of sea-floor spreading.

Several types of evidence from the oceans supported Hess's idea of sea-floor spreading—evidence from molten material, magnetic stripes, and drilling samples. This evidence also led sci-

Figure 20 The submersible *Alvin* photographed pillow lava along the mid-ocean ridge. These "pillows" form under water when cold ocean water causes a crust to form on erupting molten material. Each pillow expands until it bursts, allowing molten material to flow out and form the next pillow.

Evidence From Molten Material In the 1960s, scientists found evidence that new material is indeed erupting along the mid-ocean ridge. The scientists were carried to the ocean floor in *Alvin*, a small submersible built to withstand the crushing pressures four kilometers below the ocean's surface. In the central valley of the mid-ocean ridge, *Alvin's* crew found strange rocks shaped like pillows or like toothpaste squeezed from a tube. Such rocks can form only when molten material hardens quickly after erupting under water. The presence of these rocks showed that molten material has erupted again and again from cracks along the central valley of the mid-ocean ridge.

Evidence From Magnetic Stripes When scientists studied patterns in the rocks of the ocean floor, they found more support for sea-floor spreading.

INTEGRATING PHYSICS

In Section 1 you read that Earth behaves like a giant magnet, with a north pole and a south pole. Evidence shows that Earth's magnetic poles have reversed themselves. This last happened 780,000 years ago. If the magnetic poles suddenly reversed themselves today, you would find that your compass needle pointed south. Scientists discovered that the rock that makes up the ocean floor lies in a pattern of magnetized "stripes." These stripes hold a record of reversals in Earth's magnetic field.

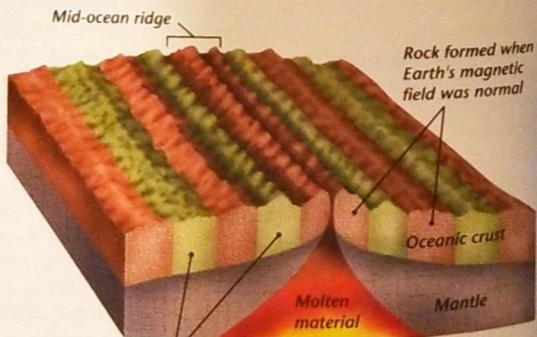


Figure 21 Magnetic stripes in the rock of the ocean floor show the direction of Earth's magnetic field at the time the rock hardened. *Interpreting Diagrams How does the pattern of matching stripes show evidence of sea-floor spreading?*

The rock of the ocean floor, which contains iron, began as molten material. As the molten material cooled, the iron inside lined up in the direction of Earth's magnetic poles. When the rock hardened completely, it locked the iron in place, giving the rocks a permanent "magnetic memory." You can think of it as setting thousands of tiny compass needles in cement.

Using sensitive instruments, scientists recorded the magnetic memory of rocks on both sides of the mid-ocean ridge. They found that a stripe of rock that shows when Earth's magnetic field pointed north is followed by a parallel stripe of rock that shows when the magnetic field pointed south. As you can see in Figure 21, the pattern is the same on both sides of the ridge. Rock that hardens at the same time has the same magnetic memory.

Evidence From Drilling Samples Additional proof of sea-floor spreading came from rock samples obtained by drilling into the ocean floor. The *Glomar Challenger*, a drilling ship built in 1968, gathered the samples. The *Glomar Challenger* sent drilling pipes through water 6 kilometers deep to drill holes in the ocean floor. This feat has been compared to using a sharp-ended wire to dig a hole into a sidewalk from the top of the Empire State Building.

Samples from the sea floor were brought up through the pipes. Then the scientists determined the ages of the rocks in the samples. They found that the farther away from the ridge, the older the rocks were. The youngest rocks were always in the center of the ridges. The combined evidence is strong support for the idea that sea-floor spreading has taken place.

