FORCES WITHIN

Chapter Preview

Inquiry Activity

How Can Buildings Be Made Earthquake-Safe?

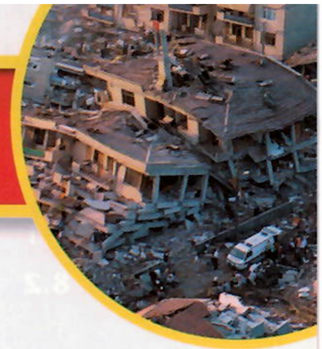
Procedure

1. Construct a model of a one-story brick building using two thin pieces of cardboard as the floor and roof. Use sugar cubes as bricks and peanut butter, frosting, or double-sided tape to hold the bricks together.
2. Construct a second building. Make this building a two-story structure.
3. To test how well your buildings stand up to a simulated earthquake, place the one-story building on a table or desk. Then either drop a large book on the table, or gently shake the edge of the table. Record your observations.
4. Repeat Step 3 with the two-story model building. Record your observations.
5. Construct a third building using small pieces of window screen as reinforcement. This building should be a one-story structure. Spread a thin layer of peanut butter or frosting on the inside of the walls and carefully attach pieces of screen to each of the inside walls. Use extra peanut butter or frosting to reinforce the inside corners.
6. Repeat Step 3 with the reinforced building. Record your observations.

Think About It

1. **Observing** What happened to each building during the simulated earthquakes?
2. **Comparing and Contrasting** Compare the amount of earthquake damage in the three model buildings.

8.1 What Is an Earthquake?



Reading Focus

Key Concepts

- What is a fault?
- What is the cause of earthquakes?

Vocabulary

- earthquake
- focus
- epicenter
- fault
- elastic rebound hypothesis
- aftershock
- foreshock

Reading Strategy

Building Vocabulary Copy the table below. Then as you read the section, write a definition for each vocabulary term in your own words.

Vocabulary	Definition
earthquake	a. ?
b. ?	c. ?
d. ?	e. ?
f. ?	g. ?

Each year, more than 30,000 earthquakes occur worldwide that are strong enough to be felt. Fortunately, most of these earthquakes are minor tremors and do very little damage. Generally, only about 75 major earthquakes take place each year. Most of these occur in remote regions. However, occasionally a large earthquake occurs near a city. Under these conditions, an earthquake is one of the most destructive natural forces on Earth, as shown in Figure 1.

Earthquakes

An **earthquake** is the vibration of Earth produced by the rapid release of energy. Earthquakes are often caused by slippage along a break in Earth's crust.

Figure 1 This damage occurred in San Francisco's Marina District from the 1989 Loma Prieta earthquake.

Focus and Epicenter The point within Earth where the earthquake starts is called the **focus.** The released energy radiates in all directions from the focus in the form of waves. These waves are similar to the waves produced when a stone is dropped into a calm pond. The impact of the stone sets water waves in motion. An earthquake is similar because it produces seismic waves that radiate throughout Earth.

The focus of an earthquake is the place within Earth where the earthquake originates. When you see a news report about an earthquake, the reporter always mentions the place on Earth's surface where the earthquake has been located. The **epicenter** is the location on the surface directly above the focus, as shown in Figure 2.

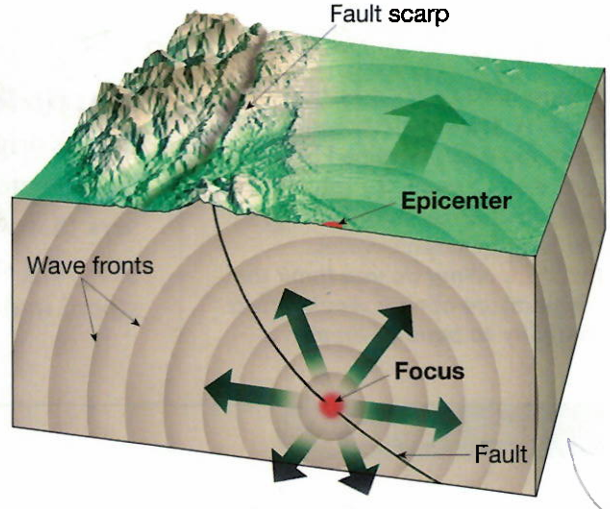


Figure 2 The focus of each earthquake is the place within Earth where the earthquake originated. The foci (plural of focus) are located along faults. The surface location directly above the focus is called the epicenter.
Predicting ***Where do you think the damage from an earthquake is usually greatest?***

Faults A lot of evidence shows that Earth is constantly changing. We know that Earth's crust has been uplifted at times. We have found many ancient wave-cut features meters above the level of the highest tides. Offsets in fence lines, roads, and other structures indicate that horizontal movements of Earth's crust are also common, as seen in Figure 3. Earthquakes are usually associated with large fractures in Earth's crust and mantle called **faults.** **Faults are fractures in Earth where movement has occurred.**

Reading Checkpoint ***What is a fault?***

Cause of Earthquakes

Before the great 1906 San Francisco earthquake, the actual causes and effects of earthquakes were not understood. The San Fransisco earthquake caused horizontal shifts in Earth's surface of several meters along the northern portion of the San Andreas Fault. The 1300-kilometer San Andreas fracture extends north and south through southern California. Studies following the 1906 quake found that during this single event, the land on the western side of the San Andreas Fault moved as much as 4.7 meters to the north compared to the land on the eastern side of the fault.

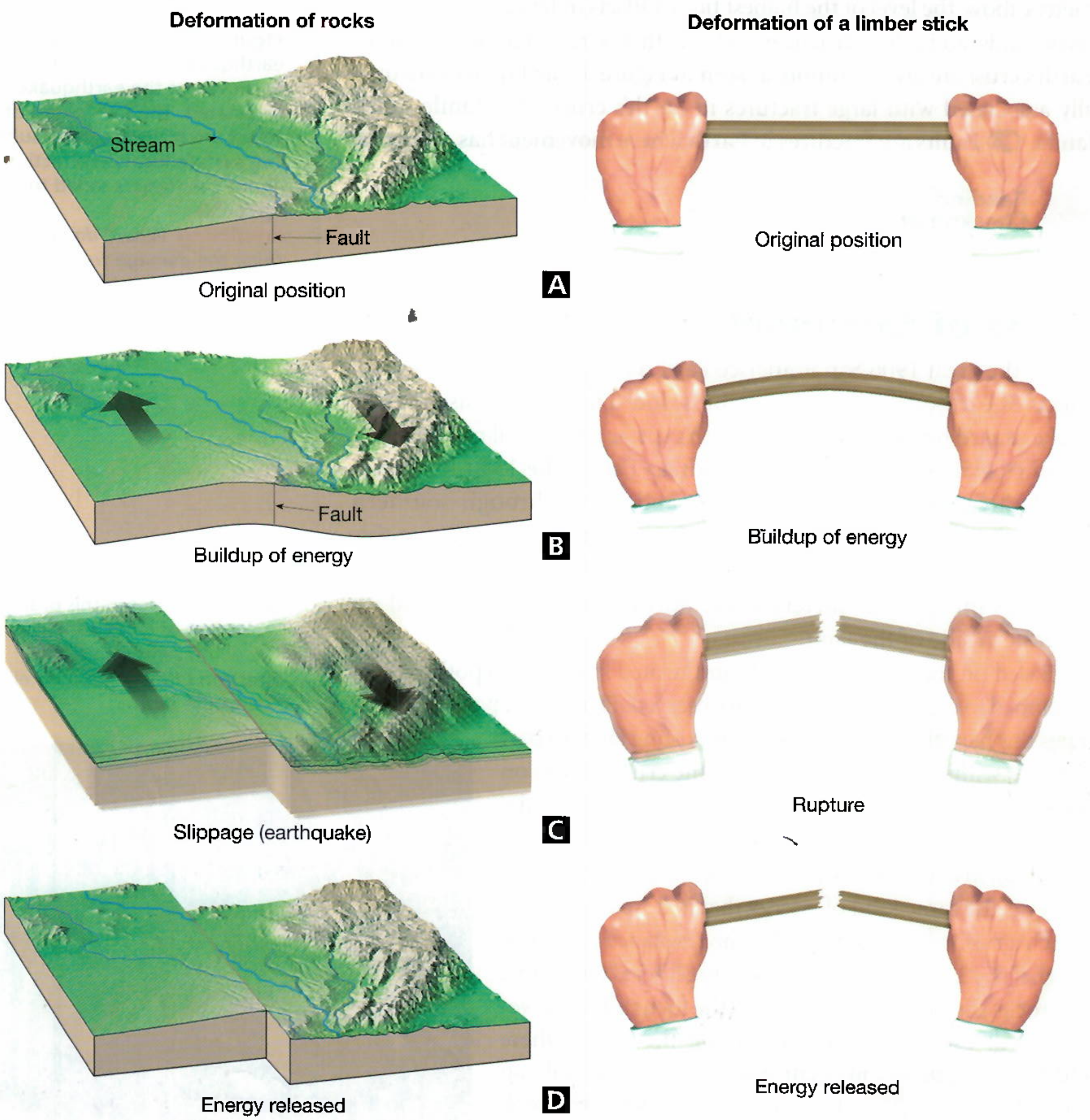
Based on these measurements and related studies, a hypothesis was developed to explain what had been observed. Figure 4 on page 220 illustrates this hypothesis. Part A shows an existing fault. In part B, forces within Earth slowly deform the crustal rocks on both sides of the fault, shown by the bent features of the rocks. These forces cause the rocks to bend and store elastic energy, just like a wooden stick does if it is bent. Elastic energy is the same kind of energy that is stored when you stretch a rubber band. Eventually, the resistance caused by internal friction that holds the rocks together is overcome. The rocks slip at the weakest point (the focus). The movement will exert forces farther along the fault, where additional slippage will occur until most of the built-up energy is released. This slippage allows the deformed rock to snap back in place. The vibrations we call an earthquake occur as the rock elastically returns to its original shape.

Figure 3 Slippage along a fault caused an offset in this orange grove east of Calexico, California. The white arrows show the direction of movement on either side of the fault.

Figure 4 As rock is stressed it bends, storing elastic energy. Once the rock is strained beyond its breaking point, it ruptures and releases the stored energy in the form of seismic waves. **Inferring** ***How do you think the temperature of rock would affect its ability to bend or break?***

Elastic Rebound Hypothesis The springing back of the rock into its original place is called elastic rebound. The rock behaves much like a stretched rubber band does when it is released. The explanation says that when rocks are deformed, they first bend and then break, releasing stored energy. This explanation for the release of energy stored in deformed rocks is called the **elastic rebound hypothesis.**

Elastic Rebound



Most earthquakes are produced by the rapid release of elastic energy stored in rock that has been subjected to great forces. When the strength of the rock is exceeded, it suddenly breaks, causing the vibrations of an earthquake. Earthquakes most often happen along existing faults. They occur when the frictional forces on the fault surfaces are overcome.

Go Online
SCILINKS NSTA
For: Links on earthquakes
Visit: www.SciLinks.org
Web Code: cjn-3081

Aftershocks and Foreshocks The intense shaking of the 1906 San Francisco earthquake lasted about 40 seconds. Most of the movement along the fault occurred in this short time period. However, additional movements along this and nearby faults continued for several days. The movements that follow a major earthquake often produce smaller earthquakes called **aftershocks.** These aftershocks are usually much weaker than the main earthquake, but they can sometimes destroy structures weakened by the main quake. Small earthquakes called **foreshocks** often come before a major earthquake. These foreshocks can happen days or even years before the major quake.

The San Andreas Fault is the most studied fault system in the world. Studies have shown that displacement has occurred along segments that are 100 to 200 kilometers long. Each fault segment behaves a bit differently than the other segments. Some parts of the San Andreas show a slow, gradual movement known as fault creep. This movement happens fairly smoothly. Other segments regularly slip and produce small earthquakes. However, some segments stay locked and store elastic energy for hundreds of years before they break and cause great earthquakes.

Section 8.1 Assessment

Reviewing Concepts

1. What is a fault?
2. Describe the cause of earthquakes.
3. What is an earthquake?
4. What is the source of an earthquake called?
5. What are foreshocks and aftershocks?

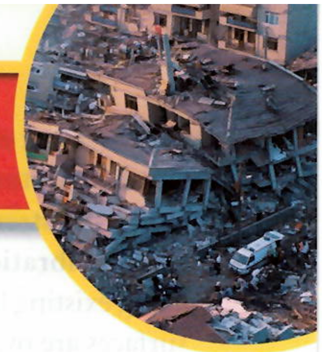
Critical Thinking

6. **Connecting Concepts** How are faults, foci, and epicenters related?
7. **Inferring** What is meant by elastic rebound?
8. **Making Judgments** Why do most earthquakes cause little damage and loss of life?

Math Practice

9. In 25 years, how much movement will result from a fault that slowly slips 1.5 centimeters per year?

8.2 Measuring Earthquakes



Reading Focus

Key Concepts

- What are the types of seismic waves?
- How is an earthquake epicenter located?
- How is the size of an earthquake measured?

Vocabulary

- seismograph
- seismogram
- surface wave
- P wave
- S wave
- moment magnitude

Reading Strategy

Outlining As you read, make an outline of the important ideas in this section. Use the green headings as the main topics and the blue headings as subtopics.

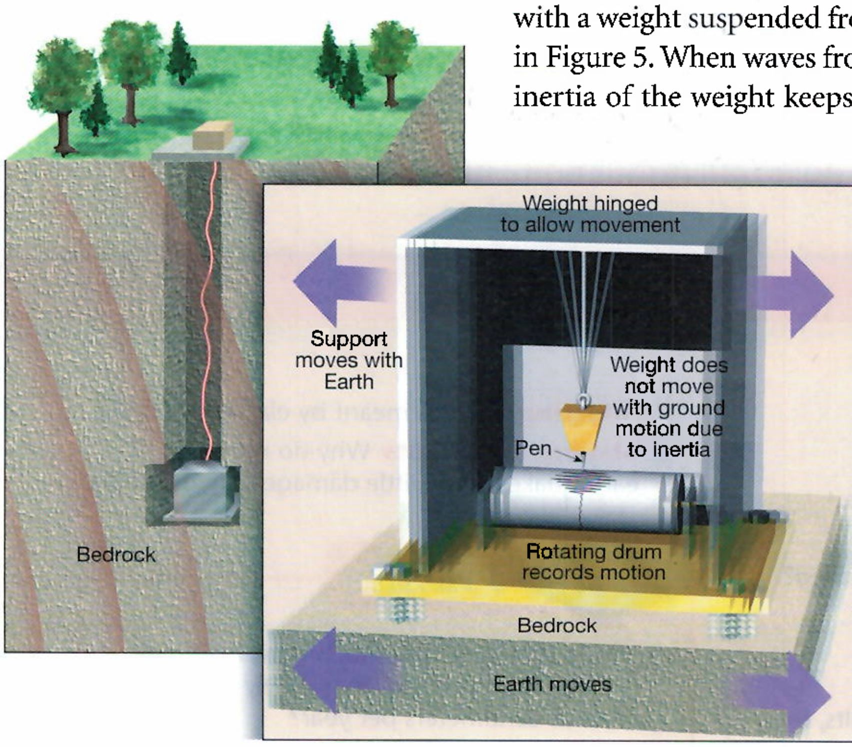
Measuring Earthquakes

I. Earthquake Waves
    A. Surface Waves
    B. ____?____
II. ____?____
    A. ____?____

The study of earthquake waves, or seismology, dates back almost 2000 years. The first attempts to discover the direction of earthquakes were made by the Chinese. **Seismographs** are instruments that record earthquake waves. The idea behind seismographs can be demonstrated with a weight suspended from a support attached to bedrock as shown in Figure 5. When waves from an earthquake reach the instrument, the inertia of the weight keeps it stationary, while Earth and the support vibrate. Because the weight stays almost motionless, it provides a reference point to measure the amount of movement that occurs as waves pass through the ground below. The movement of Earth compared to the stationary weight can be recorded on a rotating drum, shown in Figure 5.

Modern seismographs amplify and electronically record ground motion, producing a trace, called a **seismogram.** A typical seismogram (*seismos* = shake, *gramma* = what is written) is shown in Figure 6.

Figure 5 The seismograph (*seismos* = shake, *graph* = write) amplifies and records ground motion.



Earthquake Waves

The energy from an earthquake spreads outward as waves in all directions from the focus. Seismograms show that two main types of seismic waves are produced by an earthquake—surface waves and body waves.