✓ *Checkpoint* ***What evidence did scientists find for sea-floor spreading?***

TRY THIS

Reversing Poles

ACTIVITY

1. Cut six short pieces, each about 2.5 cm long, from a length of audiotape.
2. Tape one end of each piece of audiotape to a flat surface. The pieces should be spaced 1 cm apart and line up lengthwise in a single line.
3. Touch a bar magnet's north pole to the first piece of audiotape. Then reverse the magnet and touch its south pole to the next piece.
4. Repeat Step 3 until you have applied the magnet to each piece of audiotape.
5. Sweep one end of the magnet about 1 cm above the line of audiotape pieces. Observe what happens.

Making Models What characteristic of the ocean floor did you observe as you swept the magnet along the line of audiotape pieces?

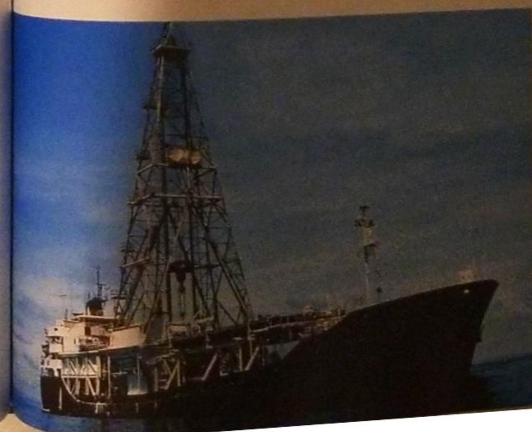


Figure 22 The *Glomar Challenger* was the first research ship designed to drill samples of rock from the deep-ocean floor.

Subduction at Deep-Ocean Trenches

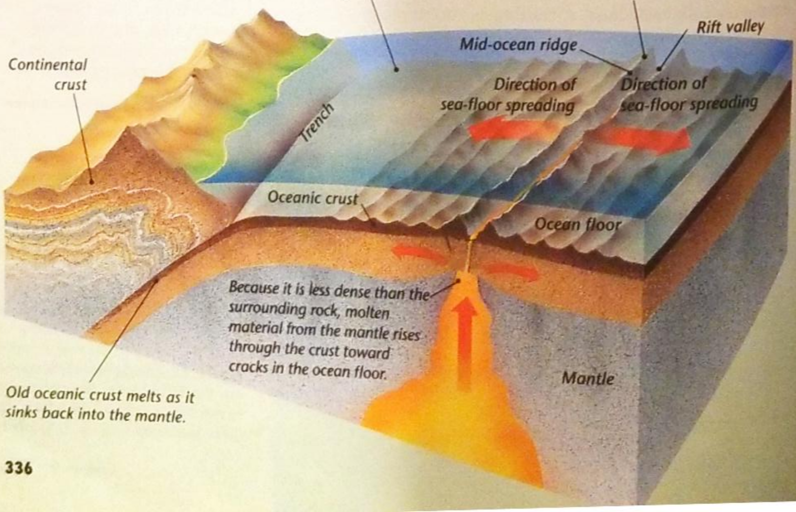
How can the ocean floor keep getting wider and wider? The answer is that the ocean floor generally does not just keep spreading. Instead, the ocean floor plunges into deep underwater canyons called **deep-ocean trenches.** A deep-ocean trench forms where the oceanic crust bends downward.

Where there are deep-ocean trenches, subduction takes place. **Subduction** (sub DUK shun) is the process by which the ocean floor sinks beneath a deep-ocean trench and back into the mantle. Convection currents under the lithosphere push new crust that forms at the mid-ocean ridge away from the ridge and toward a deep-ocean trench.

New oceanic crust is hot. But as it moves away from the mid-ocean ridge, it cools and becomes more dense. Eventually, as shown in Figure 23, gravity pulls this older, denser oceanic crust down beneath the trench. The sinking crust is like the washcloth in the Discover activity at the beginning of this section. As the dry washcloth floating on the water gets wet, its density increases and it begins to sink.

At deep-ocean trenches, subduction allows part of the ocean floor to sink back into the mantle in a process that takes tens of millions of years. You can think of sea-floor spreading and subduction together as if the ocean floor were moving out from the mid-ocean ridge on a giant conveyor belt.

Figure 23 Oceanic crust formed along the mid-ocean ridge is recycled at a deep-ocean trench. In the process of subduction, oceanic crust sinks down beneath the trench into the mantle. *Drawing Conclusions Where would denser oceanic crust be found?*



Subduction and Earth's Oceans

The processes of subduction and sea-floor spreading can change the size and shape of the oceans. Because of these processes, the ocean floor is renewed about every 200 million years. That is the time it takes for new rock to form at the mid-ocean ridge, move across the ocean, and sink into a trench.

Subduction in the Pacific Ocean The vast Pacific Ocean covers almost one third of the planet. And yet it is shrinking. How could that be? Sometimes a deep ocean trench swallows more oceanic crust than the mid-ocean ridge can produce. Then, if the ridge does not add new crust fast enough, the width of the ocean will shrink. This is happening to the Pacific Ocean, which is ringed by many trenches.

Figure 24 It is cold and dark in the deep ocean trenches where subduction occurs. But even here, scientists have found living things, such as this fish.

Subduction in the Atlantic Ocean The Atlantic Ocean, on the other hand, is expanding. Unlike the Pacific Ocean, the Atlantic Ocean has only a few short trenches. As a result, the spreading ocean floor has virtually nowhere to go. In most places, the oceanic crust of the Atlantic Ocean floor is attached to the continental crust of the continents around the ocean. So as the Atlantic's ocean floor spreads, the continents along its edges also move. Over time, the whole ocean gets wider. The spreading floor of the North Atlantic Ocean and the continent of North America move together like two giant barges pushed by the same tugboat.

Section 4 Review

1. What is the role of the mid-ocean ridge in sea-floor spreading?
2. Describe the process of subduction at a deep-ocean trench.
3. What is the evidence for sea-floor spreading?
4. **Thinking Critically Relating Cause and Effect** Where would you expect to find the oldest rock on the ocean floor? Explain your answer.
5. **Thinking Critically Predicting** As you can see in Figure 18, the mid-ocean ridge extends into the Red Sea between Africa and Asia. What do you think will happen to the Red Sea in the future? Explain your answer.

CHAPTER PROJECT

Check Your Progress

Now that you have learned about sea-floor spreading, begin to sketch your model. Does the plate that you chose include oceanic crust, part of the mid-ocean ridge, or a trench? How will you show these features in your model? Improve your original ideas for your model and add new ideas. Revise your list of materials if necessary.

SECTION 5 The Theory of Plate Tectonics

DISCOVER ACTIVITY

How Well Do the Continents Fit Together?

1. Using a world map in an atlas, trace the shapes of the continents North America, South America, Africa, and Europe, including Great Britain and Ireland.
2. Carefully cut apart the landmasses. When you cut out Europe, leave Britain and Ireland attached to Europe.
3. Piece together these landmasses as they may have looked before Pangaea split apart, creating the Atlantic Ocean.
4. Attach your partial reconstruction of Pangea to a piece of paper.

5. Obtain a map that shows the continental shelf. The continental shelf is the apron of continental crust that extends under water around the edges of the continents. Trace around the continental shelves of the same continents used in Step 1.
6. Repeat Steps 2 through 4.

Think It Over

Drawing Conclusions Do your observations support the idea that the continents were once joined together? When did they fit together better: when you cut them out along their coastlines or along their continental shelves? Explain.

GUIDE FOR READING

- What is the theory of plate tectonics?
- What are the three types of plate boundaries?

Reading Tip Before you read, preview *Exploring Plate Tectonics* on pages 342–343. Write a list of any questions you have about plate tectonics. Look for answers as you read.

Key Terms plate
- plate tectonics
- fault • transform boundary
- divergent boundary
- rift valley
- convergent boundary

Have you ever dropped a hard-boiled egg? If so, you may have noticed that the eggshell cracked in an irregular pattern of broken pieces. Earth's lithosphere, its solid outer shell, is not one unbroken layer. It is more like that cracked eggshell. It's broken into pieces separated by jagged cracks.