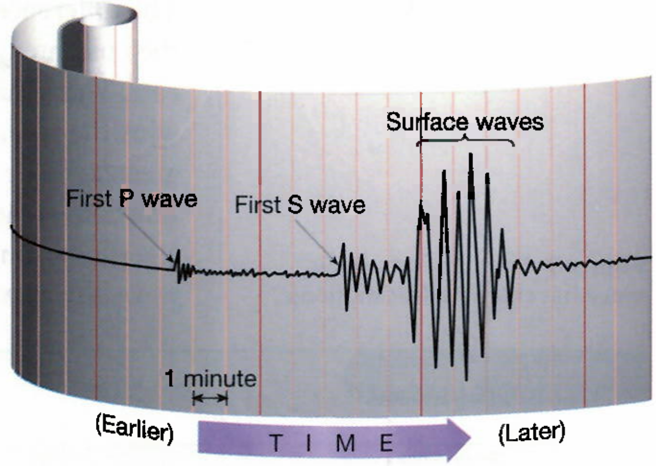


Figure 6 Typical Seismogram The first wave to arrive is the P wave, followed later by S waves. The last waves recorded are the surface waves.
Measuring ***What is the time interval in minutes between the start of the first P wave and the start of the first S wave?***

Surface Waves **Surface waves** are seismic waves that travel along Earth's outer layer. The motion of surface waves is complex. Surface waves travel along the ground and cause the ground and anything resting upon it to move. This movement is like ocean waves that toss a ship. Surface waves move in an up-and-down motion as well as a side-to-side motion, as shown in Figures 7E and 7F. The side-to-side motion is especially damaging to the foundations of buildings. These movements make surface waves the most destructive earthquake waves.

Body Waves The other waves that travel through Earth's interior are called body waves. Body waves are identified as either P waves or S waves, depending on how they travel through the materials within Earth. Figures 7B and 7D shows differences between the two kinds of waves. **P waves** are push-pull waves—they push (compress) and pull (expand) rocks in the direction the waves travel. P waves are also known as compression waves. In contrast, **S waves** shake the particles at right angles to their direction of travel. This can be shown by fastening one end of a rope and shaking the other end, as in Figure 7C. S waves are transverse waves. P waves temporarily change the volume of the material they pass through by alternately compressing and expanding it, as in Figure 7A. S waves temporarily change the shape of the material they pass through. Gases and liquids will not transmit S waves because they do not rebound elastically to their original shape.

A seismogram shows all three types of seismic waves—surface waves, P waves, and S waves. By observing a typical seismic record, as shown in Figure 8 on page 225, you can see that the first P wave arrives at the recording station, then the first S wave, and then surface waves. The waves arrive at different times because they travel at different speeds. Generally, in any solid material, P waves travel about 1.7 times faster than S waves. Surface waves travel the slowest at about 90 percent of the speed of the S waves.

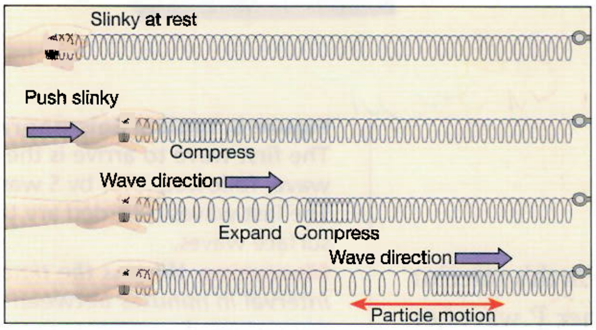
Reading Checkpoint ***Which seismic wave travels fastest?***

Locating an Earthquake

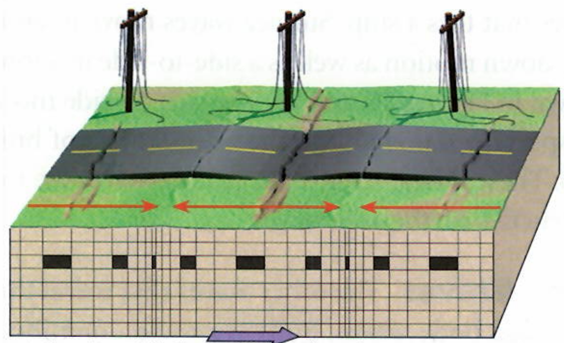
The difference in velocities of P and S waves provides a way to locate the epicenter. You can compare this difference to a race between two cars. The winning car is faster than the losing car. The P wave always wins the race, arriving ahead of the S wave. The longer the race, the greater will be the difference in arrival times of the P and S waves at the finish line (the seismic station). The greater the interval measured on a seismogram between the arrival of the first P wave and the first S wave, the greater the distance to the earthquake source.

Figure 7 Each type of seismic wave has characteristic motions.

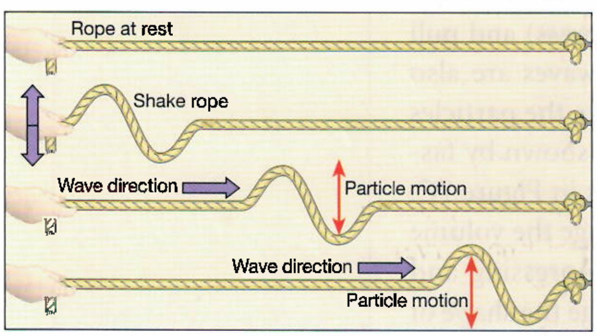
Seismic Waves



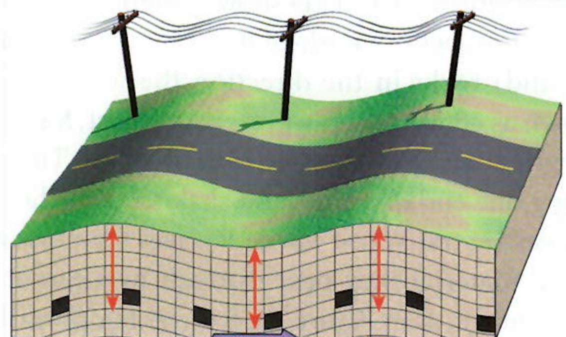
A P waves are compression waves that alternately compress and expand the material through which they pass.



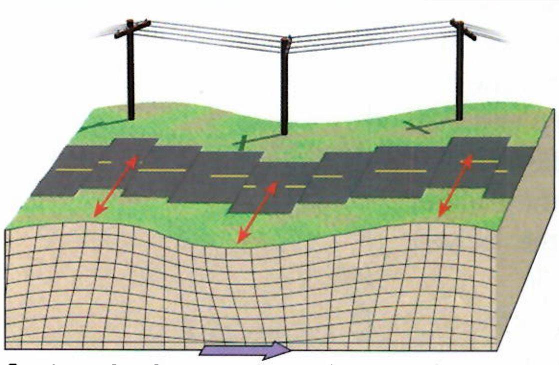
B The back-and-forth motion produced as P waves travel along the surface can cause the ground to buckle and fracture.



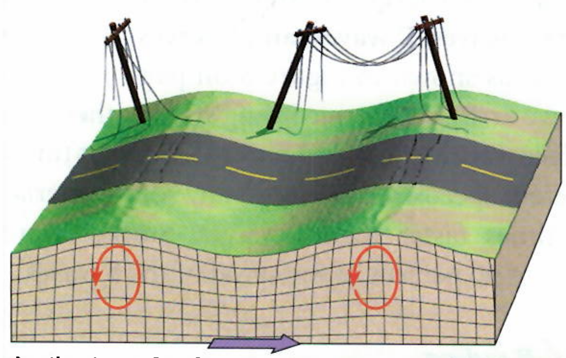
C S waves are transverse waves which cause material to shake at right angles to the direction of wave motion. The length of the red arrow is the displacement, or amplitude, of the S wave.



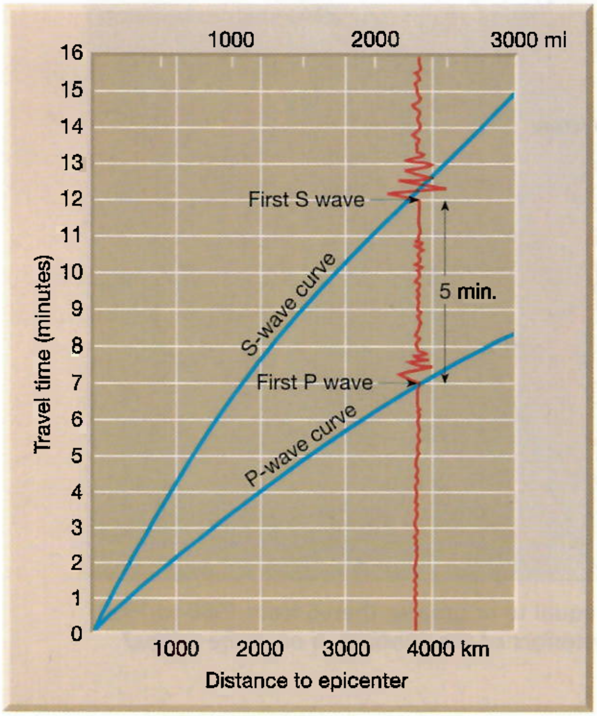
D S waves cause the ground to shake up-and-down and sideways.



E One type of surface wave moves the ground from side to side and can damage the foundations of buildings.



F Another type of surface wave travels along Earth's surface much like rolling ocean waves. The arrows show the movement of rock as the wave passes. The motion follows the shape of an ellipse.



A

B

Figure 8 Locating an Earthquake A A travel-time graph is used to determine the distance to the epicenter. The difference in arrival times of the first P wave and the first S wave in the graph is 5 minutes. So the epicenter is roughly 3800 kilometers away. **B** The epicenter is located using the distance obtained from three seismic stations. The place the circles intersect is the epicenter.

Earthquake Distance A system for locating earthquake epicenters was developed by using seismograms from earthquakes whose epicenters could be easily pinpointed from physical evidence. Travel-time graphs are constructed from these seismograms, as shown in Figure 8A. Using the sample seismogram in Figure 6 and the travel-time curves in Figure 8A, we can determine the distance from the recording station to the earthquake in two steps. First, find the time interval between the arrival of the first P wave and the first S wave on the seismogram. Second, find on the travel-time graph the equivalent time spread between the P and S wave curves. From this information, you can see that this earthquake occurred 3800 kilometers from the seismograph.

Earthquake Direction Now we know the distance, but what about the direction? The epicenter could be in any direction from the seismic station. As shown in Figure 8B, the precise location can be found when the distance is known from three or more different seismic stations. On a globe, we draw a circle around each seismic station. Each circle represents the distance of the epicenter from each station. The point where the three circles intersect is the epicenter of the quake. **Travel-time graphs from three or more seismographs can be used to find the exact location of an earthquake epicenter.**

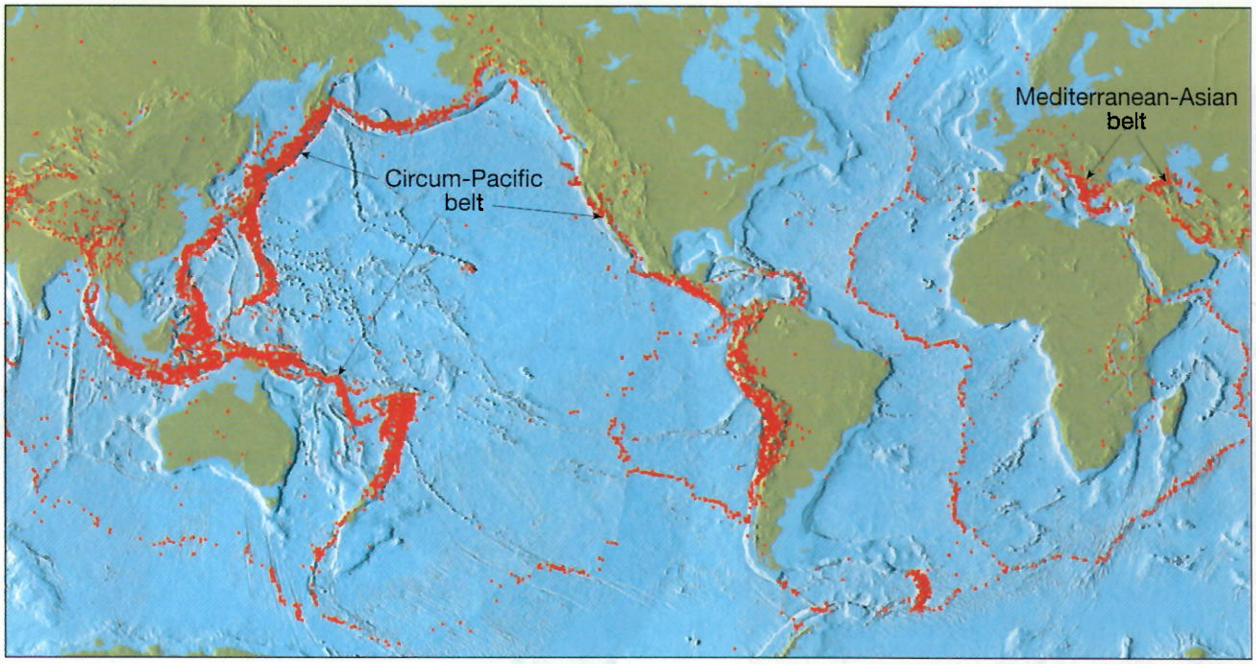


Figure 9 Distribution of the 14,229 earthquakes with magnitudes equal to or greater than 5 from 1980 to 1990.
Observing *Where do you find most of the earthquakes—in the interiors of the continents or at the edges?*

Quick Lab

Measuring the Distance to Epicenters

Procedure

1. Look at Figures 6 and 8A. Figure 6 is a seismogram and Figure 8A is a travel-time graph. Use the graph to answer the Analyze and Conclude questions.
2. Make sure to use only the bottom scale on the x-axis, measured in kilometers, to answer the questions.

Analyze and Conclude

1. **Reading Graphs** What is the difference in arrival times in minutes between the first P wave and first S wave for stations that are the following distances from an epicenter: 1000 km, 2000 km, 2400 km, and 3000 km?
2. **Inferring** How does the difference in arrival times of the first P wave and first S wave on a seismogram change? How does it change if the station is farther from the epicenter?
3. **Predicting** How do you think the vibrations recorded on a seismogram would change as the distance to the epicenter increases?

Earthquake Zones About 95 percent of the major earthquakes occur in a few narrow zones, as shown in Figure 9. Most of these earthquakes occur around the outer edge of the Pacific Ocean. This zone is known as the circum-Pacific belt. Active earthquake areas in this zone include Japan, the Philippines, Chile, and Alaska's Aleutian Islands. A second zone of earthquake activity occurs along the Mediterranean Sea. This is the Mediterranean-Asian belt. Another continuous belt extends for thousands of kilometers through the world's oceans. This zone coincides with the oceanic ridge system.

Reading Checkpoint *Where do most earthquakes occur?*

Measuring Earthquakes

Historically, scientists have used two different types of measurements to describe the size of an earthquake—intensity and magnitude. Intensity is a measure of the amount of earthquake shaking at a given location based on the amount of damage. Intensity is not a quantitative measurement because it is based on uncertain personal damage estimates. Quantitative measurements, called magnitudes, were developed that rely on calculations using seismograms. Magnitudes are a measure of the size of seismic waves or the amount of energy released at the source of the earthquake.

Richter Scale A familiar but outdated scale for measuring the magnitude of earthquakes is the Richter scale. The Richter scale is based on the amplitude of the largest seismic wave (P, S, or surface wave) recorded on a seismogram. Earthquakes vary greatly in strength, so Richter used a logarithmic scale. A tenfold increase in wave amplitude equals an increase of 1 on the magnitude scale. For example, the amount of ground shaking for a 5.0 earthquake is 10 times greater than the shaking produced by an earthquake of 4.0 on the Richter scale.

Seismic waves weaken as the distance between the earthquake focus and the seismograph increases. The Richter scale is only useful for small, shallow earthquakes within about 500 kilometers of the epicenter. Most of the earthquake measurements you hear on news reports use the Richter scale. Scientists, however, no longer use it.