A Canadian scientist, J. Tuzo Wilson, observed that there are cracks in the continents similar to those on the ocean floor. In 1965, Wilson proposed a new way of thinking about these cracks. According to Wilson, the lithosphere is broken into separate sections called **plates.** The plates fit closely together along cracks in the lithosphere. As shown in Figure 25, the plates carry the continents or parts of the ocean floor, or both.

A Theory of Plate Motion

Wilson combined what geologists knew about sea-floor spreading, Earth's plates, and continental drift into a single theory—the theory of plate tectonics (tek TAHN iks). **Plate tectonics** is the geological theory that states that pieces of Earth's lithosphere are in constant, slow motion, driven by convection currents in the mantle. **The theory of plate tectonics explains the formation, movement, and subduction of Earth's plates.**

As the plates move, they collide, pull apart, and grind past each other. No plate can budge without affecting the other plates surrounding it. What force causes Earth's plates to move? Many geologists think that convection currents in the mantle cause the movement of Earth's plates. The plates of the lithosphere float on top of the asthenosphere. Convection currents rise in the asthenosphere and spread out beneath the lithosphere. The force of the convection current drags the overlying plate along. Slowly, the convection current cools and sinks deeper into the mantle. Scientists think that this downward movement may provide the force that causes the subduction of plates carrying oceanic crust.

Some geologists think that there are other causes of plate movement. According to the "ridge push" hypothesis, magma rising along the mid-ocean ridge exerts a force that pushes an oceanic plate away from the ridge. In the "slab pull" hypothesis, the force of gravity causes plate movement by pulling cooler, denser oceanic plates down toward the mantle. Ridge push and slab pull may work together with convection currents to move Earth's plates.

Sharpen your Skills

Predicting ACTIVITY

Study the map of Earth's plates in Figure 25. Draw South America on a new piece of paper. Include compass markings on the paper. Now draw the South American plate and the Nazca plate. Show the plate boundaries and their directions of movement. In which directions are these plates moving? What do you think will happen as these plates continue to move?

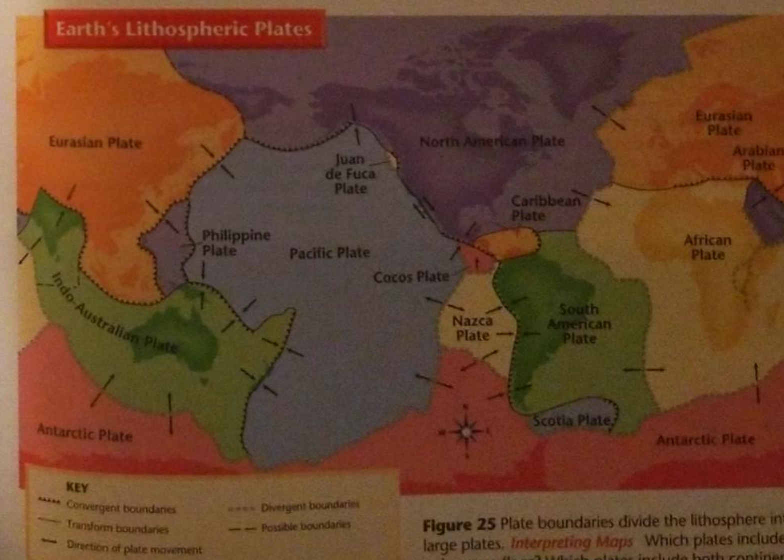


Figure 25 Plate boundaries divide the lithosphere into large plates. ***Interpreting Maps*** Which plates include only ocean floor? Which plates include both continents and ocean floor?

Plate Boundaries

The edges of different pieces of the lithosphere—Earth's rigid shell—meet at lines called plate boundaries. Plate boundaries extend deep into the lithosphere. **Faults**—breaks in Earth's crust where rocks have slipped past each other—form along these boundaries. **There are three kinds of plate boundaries: transform boundaries, divergent boundaries, and convergent boundaries.** For each type of boundary, there is a different type of plate movement, as you can see in *Exploring Plate Tectonics.*

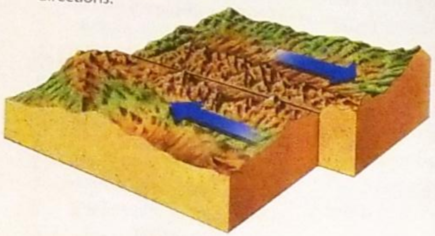


Figure 26 At a transform boundary, two plates move along the boundary in opposite directions.

Transform Boundaries Along transform boundaries, crust is neither created nor destroyed. A **transform boundary** is a place where two plates slip past each other, moving in opposite directions. Earthquakes occur frequently along these boundaries. Look at Figure 26 to see the type of plate movement that occurs along a transform boundary.

Divergent Boundaries The place where two plates move apart, or diverge, is called a **divergent boundary** (dy VUR junt). Notice in *Exploring Plate Tectonics* that divergent boundaries are found both in the oceans and on land. Most divergent boundaries occur at the mid-ocean ridge. In Section 4, you learned how oceanic crust forms along the mid-ocean ridge as sea-floor spreading occurs.

Other divergent boundaries occur on land. When a divergent boundary develops on land, two of Earth's plates slide apart. A deep valley called a **rift valley** forms along the divergent boundary. For example, the Great Rift Valley in east Africa marks a deep crack in the African continent that runs for about 3,000 kilometers. Along this crack, a divergent plate boundary is slowly spreading apart. The rift may someday split the eastern part of Africa away from the rest of the continent. As a rift valley widens, its floor drops. Eventually, the floor may drop enough for the sea to fill the widening gap.

Checkpoint What is a rift valley? How are rift valleys formed?

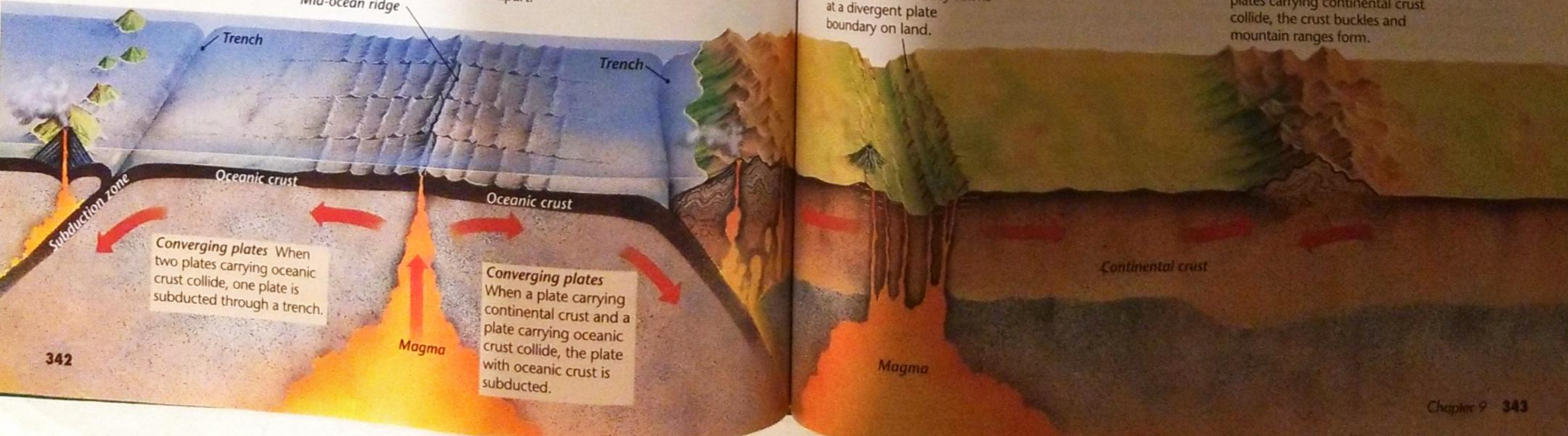
EXPLORING *Plate Tectonics*

Plate movements have built many of the features of Earth's land surfaces and ocean floors.

Diverging plates The mid-ocean ridge marks a divergent boundary where plates carrying oceanic crust move apart.