Moment Magnitude In recent years, scientists have been using a more precise means of measuring earthquakes. It is called the moment magnitude scale. The **moment magnitude** is derived from the amount of displacement that occurs along a fault zone. It doesn't measure the ground motion at some distant point. The moment magnitude is calculated using several factors. These factors include the average amount of movement along the fault, the area of the surface break, and the strength of the broken rock: (surface area of fault) × (average displacement along fault) × (rigidity of rock). Together these factors provide a measure of how much energy rock can store before it suddenly slips and releases this energy during an earthquake. **Moment magnitude is the most widely used measurement for earthquakes because it is the only magnitude scale that estimates the energy released by earthquakes.**

Table 1 describes the damage and incidence of earthquakes of different magnitudes. Compare this information to the earthquakes listed in Table 2 on page 228.

Table 1 Earthquake Magnitudes and Expected World Incidence

Moment Magnitudes	Effects Near Epicenter	Estimated Number per Year
< 2.0	Generally not felt, but can be recorded	> 600,000
2.0–2.9	Potentially perceptible	> 300,000
3.0–3.9	Rarely felt	> 100,000
4.0–4.9	Can be strongly felt	13,500
5.0–5.9	Can be damaging shocks	1,400
6.0–6.9	Destructive in populous regions	110
7.0–7.9	Major earthquakes; inflict serious damage	12
8.0 and above	Great earthquakes; destroy communities near epicenter	0–1

Table 2 Some Notable Earthquakes

Year	Location	Deaths (est.)	Magnitude†	Comments
*1886	Charleston, South Carolina	60		Greatest historical earthquake in the eastern United States
*1906	San Francisco, California	1500	7.8	Fires caused extensive damage.
1923	Tokyo, Japan	143,000	7.9	Fire caused extensive destruction.
1960	Southern Chile	5700	9.6	Possibly the largest-magnitude earthquake ever recorded
*1964	Alaska	131	9.2	Greatest North American earthquake
1970	Peru	66,000	7.8	Large rockslide
*1971	San Fernando, California	65	6.5	Damages exceeded $1 billion.
1985	Mexico City	9500	8.1	Major damage occurred 400 km from epicenter.
1988	Armenia	25,000	6.9	Poor construction practices caused great damage.
*1989	Loma Prieta, California	62	6.9	Damages exceeded $6 billion.
1990	Iran	50,000	7.3	Landslides and poor construction practices caused great damage.
1993	Latur, India	10,000	6.4	Located in stable continental interior
*1994	Northridge, California	57	6.7	Damages exceeded $40 billion.
1995	Kobe, Japan	5472	6.9	Damages estimated to exceed $100 billion.
1999	Izmit, Turkey	17,127	7.4	Nearly 44,000 injured and more than 250,000 displaced.
1999	Chi Chi, Taiwan	2300	7.6	Severe destruction; 8700 injuries
2001	El Salvador	1000	7.6	Triggered many landslides
2001	Bhuj, India	20,000†	7.9	1 million or more homeless

*U.S. earthquakes
†Widely differing magnitudes have been estimated for some earthquakes. When available, moment magnitudes are used.
SOURCE: U.S. Geological Survey

Section 8.2 Assessment

Reviewing Concepts

1. List the two categories of seismic waves.
2. Briefly describe how the epicenter of an earthquake is located.
3. Describe the two different ways to measure the size of an earthquake.
4. In what order do the basic types of seismic waves reach a seismograph?

Critical Thinking

5. **Comparing and Contrasting** Describe the differences in speed and mode of travel between primary waves and secondary waves.
6. **Applying Concepts** How does a seismograph measure an earthquake?

Writing in Science

Descriptive Paragraph Write a paragraph describing in your own words what would occur in an earthquake that has been measured as a moment magnitude of 6.0.

8.3 Destruction from Earthquakes

Reading Focus

Key Concepts

- What destructive events can be triggered by earthquakes?
- Can earthquakes be predicted?

Vocabulary

- liquefaction
- tsunami
- seismic gap

Reading Strategy

Monitoring Your Understanding Preview the Key Concepts, topic headings, vocabulary, and figures in this section. List two things you expect to learn. After reading, state what you learned about each item you listed.

What I Expect To Learn	What I Learned
a. ___?___	b. ___?___
c. ___?___	d. ___?___

The Good Friday Alaskan Earthquake in 1964 was the most violent earthquake to jar North America in the 20th century. The earthquake was felt throughout Alaska. It had a moment magnitude of 9.2 and lasted 3 to 4 minutes. The quake left 131 people dead and thousands homeless. The state's economy was also badly damaged because the quake affected major ports and towns. Had the schools and businesses been open on this holiday, the death toll would surely have been much higher.

Seismic Vibrations

The 1964 Alaskan earthquake gave geologists new insights into the role of ground shaking as a destructive force. **The damage to buildings and other structures from earthquake waves depends on several factors. These factors include the intensity and duration of the vibrations, the nature of the material on which the structure is built, and the design of the structure.**

Building Design All multistory buildings in Anchorage, Alaska, were damaged by the vibrations. However, the more flexible wood-frame buildings, such as homes, were less damaged. Figure 10 offers an example of how differences in construction can affect earthquake damage. You can see that the steel-frame building on the left withstood the vibrations. However, the poorly designed building on the right was badly damaged. Engineers have learned that unreinforced stone or brick buildings are the most serious safety threats during earthquakes.

Figure 10 Earthquake Damage This five-story building in Anchorage, Alaska, collapsed from the great earthquake of 1964. Very little structural damage was incurred by the steel-framed building to the left.
Inferring ***Why do some buildings undergo little damage, while nearby buildings are nearly destroyed?***

Q & A

Q *What is the largest wave triggered by an earthquake?*

A The largest wave ever recorded occurred in Lituya Bay, about 200 kilometers west of Juneau, Alaska. On July 9, 1958, an earthquake triggered an enormous rockslide that dumped 90 million tons of rock into the upper part of the bay. The rockslide created a huge splash wave that swept over the ridge facing the rockslide. The splash uprooted or snapped off trees 522 meters above the bay. Even larger splash waves may have occurred 65 million years ago when an estimated 900-meter wave is thought to have resulted from a meteorite impact in the Gulf of Mexico.

Liquefaction Where loosely consolidated sediments are saturated with water, earthquakes can cause a process known as **liquefaction.** Under these conditions, what had been stable soil turns into a liquid that is not able to support buildings or other structures. Buildings and bridges may settle and collapse. Underground storage tanks and sewer lines may float toward the surface.

Reading Checkpoint *When does liquefaction occur?*

Tsunamis

Most deaths associated with the 1964 Alaskan quake were caused by seismic sea waves, or **tsunamis.** These destructive waves often are called tidal waves by news reporters. However, this name is incorrect because these waves are not produced by the tidal effect of the moon or sun.

Causes of Tsunamis **A tsunami triggered by an earthquake occurs where a slab of the ocean floor is displaced vertically along a fault. A tsunami also can occur when the vibration of a quake sets an underwater landslide into motion.** Once formed, a tsunami resembles the ripples created when a pebble is dropped into a pond. A tsunami travels across the ocean at speeds of 500 to 950 kilometers per hour. Despite this speed, a tsunami in the open ocean can pass without notice because its height is usually less than 1 meter, and the distance between wave crests can range from 100 to 700 kilometers. However, when the wave enters shallower coastal water, the waves are slowed and the water begins to pile up to heights that sometimes are greater than 30 meters, as shown in Figure 11.

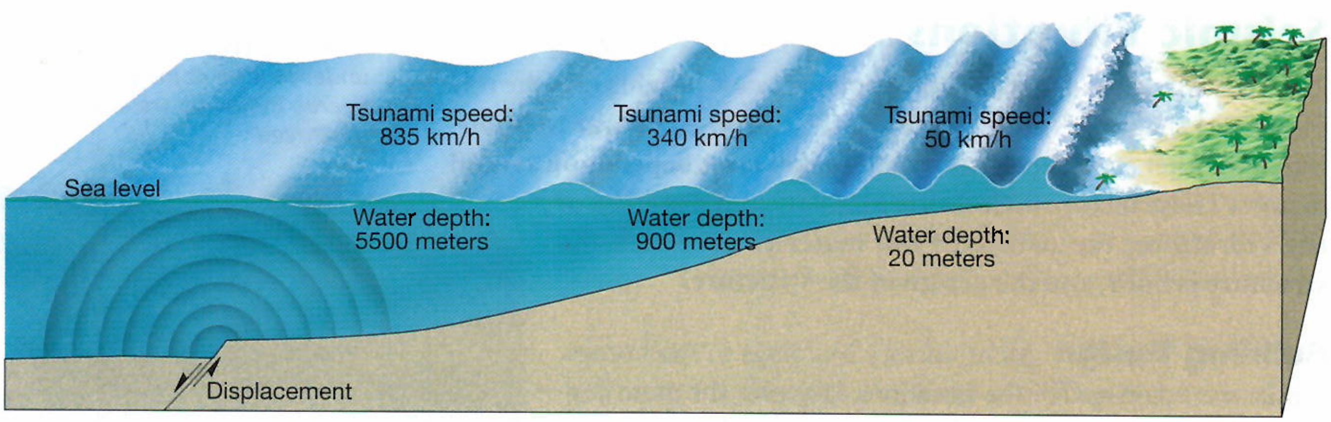


Figure 11 Movement of a Tsunami A tsunami is generated by movement of the ocean floor. The speed of a wave moving across the ocean is related to the ocean depth. Waves moving in deep water travel more than 800 kilometers per hour. Speed gradually slows to 50 kilometers per hour at depths of 20 meters. As waves slow down in shallow water, they grow in height until they topple and hit shore with tremendous force.

Tsunami Warning System The destruction from a large tsunami in the Hawaiian Islands led to the creation of a tsunami warning system for coastal areas of the Pacific. Large earthquakes are reported to the Tsunami Warning Center in Honolulu from seismic stations around the Pacific. Scientists use water levels in tidal gauges to determine whether a tsunami has formed. Within an hour of the reports, a warning is issued. Although tsunamis travel very rapidly, there is sufficient time to evacuate all but the area closest to the epicenter. Fortunately, most earthquakes do not generate tsunamis. On the average, only one or two destructive tsunamis are generated worldwide every year. Only about one tsunami in every 10 years causes major damage and loss of life.

Reading Checkpoint *What areas are protected by the tsunami warning system?*

Other Dangers

The vibrations from earthquakes cause other dangers, including landslides, ground subsidence, and fires.

Figure 12 This landslide caused by the 1964 Alaskan earthquake destroyed many homes. More than 200 acres of land slid toward the ocean.
Interpreting Photos ***Assuming the land was originally horizontal, to what angle have the trees on the left side of the photo been tilted?***

Landslides **With many earthquakes, the greatest damage to structures is from landslides and ground subsidence, or the sinking of the ground triggered by the vibrations.** The violent shaking of an earthquake can cause the soil and rock on slopes to fail, resulting in landslides. Figure 12 shows some of the damage landslides can cause. Earthquake vibration can also cause large sections of the ground to collapse, liquefy, or subside. Ground subsidence can cause foundations to collapse, as shown in Figure 12. It can also rupture gas and water pipelines.

Fire The 1906 San Francisco earthquake reminds us of the major threat of fire. The city contained mostly large wooden structures and brick buildings. The greatest destruction was caused by fires that started when gas and electrical lines were cut. Many of the city's water lines had also been broken by the quake, which meant that the fires couldn't be stopped. A 1923 earthquake in Japan caused an estimated 250 fires. They devastated the city of Yokohama and destroyed more than half the homes in Tokyo. The fires spread quickly due to unusually high winds. More than 100,000 people died in the fires.

Figure 13 Effects of Subsidence Due to Liquefaction This tilted building rests on unconsolidated sediment that imitated quicksand during the 1985 earthquake in Mexico.

Predicting Earthquakes

The earthquake in Northridge, California, in 1994 caused 57 deaths and about $40 billion in damage. Scientists warn that quakes of similar or greater strength will occur. But can earthquakes be predicted?

Short-Range Predictions The goal of short-range prediction is to provide an early warning of the location and magnitude of a large earthquake. Researchers monitor possible precursors—things that precede and may warn of a future earthquake. They measure uplift, subsidence, and strain in the rocks near active faults. They measure water levels and pressures in wells. Radon gas emissions from fractures and small changes in the electromagnetic properties of rocks are also monitored. **So far, methods for short-range predictions of earthquakes have not been successful.**

Long-Range Forecasts Long-range forecasts give the probability of a certain magnitude earthquake occurring within 30 to 100-plus years. These data are important for updating building codes, which have standards for designing earthquake-resistant structures. Long-range forecasts are based on the idea that earthquakes are repetitive or cyclical. In other words, as soon as one earthquake is over, the forces in Earth will begin to build strain in the rocks again. Eventually the rocks will slip again, causing another earthquake. Scientists study historical records of earthquakes to see if there are any patterns of recurrence. They also study seismic gaps. A **seismic gap** is an area along a fault where there has not been any earthquake activity for a long period of time. There has been only limited success in long-term forecasting. **Scientists don't yet understand enough about how and where earthquakes will occur to make accurate long-term predictions.**

Go Online
SCILINKS NSTA

For: Links on predicting earthquakes
Visit: www.SciLinks.org
Web Code: cjn-3082

Section 8.3 Assessment

Reviewing Concepts

1. What destructive events can be triggered by an earthquake?
2. What physical changes have been used in the attempts to predict earthquakes?
3. What is a tsunami?
4. What is a seismic gap?

Critical Thinking

5. **Making Judgments** Do you think scientists are close to being able to accurately predict earthquakes? Explain your answer.
6. **Drawing Conclusions** Why is it incorrect to refer to tsunamis as tidal waves?

Connecting Concepts

Earthquakes In Section 8.1, you learned about the elastic energy stored in rocks before an earthquake and the elastic rebound hypothesis. How could this information be used to try to predict earthquakes?

8.4 Earth's Layered Structure

Reading Focus

Key Concepts

- What is Earth's internal structure?
- What is the composition of Earth's interior?

Vocabulary

- crust
- mantle
- lithosphere
- asthenosphere
- outer core
- inner core
- Moho

Reading Strategy

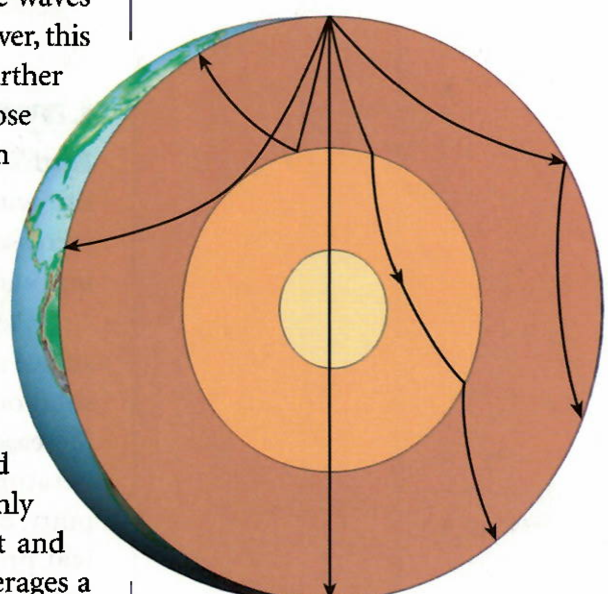
Sequencing Copy the flowchart. After you read, complete the sequence of layers in Earth's interior.

Earth's Internal Structure

Lithosphere → a. __?__ → b. __?__ → Outer core → c. __?__

Earth's interior lies not very far beneath our feet, but we can't reach it. The deepest well has drilled only 12 kilometers into Earth's crust. With such limited access, how do we know what Earth's interior is like? Most knowledge of the interior comes from the study of earthquake waves that travel through Earth.

Figure 14 The arrows show only a few of the many possible paths that seismic waves take through Earth.
Inferring ***What causes the wave paths to change?***

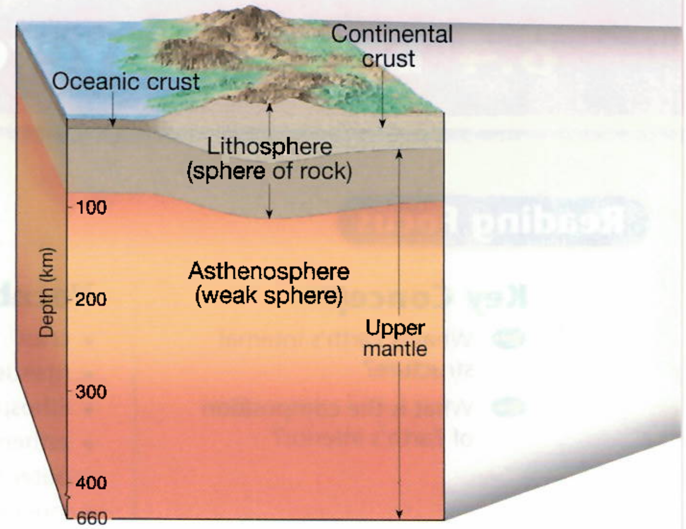


Layers Defined by Composition

If Earth were made of the same materials throughout, seismic waves would spread through it in straight lines at constant speed. However, this is not the case. Seismic waves reaching seismographs located farther from an earthquake travel at faster average speeds than those recorded at locations closer to the event. This general increase in speed with depth is due to increased pressure, which changes the elastic properties of deeply buried rock. As a result, the paths of seismic waves through Earth are refracted, or bent, as they travel. Figure 14 shows this bending. **Earth's interior consists of three major zones defined by its chemical composition—the crust, mantle, and core.**

Crust The **crust,** the thin, rocky outer layer of Earth, is divided into oceanic and continental crust. The oceanic crust is roughly 7 kilometers thick and composed of the igneous rocks basalt and gabbro. The continental crust is 8–75 kilometers thick, but averages a thickness of 40 kilometers. It consists of many rock types. The average composition of the continental crust is granitic rock called granodiorite. Continental rocks have an average density of about 2.7 g/cm^3 and some are over 4 billion years old. The rocks of the oceanic crust are younger (180 million years or less) and have an average density of about 3.0 g/cm^3.

Figure 15 **Earth's Layered Structure** The left side of the globe shows that Earth's interior is divided into three different layers based on compositional differences—the crust, mantle, and core. The right side of the globe shows the five main layers of Earth's interior based on physical properties and mechanical strength—the lithosphere, asthenosphere, mesosphere, outer core, and inner core. The block diagram shows an enlarged view of the upper portion of Earth's interior.



Mantle Over 82 percent of Earth's volume is contained in the **mantle**—a solid, rocky shell that extends to a depth of 2890 kilometers. The boundary between the crust and mantle represents a change in chemical composition. The dominant rock type in the uppermost mantle is peridotite, which has a density of 3.4 g/cm^3.

Core The core is a sphere composed of an iron-nickel alloy. At the extreme pressures found in the center of the core, the iron-rich material has an average density of almost 13 g/cm^3 (13 times heavier than water).

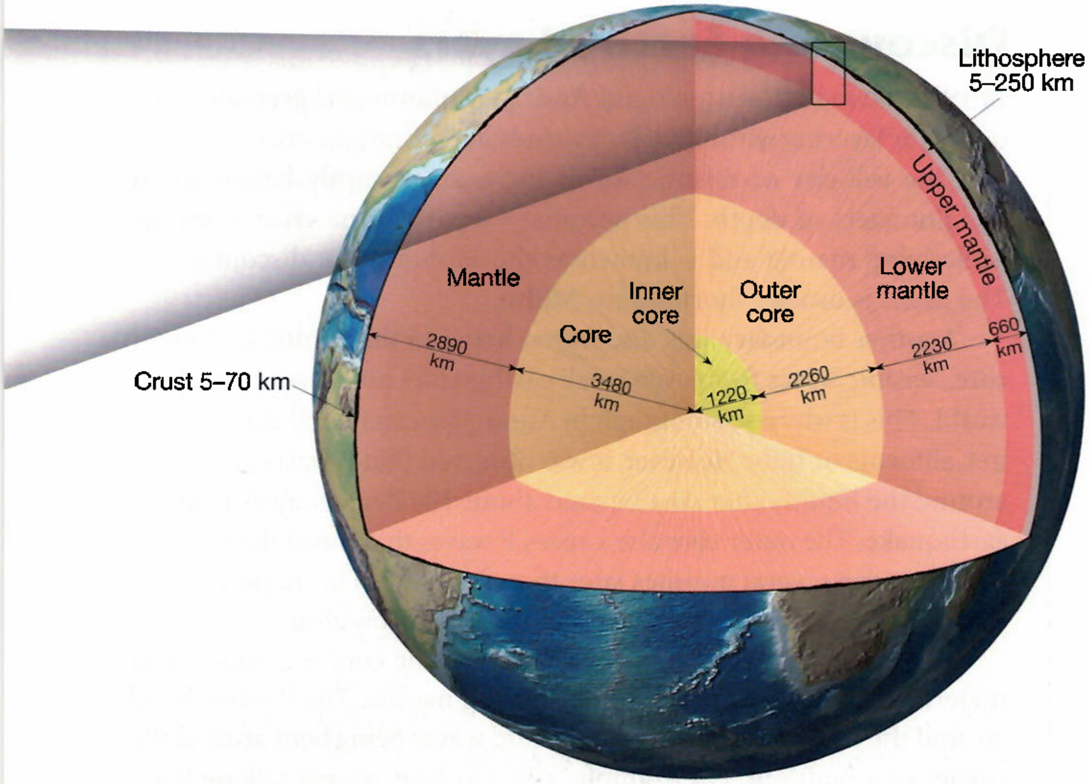
Reading Checkpoint *What is the composition of the core?*

Layers Defined by Physical Properties

Earth's interior has a gradual increase in temperature, pressure, and density with depth. When a substance is heated, the transfer of energy increases the vibrations of particles. If the temperature exceeds the melting point, the forces between particles are overcome and melting begins.

If temperature were the only factor that determined whether a substance melted, our planet would be a molten ball covered with a thin, solid outer shell. Fortunately, pressure also increases with depth and increases rock strength. Depending on the physical environment (temperature and pressure), a material may behave like a brittle solid, a putty, or a liquid. **Earth can be divided into layers based on physical properties—the lithosphere, asthenosphere, outer core, and inner core.**

Lithosphere and Asthenosphere Earth's outermost layer consists of the crust and uppermost mantle and forms a relatively cool, rigid shell called the **lithosphere**. This layer averages about 100 kilometers in thickness.



Beneath the lithosphere lies a soft, comparatively weak layer known as the **asthenosphere.** The asthenosphere has temperature/pressure conditions that may result in a small amount of melting. Within the asthenosphere, the rocks are close enough to their melting temperatures that they are easily deformed. Thus, the asthenosphere is weak because it is near its melting point, just as hot wax is weaker than cold wax. The lower lithosphere and asthenosphere are both part of the upper mantle.

Lower Mantle From a depth of about 660 kilometers down to near the base of the mantle lies a more rigid layer called the lower mantle. Despite their strength, the rocks of the lower mantle are still very hot and capable of gradual flow. The bottom few hundred kilometers of the mantle, laying on top of the hot core, contains softer, more flowing rock like that of the asthenosphere.

Inner and Outer Core The core, which is composed mostly of an iron-nickel alloy, is divided into two regions with different physical properties. The **outer core** is a liquid layer 2260 kilometers thick. The flow of metallic iron within this zone generates Earth's magnetic field. The **inner core** is a sphere having a radius of 1220 kilometers. Despite its higher temperature, the material in the inner core is compressed into a solid state by the immense pressure.

Reading Checkpoint *Why is the inner core solid?*

Discovering Earth's Layers

In 1909, a Croatian seismologist, Andrija Mohorovičić, presented evidence for layering within Earth. By studying seismic records, he found that the velocity of seismic waves increases abruptly below about 50 kilometers of depth. This boundary separates the crust from the underlying mantle and is known as the Mohorovičić discontinuity. The name is usually shortened to **Moho.**

Another boundary was discovered between the mantle and outer core. Seismic waves from even small earthquakes can travel around the world. This is why a seismograph in Antarctica can record earthquakes in California or Italy. However, it was observed that P waves were bent around the liquid outer core beyond about 100 degrees away from an earthquake. The outer core also causes P waves that travel through the core to arrive several minutes later than expected. This region, where bent P waves arrive, is sometimes called the shadow zone.

The bent wave paths can be explained if the core is composed of material that is different from the overlying mantle. The P waves bend around the core in a way similar to sound waves being bent around the corner of a building. For example, you can hear people talking from around the side of a building even if you cannot see them. In this way, rather than actually stopping the P waves in the shadow zone, the outer core bends them, as you can see modeled in Figure 16. It was further shown that S waves could not travel through the outer core. Therefore, geologists concluded that this region is liquid.

Reading Checkpoint *What is the Moho?*

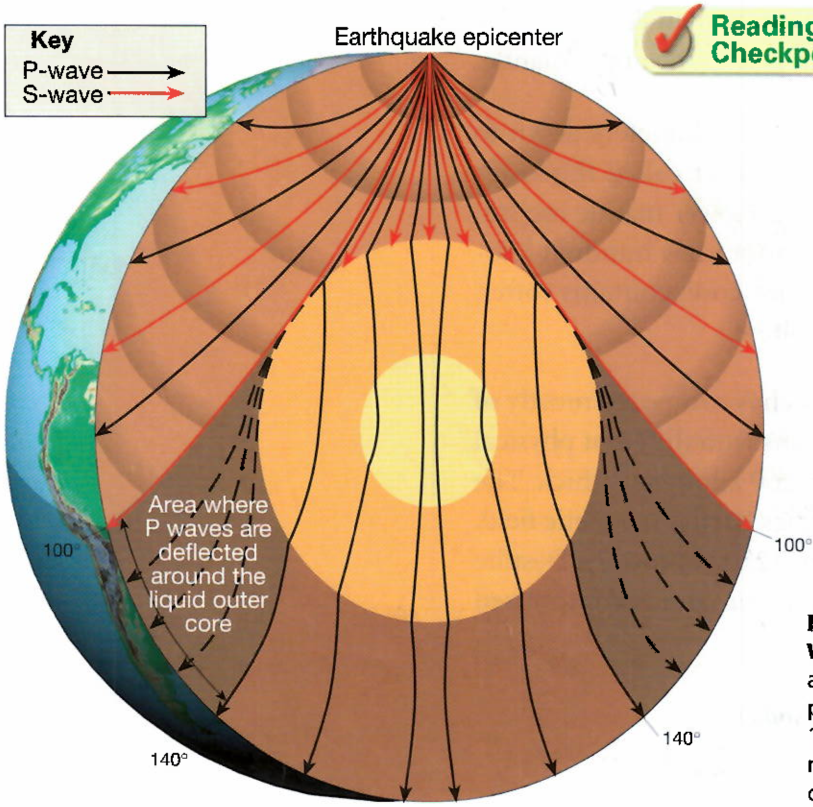


Figure 16 Earth's Interior Showing P and S Wave Paths The change in physical properties at the mantle-core boundary causes the wave paths to bend sharply. Any location more than 100 degrees from an earthquake epicenter will not receive direct S waves because the liquid outer core will not transmit them.

Discovering Earth's Composition

We have examined Earth's structure, so now let's look at the composition of each layer. **Early seismic data and drilling technology indicate that the continental crust is mostly made of lighter, granitic rocks.** Until the late 1960s, scientists had only seismic evidence they could use to determine the composition of oceanic crust. The recovery of ocean-floor samples was made possible with the development of deep-sea drilling technology. **The crust of the ocean floor has a basaltic composition.**

The composition of the rocks of the mantle and core is known from more indirect data. Some of the lava that reaches Earth's surface comes from the partially melted asthenosphere within the mantle. In the laboratory, experiments show that partially melting the rock called peridotite produces a substance that is similar to the lava that erupts during volcanic activity of islands such as Hawaii.

Surprisingly, meteorites that collide with Earth provide evidence of Earth's inner composition. Meteorites are assumed to be composed of the original material from which Earth was formed. Their composition ranges from metallic meteorites made of iron and nickel to stony meteorites composed of dense rock similar to peridotite. Because Earth's crust contains a smaller percentage of iron than do meteorites, geologists believe that the dense iron, and other dense metals, sank toward Earth's center during the planet's formation. Lighter substances may have floated to the surface, creating the less-dense crust. **Earth's core is thought to be mainly dense iron and nickel, similar to metallic meteorites. The surrounding mantle is believed to be composed of rocks similar to stony meteorites.**

Section 8.4 Assessment

Reviewing Concepts

1. List the major layers of Earth's internal structure based on physical properties. List the layers in order from Earth's center to the surface.
2. What is the composition of Earth's core?
3. What evidence indicates that Earth's outer core is liquid?
4. What is the composition of the mantle?

Critical Thinking

5. **Comparing and Contrasting** Compare the physical properties of the asthenosphere and the lithosphere.
6. **Inferring** Why are meteorites considered important clues to the composition of Earth's interior?

Writing in Science

Creative Writing Write a short fictional story about a trip to Earth's core. Make sure the details about the layers of Earth's interior are scientifically accurate.

Effects of Earthquakes

An **earthquake** is a shaking of the ground caused by sudden movements in the Earth's crust. The biggest quakes are set off by the movement of tectonic plates. Some plates slide past one another gently. However, others get stuck, and the forces pushing the plates build up. The stress mounts until the plates suddenly shift their positions and cause the Earth to shake. Most earthquakes last less than one minute. Even so, the effects of an earthquake can be devastating and long-lasting.

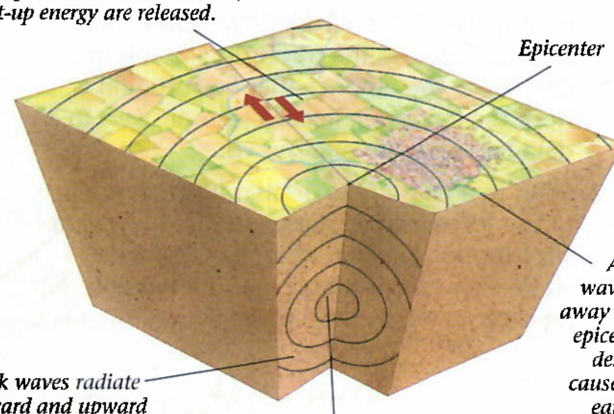
TSUNAMI
In 1755, an earthquake in Lisbon, Portugal, caused a tsunami, as illustrated in this painting. A **tsunami** is a huge sea wave that is set off by an undersea earthquake or volcanic eruption. When tsunamis break on shore, they often devastate coastal areas. Tsunamis can race at speeds of about 450 miles per hour and may reach heights of about 100 feet (30.5 m).

LANDSLIDE
In January 2001, an earthquake struck El Salvador. It caused the landslide that left these Salvadoran women homeless. A **landslide** is a sudden drop of a mass of land down a mountainside or hillside. Emergency relief workers from around the world often rush to the site of an earthquake disaster like the one that occurred in El Salvador.

INFRASTRUCTURE DAMAGE
When an earthquake occurred in Los Angeles in 1994, underground gas and water lines burst, causing fires and floods. Earthquakes often cause tremendous damage to the **infrastructure**—the network of services that supports a community. Infrastructure includes power utilities, water supplies, and transportation and communication facilities.

AVALANCHE
Earthquakes may trigger an **avalanche**—a sudden fall of a mass of ice and snow. In 1970, a severe earthquake off the coast of Peru caused a disastrous slide of snow and rock that killed some 18,000 people in the valley below.

WHEN THE EARTH CRACKS
Most people killed or injured by an earthquake are hit by debris from buildings. Additional damage can be caused by **aftershocks**—tremors that can occur hours, days, or even months after an earthquake. The scene above shows the city of Anchorage, Alaska, after a major earthquake. Extensive ground tremors caused the street to break up as the soil below it collapsed. Buildings and cars were dropped more than 10 feet (3 m) below street level.



SEISMIC WAVES
As tectonic forces build, rock beneath the surface bends until it finally breaks. The tectonic plates suddenly move, causing **seismic waves,** or vibrations, to travel through the ground. The waves radiate outward from an underground area called the focus, or hypocenter. Damage is usually greatest near the **epicenter,** the point on the surface directly above the focus.

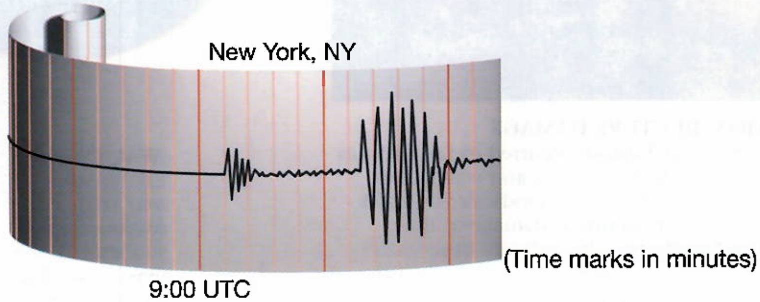
ASSESSMENT

1. **Key Terms** Define **(a)** earthquake, **(b)** tsunami, **(c)** landslide, **(d)** infrastructure, **(e)** avalanche, **(f)** aftershock, **(g)** seismic wave, **(h)** epicenter.
2. **Physical Processes** What physical processes cause an earthquake to occur?
3. **Environmental Change** How can an earthquake cause changes to the physical characteristics of a place?
4. **Natural Hazards** **(a)** How can an earthquake change the human characteristics of a place? **(b)** How does the international community respond to a devastating earthquake?
5. **Critical Thinking** **Solving Problems** What can a community do to reduce the amount of earthquake damage that might occur in the future?