Rift valley A rift valley forms at a divergent plate boundary on land.

Converging plates Where two plates carrying continental crust collide, the crust buckles and mountain ranges form.



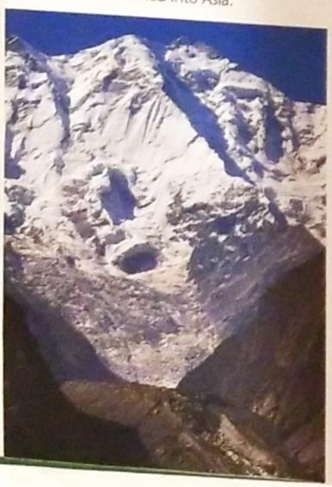
Converging plates When two plates carrying oceanic crust collide, one plate is subducted through a trench.

Converging plates When a plate carrying continental crust and a plate carrying oceanic crust collide, the plate with oceanic crust is subducted.

225 million years ago
All Earth's major landmasses were joined in the supercontinent Pangaea before plate movements began to split it apart.

180–200 million years ago
Pangaea continued to split apart, opening narrow seas that later became oceans.

Figure 27 A collision between two continental plates produced the majestic Himalayas. The collision began 50 million years ago, when the plate that carries India slammed into Asia.



Convergent Boundaries The place where two plates come together, or converge, is called a **convergent boundary** (kun VUR junt). When two plates converge, the result is called a collision. Collisions may bring together oceanic crust and oceanic crust, oceanic crust and continental crust, or continental crust and continental crust.

When two plates collide, the density of the plates determines which one comes out on top. Oceanic crust, which is made mostly of basalt, is more dense than continental crust, which is made mostly of granite. And oceanic crust becomes cooler and denser as it spreads away from the mid-ocean ridge.

Where two plates carrying oceanic crust meet at a trench, the plate that is more dense dives under the other plate and returns to the mantle. This is the process of subduction that you learned about in Section 4.

Sometimes a plate carrying oceanic crust collides with a plate carrying continental crust. The less dense continental crust can't sink under the more dense oceanic crust. Instead, the oceanic plate begins to sink and plunges beneath the continental plate.

When two plates carrying continental crust collide, subduction does not take place. Both continental plates are mostly low-density granite rock. Therefore, neither plate is dense enough to sink into the mantle. Instead, the plates crash head-on. The collision squeezes the crust into mighty mountain ranges.

☑ ***Checkpoint*** *What types of plate movement occur at plate boundaries?*

135 million years ago Gradually, the landmasses that became today's continents began to drift apart.

Earth today
Note how far to the north India has drifted—farther than any other major landmass.

65 million years ago
India was still a separate continent, charging toward Asia, while Australia remained attached to Antarctica.

Figure 28 It has taken about 225 million years for the continents to move to their present locations. *Posing Questions* What questions would you need to answer in order to predict where the continents will be in 50 million years?

The Continents' Slow Dance

The plates move at amazingly slow rates: from about one to ten centimeters per year. The North American and Eurasian plates are floating apart at a rate of 2.5 centimeters per year—that's about as fast as your fingernails grow. This may not seem like much, but these plates have been moving for tens of millions of years.

About 260 million years ago, the continents were joined together in the supercontinent that Wegener called Pangaea. Then, about 225 million years ago, Pangaea began to break apart. Figure 28 shows how Earth's continents and other landmasses have moved since the break-up of Pangaea.

Section 5 Review

1. What is the theory of plate tectonics?
2. What are the different types of boundaries found along the edges of Earth's plates?
3. What major event in Earth's history began about 225 million years ago? Explain.
4. **Thinking Critically** **Predicting** Look at Figure 25 on page 341 and find the divergent boundary that runs through the African plate. Predict what could eventually happen along this boundary.

Check Your Progress

Complete your research on your chosen plate. You should be able to describe the makeup of the plate as well as the direction and rate of its movement. Now that you have learned about plate tectonics, add to your sketch any transform boundary, convergent boundary on land, or divergent boundary on land. How will you show what happens *where* your plate interacts with another plate? Begin building your model.