Exploration Lab

Locating an Earthquake

The focus of an earthquake is the actual place within Earth where the earthquake originates. When locating an earthquake on a map, scientists plot the epicenter, the point on Earth's surface directly above the focus. To locate an epicenter, records from three different seismographs are needed.

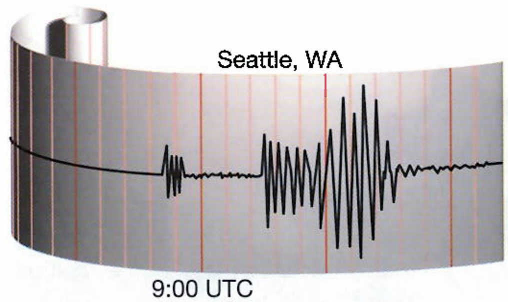


Problem How can you determine the location of an earthquake's epicenter?

Materials

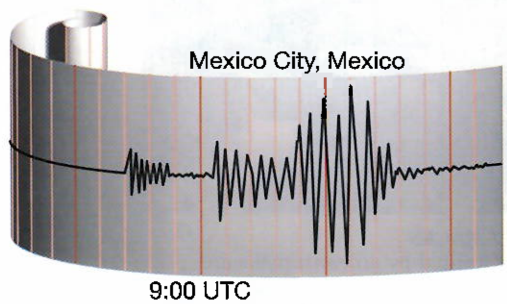
- pencil
- drawing compass
- world map or atlas
- photocopy of map on page 241

Skills Measuring, Interpreting Maps, Interpreting Graphs



Procedure

1. These three seismograms recorded the same earthquake, in New York City, Seattle, and Mexico City. Use the travel-time graph to determine the distance that each station is from the epicenter. Record your answers in a data table like the one shown.
2. Refer to a world map or atlas for the locations of the three seismic stations. Place a small dot showing the location of each of the three stations on the photocopy of the map on the next page. Neatly label each city on the map.



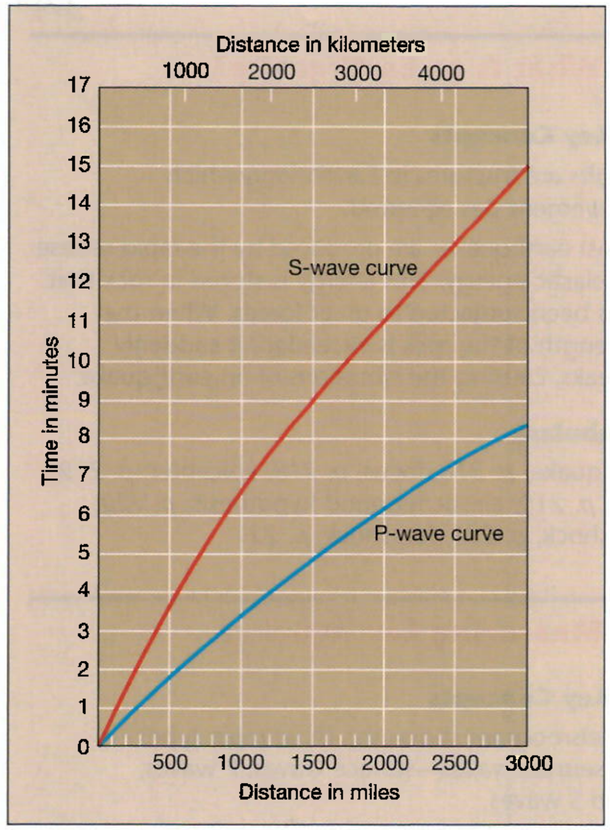
Data Table

	New York	Seattle	Mexico City
Elapsed time between first P and first S waves			
Distance from epicenter in miles			

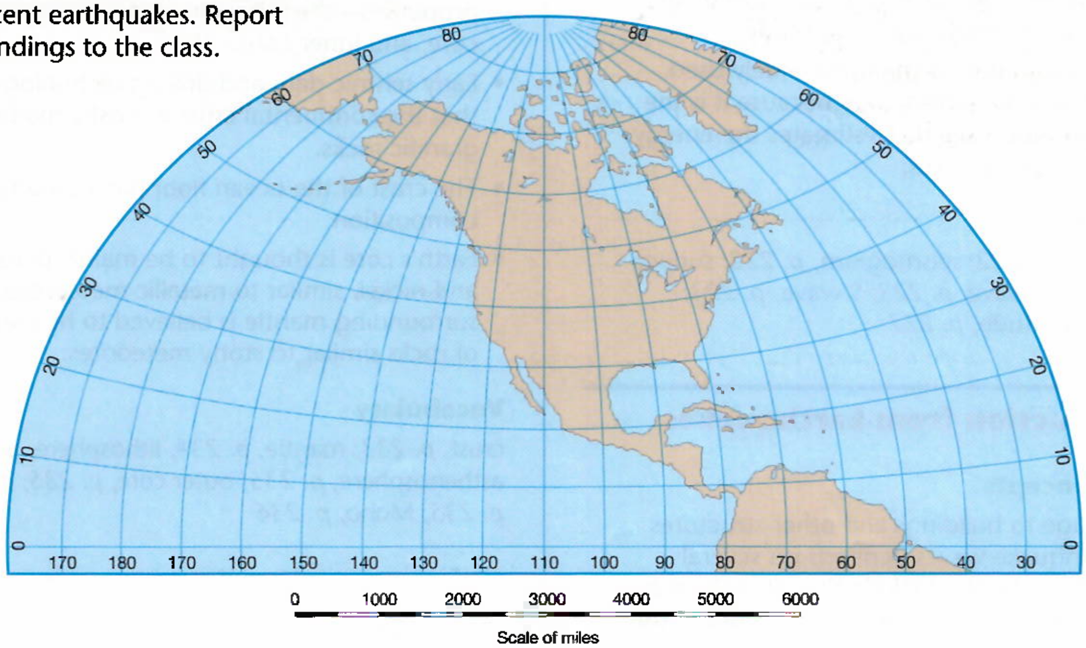
3. On the map, use a drawing compass to draw a circle around each of the three stations. The radius of the circle, in miles, should be equal to each station's distance from the epicenter. Use the scale on the map to set the distance on the drawing compass for each station. **CAUTION** *Use care when handling the drawing compass.*

Analyze and Conclude

1. **Using Graphs** How far from the epicenter are the three cities located?
2. **Calculating** What would the distances from the epicenter to the cities be in kilometers?
3. **Interpreting Maps** What is the approximate latitude and longitude of the epicenter of the earthquake that was recorded by the three stations?
4. **Drawing Conclusions** On the New York seismogram the first P wave was recorded at 9:01 UTC. UTC is the international standard on which most countries base their time. At what time (UTC) did the earthquake actually occur? Explain.



Go Further Use the Internet or the library to find the locations of recent earthquake epicenters. Make a data table displaying the location, date, and magnitude of ten recent earthquakes. Report your findings to the class.



CHAPTER 8

Study Guide

8.1 What Is an Earthquake?

Key Concepts

- Faults are fractures in Earth along which movement has occurred.
- Most earthquakes are produced by the rapid release of elastic energy. This energy is stored in rock that has been subjected to great forces. When the strength of the rock is exceeded, it suddenly breaks, causing the vibrations of an earthquake.

Vocabulary

earthquake, *p. 218;* focus, *p. 218;* epicenter, *p. 219;* fault, *p. 219;* elastic rebound hypothesis, *p. 220;* aftershock, *p. 221;* foreshock, *p. 221*

8.2 Measuring Earthquakes

Key Concepts

- A seismogram shows the three main types of seismic waves—surface waves, P waves, and S waves.
- Travel-time graphs from three or more seismographs can be used to find the exact location of an earthquake epicenter.
- Historically, scientists have used two different measurement types to describe the size of an earthquake—intensity and magnitude.
- Moment magnitude is the most widely used measurement for earthquakes because it is the only magnitude scale that estimates the energy released by earthquakes.

Vocabulary

seismograph, *p. 222;* seismogram, *p. 222;* surface wave, *p. 223;* P wave, *p. 223;* S wave, *p. 223;* moment magnitude, *p. 227*

8.3 Destruction from Earthquakes

Key Concepts

- The damage to buildings and other structures from earthquake waves depends on several factors. These factors include the intensity and the duration of the vibrations, the nature of the material on which the structure is built, and the design of the structure.
- A tsunami triggered by an earthquake occurs where a slab of the ocean floor is displaced vertically along a fault. A tsunami also can occur when the vibration of a quake sets an underwater landslide into motion.
- With many earthquakes, the greatest damage to structures is from landslides and ground subsidence, or the sinking of the ground triggered by the vibrations.
- So far, methods for short-range predictions of earthquakes have not been successful.
- Scientists don't yet understand enough about how and where earthquakes will occur to make accurate long-term predictions.

Vocabulary

liquefaction, *p. 230;* tsunami, *p. 230;* seismic gap, *p. 232*

8.4 Earth's Layered Structure

Key Concepts

- Earth's interior consists of three major zones defined by its chemical composition—the crust, mantle, and core.
- Earth can be divided into layers based on physical properties—the lithosphere, asthenosphere, outer core, and inner core.
- Early seismic data and drilling technology indicate that the continental crust is mostly made of lighter, granitic rocks.
- The crust of the ocean floor has a basaltic composition.
- Earth's core is thought to be mainly dense iron and nickel, similar to metallic meteorites. The surrounding mantle is believed to be composed of rocks similar to stony meteorites.

Vocabulary

crust, *p. 233;* mantle, *p. 234;* lithosphere, *p. 234;* asthenosphere, *p. 235;* outer core, *p. 235;* inner core, *p. 235;* Moho, *p. 236*

CHAPTER 8

Assessment

Interactive textbook with assessment at PHSchool.com

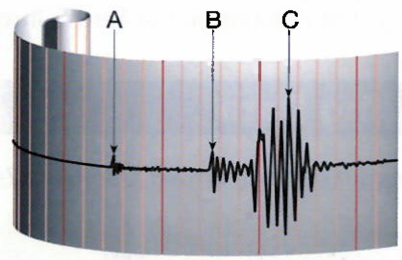
Reviewing Content

Choose the letter that best answers the question or completes the statement.

1. Approximately how many earthquakes are strong enough to be felt each year worldwide?
   a. 500 b. 1000
   c. 10,000 d. 30,000
2. What is the location on the surface directly above the earthquake focus called?
   a. epicenter b. fault
   c. magnitude d. Moho
3. The rigid layer of Earth that includes the entire crust and the uppermost part of the mantle is called the
   a. asthenosphere. b. mesosphere.
   c. lithosphere. d. Moho.
4. The instrument that records earthquakes is called
   a. a seismogram. b. a seismologist.
   c. seismology. d. a seismograph.
5. Which of the following regions has the greatest amount of earthquake activity?
   a. central Europe
   b. the circum-Pacific belt
   c. the eastern United States
   d. central Africa
6. What material do scientists believe makes up a large part of the upper mantle?
   a. basalt b. granite
   c. iron d. peridotite
7. The point at which an earthquake begins is called
   a. a foreshock. b. the epicenter.
   c. the focus. d. the Moho.
8. In areas where loosely consolidated materials are saturated with water, earthquakes can turn stable soil into a liquid during a process called
   a. faulting. b. liquefaction.
   c. tsunamis. d. subsidence.
9. To find the epicenter of an earthquake, what is the minimum number of seismic stations that are needed?
   a. three b. nine
   c. five d. two
10. What scale is currently used to express the magnitude of an earthquake?
    a. Richter scale
    b. moment magnitude
    c. tsunami scale
    d. Moho scale

Understanding Concepts

Use the diagram below to answer Questions 11 and 12.



11. The diagram shows a typical recording of an earthquake. What is the record called?
12. Identify the waves recorded at A, B, and C on the diagram.
13. Does all motion along large faults occur in the form of destructive earthquakes?
14. What type of seismic wave causes the greatest destruction to buildings?
15. In addition to the damage caused directly by seismic vibrations, list three other types of destructive events that can be triggered by earthquakes.
16. Describe the composition and physical properties of the crust.
17. What is liquefaction and how can earthquakes cause liquefaction to occur?
18. List the major differences between P waves and S waves.
19. How much does the amplitude of the waves increase between an earthquake that measures 4.2 on the Richter scale and an earthquake that measures 6.2 on the Richter scale?
20. What are two factors that can determine the amount of destruction that results from an earthquake?

CHAPTER 8

Assessment *continued*

Critical Thinking

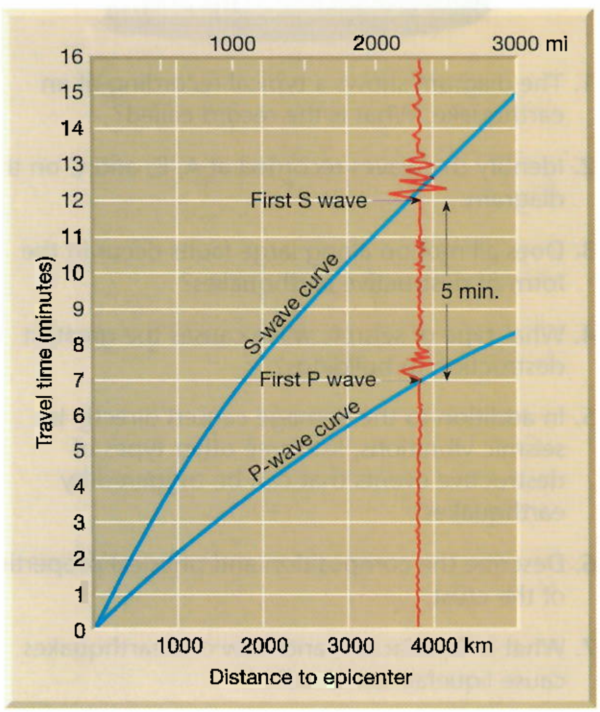
21. **Applying Concepts** Give two reasons why an earthquake with a moderate magnitude might cause more extensive damage than an earthquake with a high magnitude.

22. **Comparing and Contrasting** How are the moment magnitude scale and the Richter scale different?

23. **Inferring** How did scientists determine the structure and composition of Earth's interior?

Analyzing Data

Use the diagram below to answer Questions 24–26.



24. **Using Graphs** Determine the distance between an earthquake and seismic station if the first S wave arrives three minutes after the first P wave.

25. **Using Graphs** If a seismic station is 2500 kilometers from the earthquake's epicenter, approximately when will the first P wave be received? When will the first S wave be received?

26. **Calculating** What is the difference in the travel-times of the first P wave and the first S wave if the seismic station is 1000 kilometers from the earthquake epicenter?

Concepts in Action

27. **Applying Concepts** Why is the moment magnitude the most commonly used scale by scientists for measuring earthquakes?

28. **Classifying** In what major earthquake zone would an earthquake in Indonesia be located?

29. **Hypothesizing** You are on a large ocean research ship. You have generated seismic waves by causing an explosion on a platform towed behind the ship. What seismic waves will be recorded by a seismograph located on the ocean floor beneath the ship? Explain your answer.

30. **Writing in Science** Research a recent earthquake and write about the earthquake damage in the style of a newspaper article.

Performance-Based Assessment

Designing an Experiment Design a model seismograph to record simulated earthquakes. When your model is completed, test it for the class. Then determine how your seismograph design could be improved or changed if it doesn't work well.

Standardized Test Prep

Test-Taking Tip

Narrowing the Choices
If, after reading all the answer choices, you are not sure which one is correct, eliminate those answers that you know are wrong. In the question below, first eliminate the choices you know are wrong. For example, answer choice A can be eliminated since the fact that earthquakes are destructive does not affect long-range forecasting. Then focus on the remaining choices.

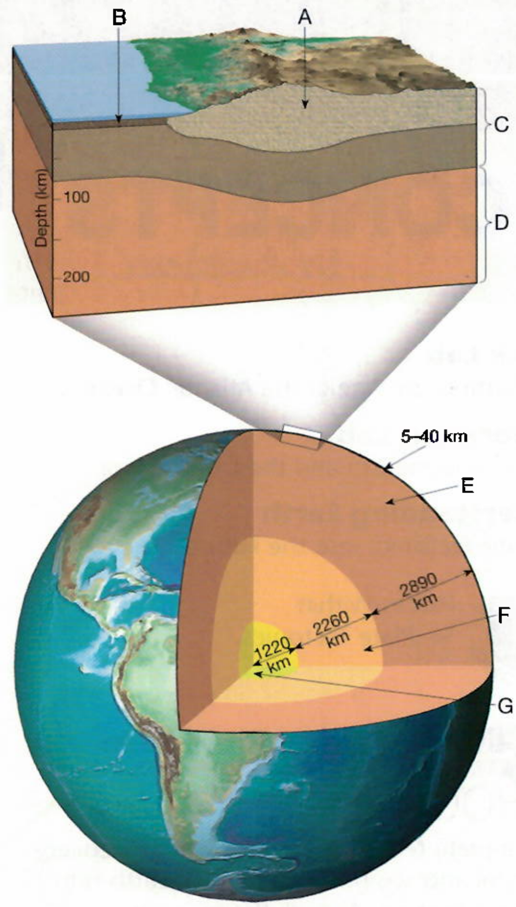
Long-range earthquake forecasts are based on the assumption that earthquakes are
(A) destructive.
(B) random.
(C) fully understood.
(D) repetitive.

(Answer: D)

Choose the letter that best answers the question or completes the statement.

1. What property that is different for P and S waves provides a method for locating the epicenter of an earthquake?
   (A) magnitude
   (B) foci
   (C) modes of travel
   (D) speed
2. Movements that follow a major earthquake often generate smaller earthquakes called
   (A) aftershocks.
   (B) foreshocks.
   (C) surface waves.
   (D) landslides.
3. An earthquake in the ocean floor can cause a destructive sea wave called a
   (A) P wave.
   (B) S wave.
   (C) Moho.
   (D) tsunami.

Use the diagram below to answer Questions 4–6.



4. What layer of Earth's interior is labeled F in the diagram? Explain this layer.
5. What layer is labeled A in the diagram? What type of rock makes up this layer?
6. In the diagram which letters would indicate layers that form the lithosphere? Explain the layers.
7. Describe the composition (mineral/rock makeup) of Earth's crust, mantle, and core. How did scientists determine the composition of each layer?
8. Discuss the conditions that cause earthquakes to occur.

CHAPTER 9 Plate Tectonics

CONCEPTS in Action

Quick Lab
Charting the Age of the Atlantic Ocean

Exploration Lab
Paleomagnetism and the Ocean Floor

Understanding Earth
Plate Tectonics into the Future

GEODe EARTH SCIENCE Forces Within
↳ Plate Tectonics

Discovery Channel School **Video Field Trip**
Plate Tectonics

Take a plate tectonics field trip with Discovery Channel and see how the crust of Earth is in constant motion. Answer the following questions after watching the video.

1. What does the discovery of identical basalt rock in South America and Africa help to prove?
2. How was the Atlantic Ocean formed?

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This photograph is a composite satellite ▶ image of Europe, North Africa, and the Arabian Peninsula.

FORCES WITHIN

Chapter Preview

Inquiry Activity

How Do the Continents Fit Together?

Procedure

1. Get a copy of a world map from your teacher. Cut out the major continents along their coastlines. **CAUTION** *Be careful when using scissors.*
2. Try to fit together the pieces into one large landmass. Look for a "best-fit" configuration.
3. Compare your large landmass with those of other students. Did anyone come up with a landmass that was very different from the others?

Think About It

1. **Observing** From your continental reconstruction, where did the continents fit together well? Where did problems occur?
2. **Developing Hypotheses** Use your observations to develop a hypothesis on how to get a better fit of the continents. How could the overlaps and large gaps be explained? (*Hint:* What if the outline of the coasts was not the same as the boundaries of the continents themselves?)

9.1 Continental Drift

Reading Focus

Key Concepts

- What is the hypothesis of continental drift?
- What evidence supported continental drift?

Vocabulary

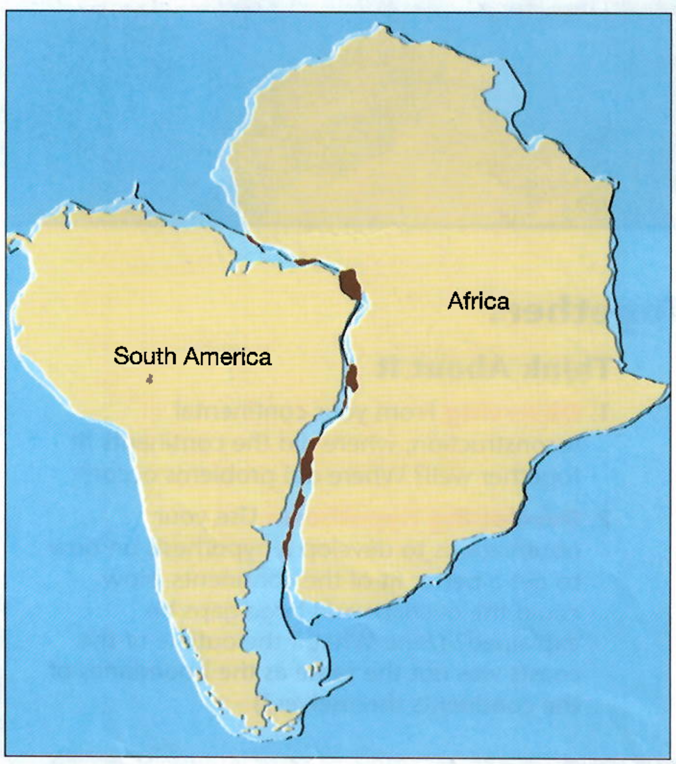
- continental drift
- Pangaea

Reading Strategy

Summarizing Copy the table. Fill it in as you read to summarize the evidence of continental drift.

Hypothesis	Evidence
Continental Drift	a. continental puzzle
	b. ___?___
	c. ___?___
	d. ___?___

Figure 1 A Curious Fit This map shows the best fit of South America and Africa at a depth of about 900 meters. The areas where continents overlap appear in brown.
Inferring ***Why are there areas of overlap?***



Will California eventually slide into the ocean? Have continents really drifted apart over the centuries? Early in the twentieth century, most geologists thought that the positions of the ocean basins and continents were fixed. During the last few decades, however, new data have dramatically changed our understanding of how Earth works.

An Idea Before Its Time

The idea that continents fit together like pieces of a jigsaw puzzle came about when better world maps became available. Figure 1 shows the two most obvious pieces of this jigsaw puzzle. However, little significance was given this idea until 1915, when Alfred Wegener, a German scientist, proposed his radical hypothesis of **continental drift.** **Wegener's continental drift hypothesis stated that the continents had once been joined to form a single supercontinent.** He called this supercontinent **Pangaea,** meaning *all land.*

Wegener also hypothesized that about 200 million years ago Pangaea began breaking into smaller continents. These continents then drifted to their present positions, as shown on page 250. Wegener and others collected much evidence to support these claims. Let's examine their evidence.

Evidence: The Continental Puzzle Wegener first thought that the continents might have been joined when he noticed the similarity between the coastlines on opposite sides of the South Atlantic Ocean. He used present-day shorelines to show how the continents fit together. However, his opponents correctly argued that erosion continually changes shorelines over time.

Evidence: Matching Fossils **Fossil evidence for continental drift includes several fossil organisms found on different landmasses.** Wegener reasoned that these organisms could not have crossed the vast oceans presently separating the continents. An example is *Mesosaurus,* an aquatic reptile whose fossil remains are limited to eastern South America and southern Africa, as shown in Figure 2. If *Mesosaurus* had been able to swim well enough to cross the vast South Atlantic Ocean, its fossils should be more widely distributed. This is not the case. Therefore, Wegener argued, South America and Africa must have been joined somehow.

The idea of land bridges was once the most widely accepted explanation for similar fossils being found on different landmasses. Most scientists believed that during a recent glacial period, the lowering of sea level allowed animals to cross the narrow Bering Strait between Asia and North America. However, if land bridges did exist between South America and Africa, their remnants should still lie below sea level. But no signs of such land bridges have ever been found in the Atlantic Ocean.

Reading Checkpoint *How does the distribution of* Mesosaurus *fossils provide evidence for continental drift?*

Q&A

Q *If all the continents were once joined as Pangaea, what did the rest of Earth look like?*

A When all the continents were together, there must also have been one huge ocean surrounding them. This ocean is called *Panthalassa* (*pan* = all, *thalassa* = sea). Today all that remains of Panthalassa is the Pacific Ocean, which has been decreasing in size since the breakup of Pangaea.

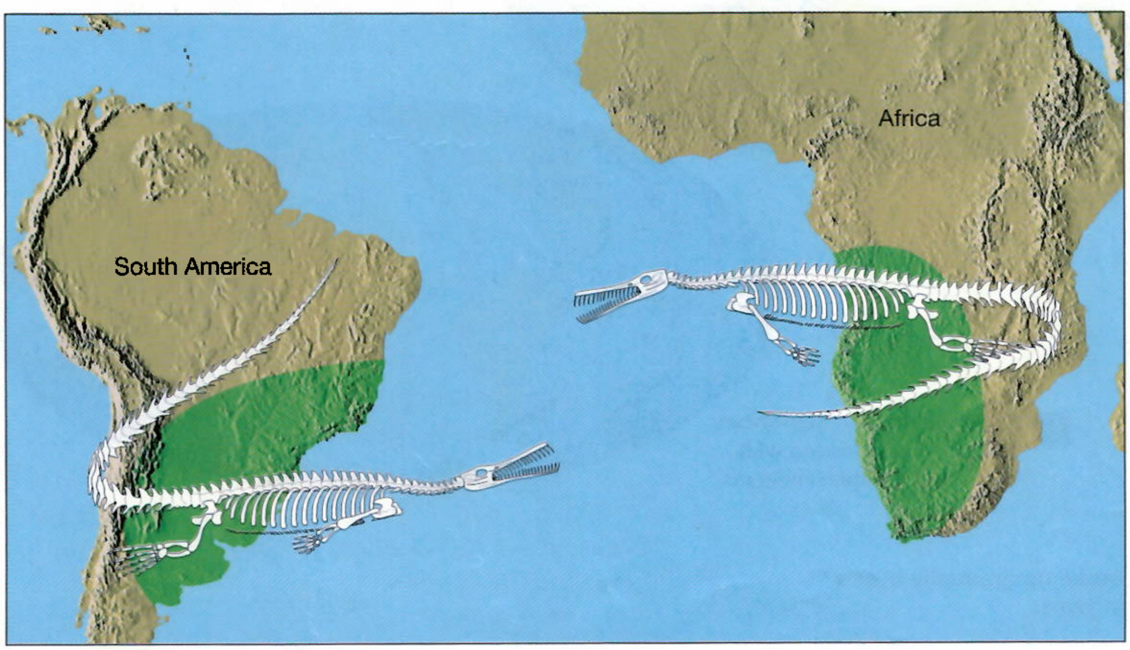
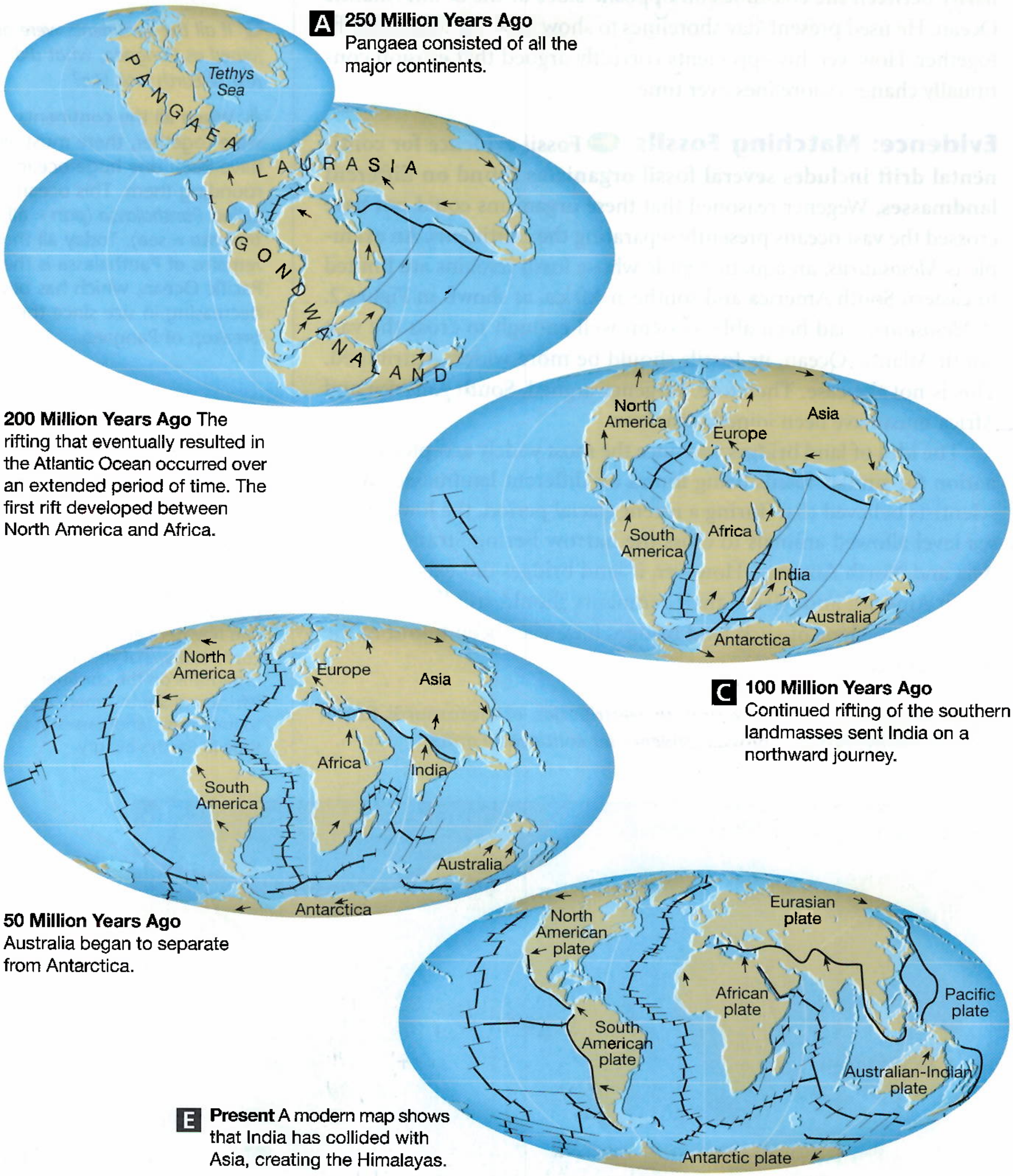


Figure 2 Location of Mesosaurus Fossils of *Mesosaurus* have been found on both sides of the South Atlantic and nowhere else in the world. Fossil remains of this and other organisms on the continents of Africa and South America appear to link these landmasses at some time in Earth's history.

Breakup of Pangaea



A **250 Million Years Ago** Pangaea consisted of all the major continents.

B **200 Million Years Ago** The rifting that eventually resulted in the Atlantic Ocean occurred over an extended period of time. The first rift developed between North America and Africa.

C **100 Million Years Ago** Continued rifting of the southern landmasses sent India on a northward journey.

D **50 Million Years Ago** Australia began to separate from Antarctica.

E **Present** A modern map shows that India has collided with Asia, creating the Himalayas.

Figure 3 Pangaea broke up gradually over a period of 200 million years.

Matching Mountain Ranges

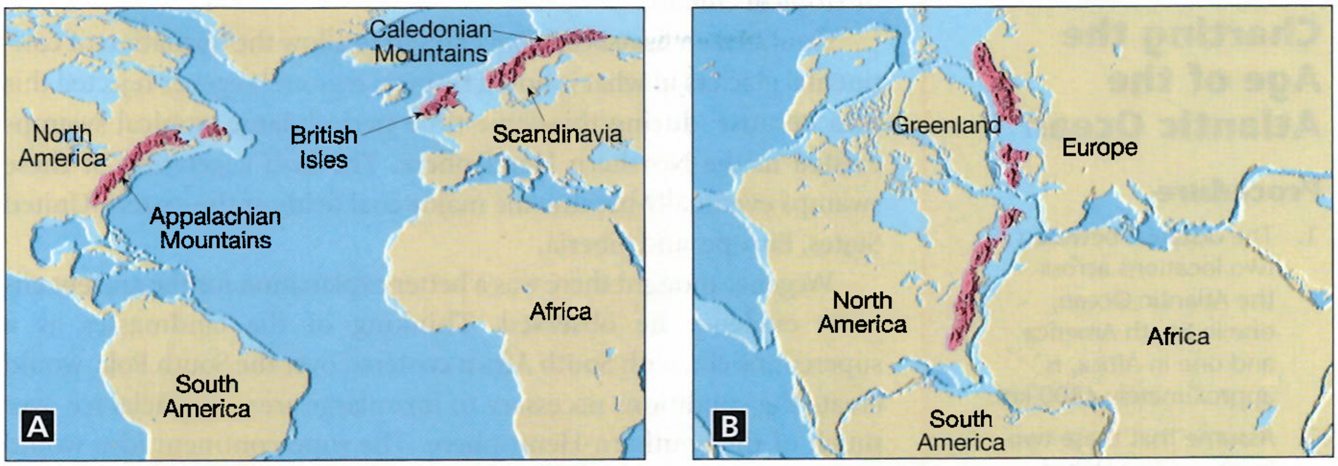


Figure 4 **A** The Appalachian Mountains run along the eastern side of North America and disappear off the coast of Newfoundland. Mountains that are similar in age and structure are found in the British Isles and Scandinavia. **B** When these landmasses are united as Pangaea, these ancient mountain chains form a nearly continuous belt.

Evidence: Rock Types and Structures Anyone who has worked a jigsaw puzzle knows that the pieces must fit together to form a clear picture. The clear picture in the continental drift puzzle is one of matching rock types and mountain belts. If the continents existed as Pangaea, the rocks found in a particular region on one continent should closely match in age and type those in adjacent positions on the adjoining continent.

Rock evidence for continental drift exists in the form of several mountain belts that end at one coastline, only to reappear on a landmass across the ocean. For example, the Appalachian mountain belt runs northeastward through the eastern United States, ending off the coast of Newfoundland, as shown in Figure 4A. Mountains of the same age with similar rocks and structures are found in the British Isles and Scandinavia. When these landmasses are fit together as in Figure 4B, the mountain chains form a nearly continuous belt.

Reading Checkpoint *How does the location of mountain chains provide evidence of continental drift?*

Evidence: Ancient Climates Wegener was a meteorologist, so he was interested in obtaining data about ancient climates to support continental drift. And he did find evidence for dramatic global climate changes. Wegener found glacial deposits showing that between 220 million and 300 million years ago, ice sheets covered large areas of the Southern Hemisphere. Layers of glacial till were found in southern Africa and South America, as well as in India and Australia. Below these beds of glacial debris lay scratched and grooved bedrock carved by the ice. In some locations, the scratches and grooves showed that the ice had moved from what is now the sea onto land. It is unusual for large continental glaciers to move from the sea

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Quick Lab

Charting the Age of the Atlantic Ocean

Procedure

1. The distance between two locations across the Atlantic Ocean, one in South America and one in Africa, is approximately 4300 km.
2. Assume that these two locations were once joined as part of Pangaea.

Analyze and Conclude

1. **Calculating** If the two landmasses moved away from each other at a rate of 3.3 cm/y, how long did it take these two locations to move to their current positions?
2. **Inferring** Do you think the Atlantic Ocean would have formed at a constant rate or would that rate have varied over time? Why?

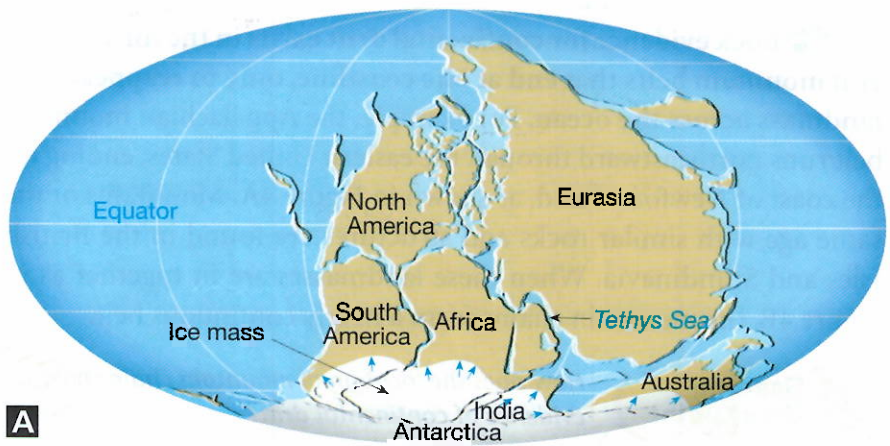
onto land. It is also interesting that much of the land area that shows evidence of this glaciation now lies near the equator in a subtropical or tropical climate.

Could Earth have been cold enough to allow the formation of continental glaciers in what is now a tropical region? Wegener rejected this idea because, during this same time period, large tropical swamps existed in the Northern Hemisphere. The lush vegetation of these swamps eventually became the major coal fields of the eastern United States, Europe, and Siberia.

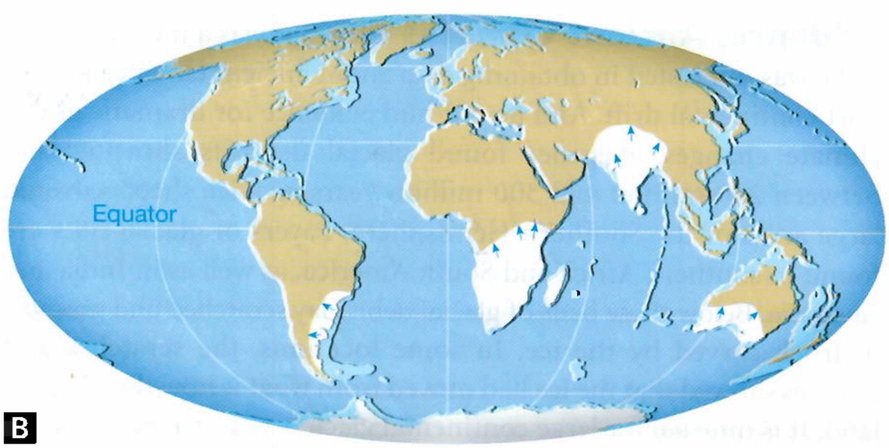
Wegener thought there was a better explanation for the ancient climate evidence he observed. Thinking of the landmasses as a supercontinent, with South Africa centered over the South Pole, would create the conditions necessary to form large areas of glacial ice over much of the Southern Hemisphere. The supercontinent idea would also place the northern landmasses nearer the tropics and account for their vast coal deposits, as shown in Figure 5.

Reading Checkpoint ***Summarize the climate evidence for continental drift.***

Glacier Evidence



A



B

Figure 5 **A** The area of Pangaea covered by glacial ice 300 million years ago. **B** The continents as they are today. The white areas indicate where evidence of the old ice sheets exists. **Interpreting Diagrams** ***Where were the continents located when the glaciers formed?***

Rejecting a Hypothesis

Wegener's drift hypothesis faced a great deal of criticism from other scientists. One objection was that Wegener could not describe a mechanism that was capable of moving the continents across the globe. Wegener proposed that the tidal influence of the Moon was strong enough to give the continents a westward motion. However, physicists quickly responded that tidal friction of the size needed to move the continents would stop Earth's rotation.

Wegener also proposed that the larger and sturdier continents broke through the oceanic crust, much like ice breakers cut through ice. However, no evidence existed to suggest that the ocean floor was weak enough to permit passage of the continents without the ocean floors being broken and deformed in the process.

Most scientists in Wegener's day rejected his hypothesis. However, a few geologists continued to search for additional evidence of continents in motion.

Reading Checkpoint *Why was Wegener's hypothesis rejected?*

A New Theory Emerges During the years that followed Wegener's hypothesis, major strides in technology enabled scientists to map the ocean floor. Extensive data on earthquake activity and Earth's magnetic field also became available. By 1968, these findings led to a new theory, known as plate tectonics. This theory provides the framework for understanding most geologic processes, such as the formation of the mountains shown in Figure 6.

Q&A

Q *Some day will the continents come back together and form a single landmass?*

A Yes, but not anytime soon. Based on current plate motions, it appears that the continents may meet up again in the Pacific Ocean—in about 300 million years.

Figure 6 Mountain ranges are commonly formed at plate boundaries. This photograph shows part of the Canadian Rockies in Banff National Park, Alberta, Canada.

Section 9.1 Assessment

Reviewing Concepts

1. What is the hypothesis of continental drift?
2. List the evidence that supported the hypothesis of continental drift.
3. What was one of the main objections to Wegener's continental drift hypothesis?
4. What is Pangaea?

Critical Thinking

5. **Applying Concepts** Would the occurrence of the same plant fossils in South America and Africa support continental drift? Explain.
6. **Drawing Conclusions** How did Wegener explain the existence of glaciers in the southern landmasses, and the lush tropical swamps in North America, Europe, and Siberia?

Writing in Science

Descriptive Paragraph Write a paragraph describing Pangaea. Include the location and climate of Pangaea. Use the equator as your reference for position.

9.2 Plate Tectonics

Reading Focus

Key Concepts

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

Vocabulary

- plate tectonics
- plate
- divergent boundary
- convergent boundary
- transform fault boundary

Reading Strategy

Comparing and Contrasting Copy the table. After you read, compare the three types of plate boundaries by completing the table.

Boundary Type	Relative Plate Motion
convergent	a. ___?___
divergent	b. ___?___
transform fault	c. ___?___

Earth's Major Plates

According to the plate tectonics theory, the uppermost mantle, along with the overlying crust, behaves as a strong, rigid layer. This layer is known as the lithosphere. The outer shell lies over a weaker region in the mantle known as the asthenosphere. The lithosphere is divided into segments called **plates,** which move and continually change shape and size. Figure 8 on pages 256-257 shows the seven major plates. The largest is the Pacific plate, covering most of the Pacific Ocean. Notice that several of the large plates include an entire continent plus a large area of the seafloor. This is a major departure from Wegener's continental drift hypothesis, which proposed that the continents moved through the ocean floor, not with it. Note also that none of the plates is defined entirely by the margins of a continent.

The lithospheric plates move relative to each other at a very slow but continuous rate that averages about 5 centimeters per year—about as fast as your fingernails grow. This movement is driven by the unequal distribution of heat within Earth. Hot material found deep in the mantle moves slowly upward as part of Earth's internal convection system. At the same time, cooler, denser slabs of oceanic lithosphere descend into the mantle, setting Earth's rigid outer shell into motion. The grinding movements of Earth's lithospheric plates generate earthquakes, create volcanoes, and deform large masses of rock into mountains.

Reading Checkpoint *What is plate tectonics?*

Types of Plate Boundaries

All major interactions among individual plates occur along their boundaries. **The three main types of boundaries are convergent, divergent, and transform fault boundaries.**

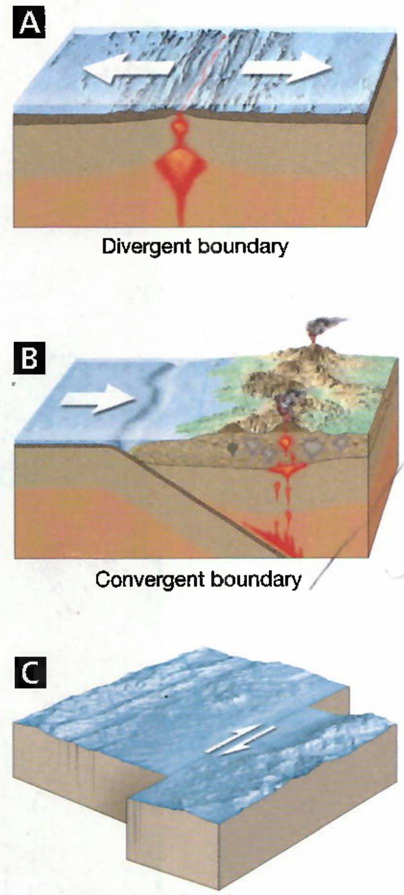
Divergent boundaries **Divergent boundaries** (also called spreading centers) occur when two plates move apart. This process results in upwelling of material from the mantle to create new seafloor, as shown in Figure 7A. A relatively new divergent boundary is located in Africa, in a region known as the East African Rift valley.

Convergent boundaries **Convergent boundaries** form where two plates move together. This process results in oceanic lithosphere plunging beneath an overriding plate, and descending into the mantle, as shown in Figure 7B. At other locations, plates carrying continental crust are presently moving toward each other. Eventually, these continents may collide and merge. Thus, the boundary that once separated two plates disappears as the plates become one.

Transform fault boundaries **Transform fault boundaries** are margins where two plates grind past each other without the production or destruction of lithosphere, as shown in Figure 7C. The San Andreas Fault zone in California is an example of a transform fault boundary.

Each plate contains a combination of these three types of boundaries. Although the total surface area of Earth does not change, plates may shrink or grow in area. This shrinking or growing depends on the locations of convergent and divergent boundaries. The Antarctic plate is growing larger. The Philippine plate is descending into the mantle along its margins and is becoming smaller. New plate boundaries can be created because of changes in the forces acting on these rigid slabs.

Figure 7 Three Types of Plate Boundaries



A Divergent boundary

B Convergent boundary

C Transform fault boundary

Section 9.2 Assessment

Reviewing Concepts

1. Define the term *lithospheric plate.*
2. List the three types of plate boundaries.
3. What theory proposes that Earth's outer shell consist of a number of rigid slabs?

Critical Thinking

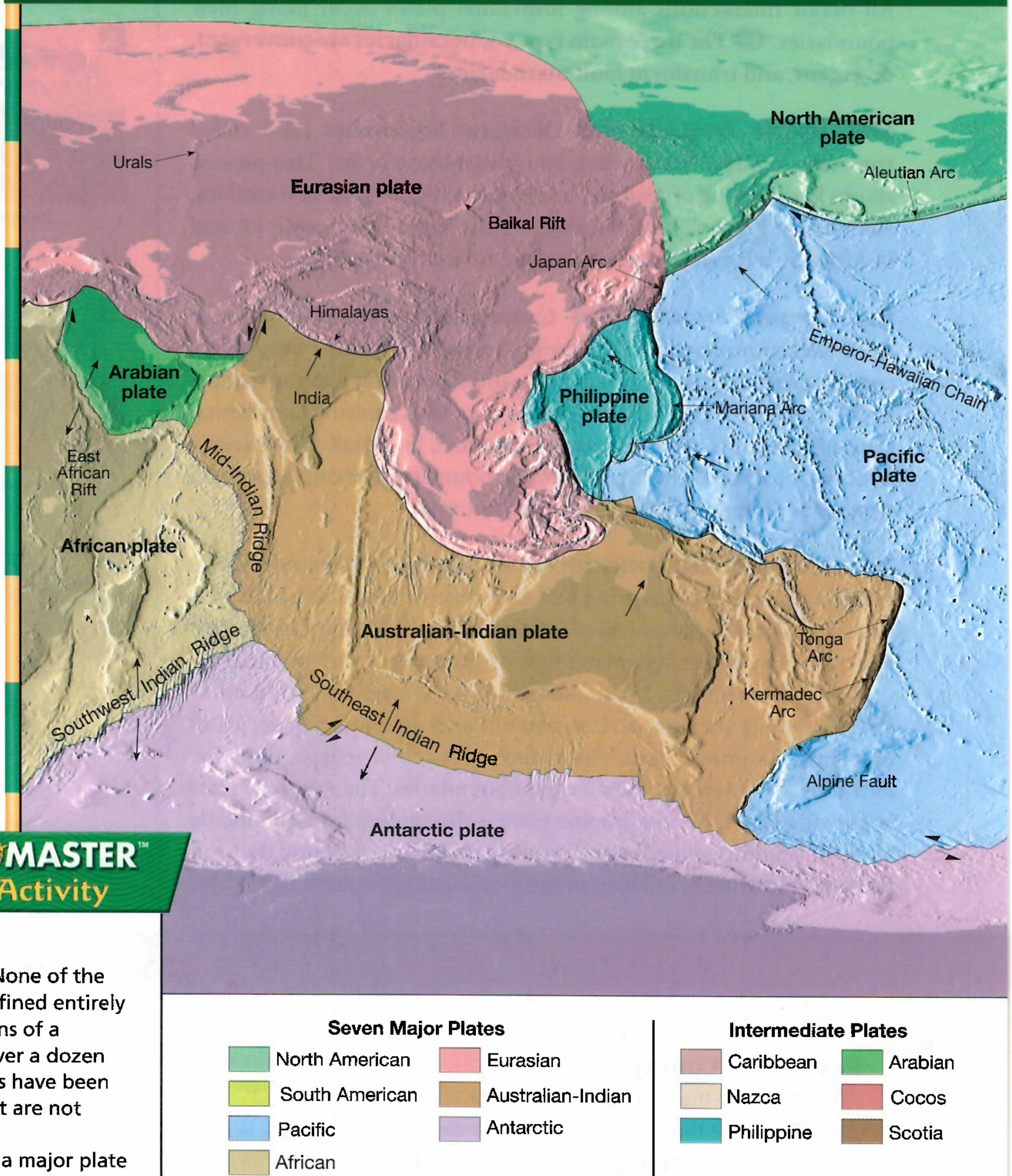
4. **Comparing and Contrasting** Compare the plate motions in the three types of boundaries.
5. **Drawing Conclusions** What is the major difference in the role of the ocean floor between the continental drift hypothesis and the theory of plate tectonics?

Connecting Concepts

Plate Boundaries Use what you have learned about plate tectonics to compare Wegener's continental drift hypothesis to the theory of plate tectonics.

Sh

Earth's Tectonic Plates



MAP MASTER™ Skills Activity

Figure 8

Location None of the plates are defined entirely by the margins of a continent. Over a dozen smaller plates have been identified but are not shown.

Locate Find a major plate that includes an entire continent plus a large area of seafloor. Name two other examples of a divergent boundary, a convergent boundary, and a transform fault boundary.


North American plate
Canadian Shield
Iceland
Eurasian plate
Alps
Rocky Mountains
Basin and Range
Appalachian Mts.
Juan de Fuca plate
San Andreas Fault
Caribbean plate
African plate
Mid-Atlantic Ridge
Cocos plate
Antilles Arc
Pacific plate
Galapagos Ridge
South American plate
Andes Mountains
East Pacific Rise
Nazca plate
Chile Ridge
Scotia plate
Antarctic plate

9.3 Actions at Plate Boundaries

Reading Focus

Key Concepts

- What is seafloor spreading?
- What is a subduction zone?

Vocabulary

- oceanic ridge
- rift valley
- seafloor spreading
- subduction zone
- trench
- continental volcanic arc
- volcanic island arc

Reading Strategy

Outlining Before you read, make an outline of this section. Use the green headings as the main topics and the blue headings as subtopics. As you read, add supporting details.

Actions at Boundaries
I. Divergent Boundaries
A. ____?____
B. ____?____
II. ____?____

Tremendous forces are at work where tectonic plates meet. Let's take a closer look at what happens at the three types of plate boundaries.

Divergent Boundaries

Most divergent plate boundaries are located along the crests of oceanic ridges. These plate boundaries can be thought of as *constructive plate margins* because this is where new oceanic lithosphere is generated. Look again at the divergent boundary in Figure 7A on page 255. As the plates move away from the ridge axis, fractures are created. These fractures are filled with molten rock that wells up from the hot mantle below. Gradually, this magma cools to produce new slivers of seafloor. Spreading and upwelling of magma continuously adds oceanic lithosphere between the diverging plates.

Oceanic Ridges and Seafloor Spreading Along well-developed divergent plate boundaries, the seafloor is elevated, forming the **oceanic ridge**. The system of ocean ridges is the longest physical feature on Earth's surface, stretching more than 70,000 kilometers in length. This system winds through all major ocean basins like the seam on a baseball. The term *ridge* may be misleading. These features are not narrow like a typical ridge. They are 1000 to 4000 kilometers wide. Deep faulted structures called **rift valleys** are found along the axes of some segments. As you can see in Figure 9, rift valleys and spreading centers can develop on land, too.

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Spreading Center

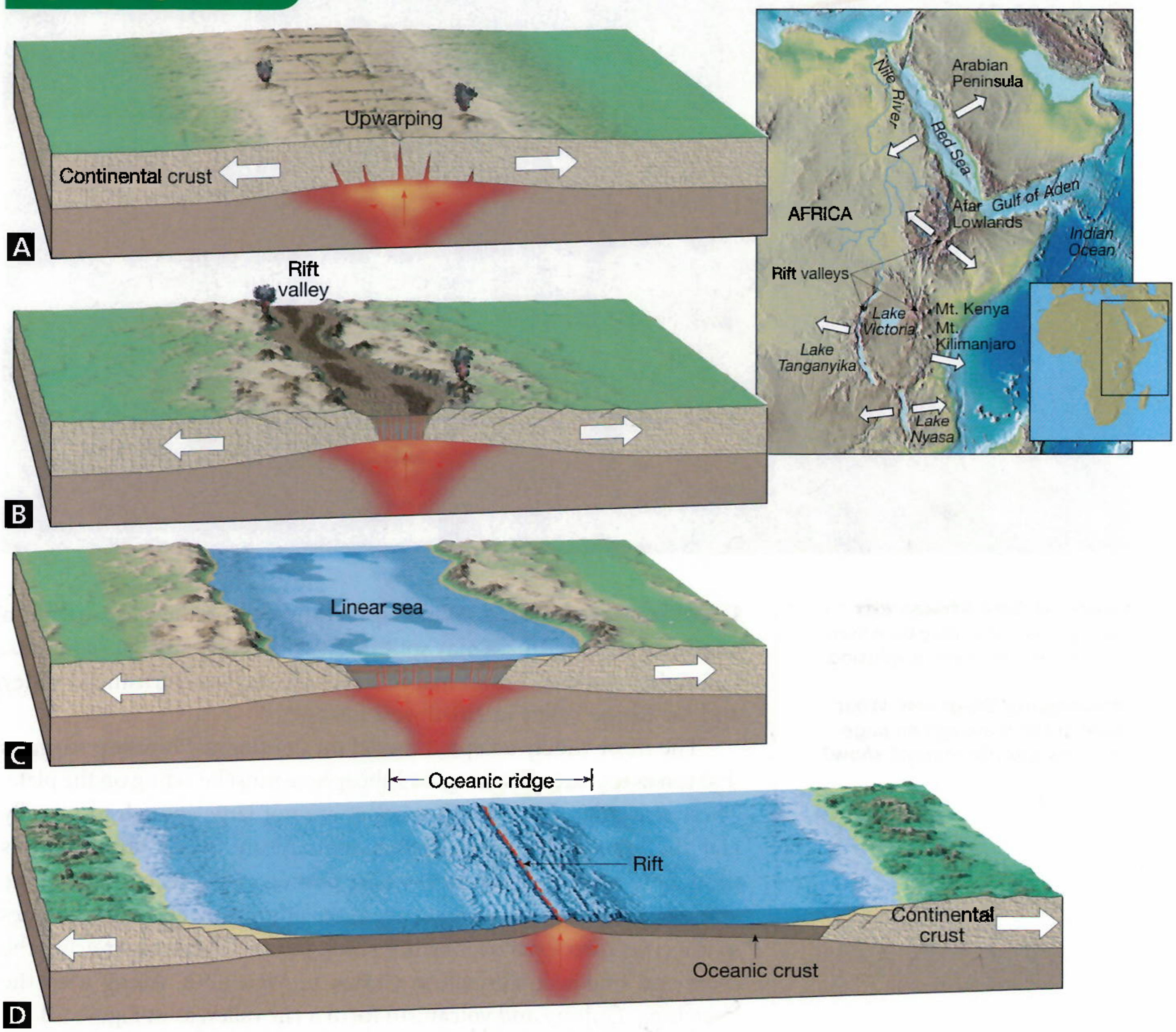


Figure 9 The East African rift valleys may represent the initial stages of the breakup of a continent along a spreading center. **A** Rising magma forces the crust upward, causing numerous cracks in the rigid lithosphere. **B** As the crust is pulled apart, large slabs of rock sink, causing a rift zone. **C** Further spreading causes a narrow sea. **D** Eventually, an ocean basin and ridge system is created.
Relating Cause and Effect ***What causes the continental crust to stretch and break?***

Seafloor spreading is the process by which plate tectonics produces new oceanic lithosphere. Typical rates of spreading average around 5 centimeters per year. These rates are slow on a human time scale. However, they are rapid enough so that all of Earth's ocean basins could have been generated within the last 200 million years. In fact, none of the ocean floor that has been dated is older than 180 million years.

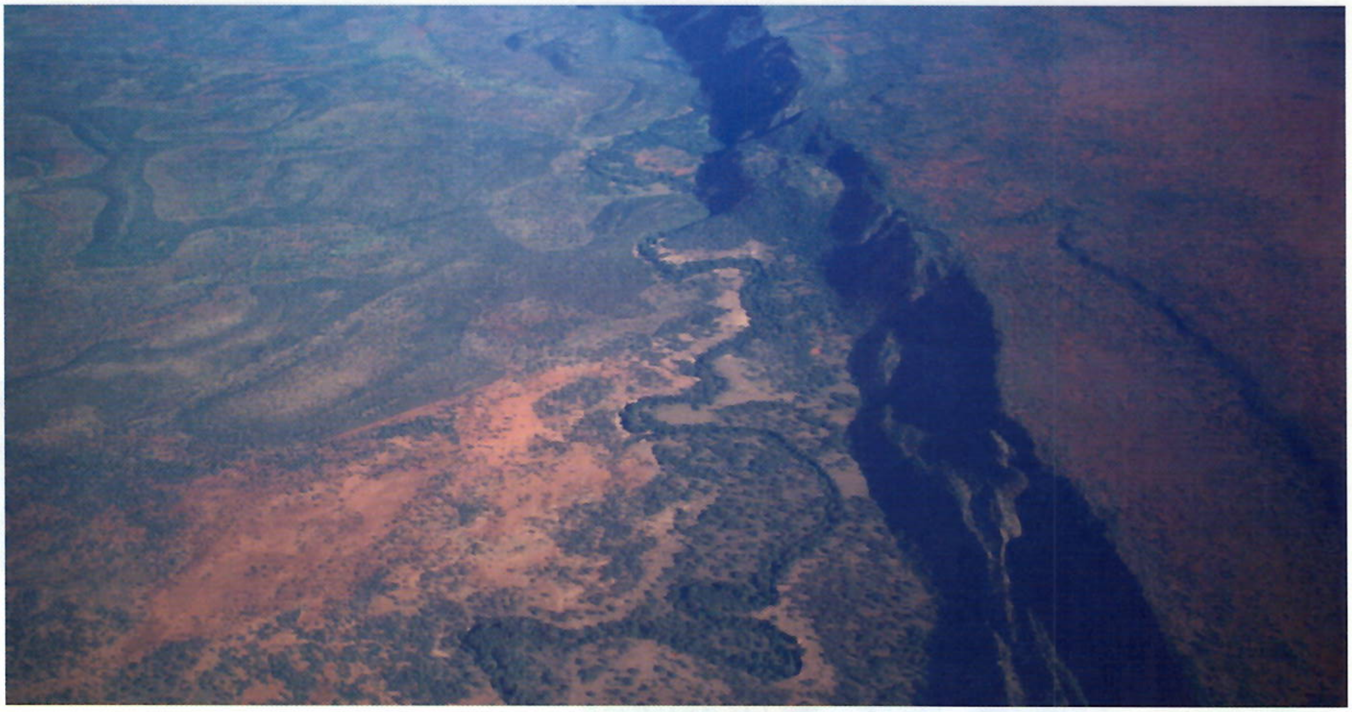


Figure 10 East African Rift Valley This valley may be where the African continent is splitting apart.
Interpreting Diagrams ***What stage in the drawings on page 259 does this photograph show?***

Continental Rifts When spreading centers develop within a continent, the landmass may split into two or more smaller segments. Examples of active continental rifts include the East African rift valley and the Rhine Valley in Northwest Europe.

The most widely accepted model for continental breakup suggests that forces that are stretching the lithosphere must be acting on the plate. These stretching forces by themselves are not large enough to actually tear the lithosphere apart. Rather, the rupture of the lithosphere is thought to begin in those areas where plumes of hot rock rise from the mantle. This hot-spot activity weakens the lithosphere and creates domes in the crust directly above the hot rising plume. Uplifting stretches the crust and makes it thinner, as shown in Figure 9A. Along with the stretching, faulting and volcanism form a rift valley, as in Figure 9B

The East African rift valley, shown in Figure 10, may represent the beginning stage in the breakup of a continent. Large mountains, such as Kilimanjaro and Mount Kenya, show the kind of volcanic activity that accompanies continental rifting. If the stretching forces continue, the rift valley will lengthen and deepen, until the continent splits in two. At this point, the rift becomes a narrow sea with an outlet to the ocean, similar to the Red Sea. The Red Sea formed when the Arabian Peninsula rifted from Africa about 20 million years ago. In this way, the Red Sea provides scientists with a view of how the Atlantic Ocean may have looked in its infancy.

Reading Checkpoint *How do rifts begin to form?*

Convergent Boundaries

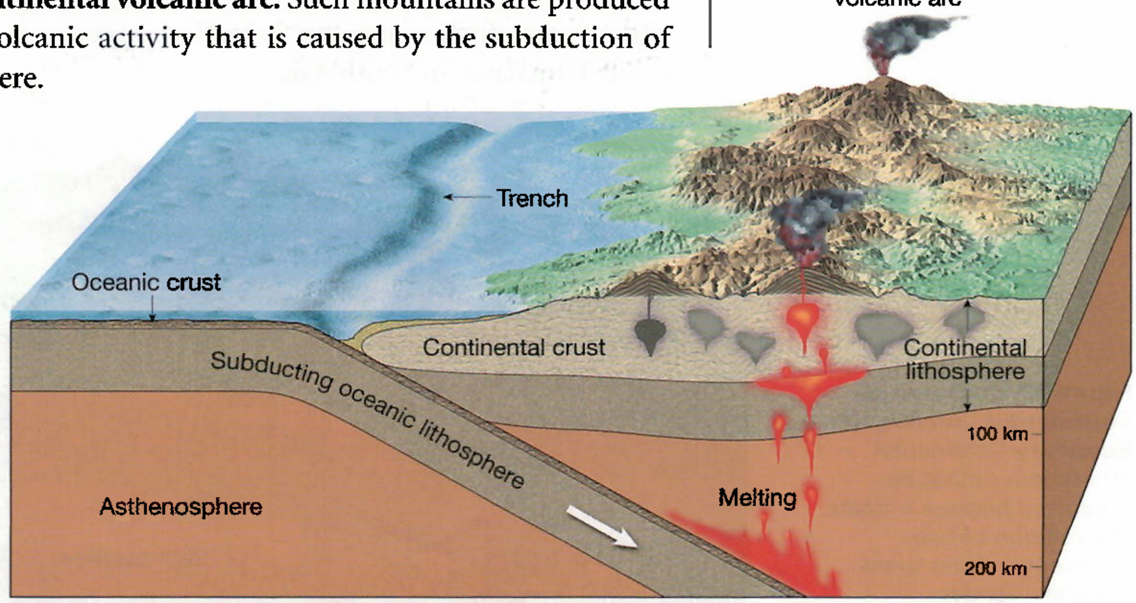
Although new lithosphere is constantly being added at the oceanic ridges, our planet is not growing larger. Earth's total surface area remains the same. How can that be? To accommodate the newly created lithosphere, older portions of oceanic plates return to the mantle along convergent plate boundaries. Because lithosphere is "destroyed" at convergent boundaries, they are also called *destructive plate margins.* As two plates slowly converge, the leading edge of one is bent downward, allowing it to slide beneath the other. Destructive plate margins where oceanic crust is being pushed down into the mantle are called **subduction zones.** The surface feature produced by the descending plate is an ocean **trench,** as shown in Figure 11. **A subduction zone occurs when one oceanic plate is forced down into the mantle beneath a second plate.**

Convergent boundaries are controlled by the type of crust involved and the forces acting on the plate. Convergent boundaries can form between two oceanic plates, between one oceanic plate and one continental plate, or between two continental plates.

Oceanic-Continental When the leading edge of a continental plate converges with an oceanic plate, the less dense continental plate remains floating. The denser oceanic slab sinks into the asthenosphere. When a descending plate reaches a depth of about 100 to 150 kilometers, some of the asthenosphere above the descending plate melts. The newly formed magma, being less dense than the rocks of the mantle, rises. Eventually, some of this magma may reach the surface and cause volcanic eruptions.

The volcanoes of the Andes, located along western South America, are the product of magma generated as the Nazca plate descends beneath the continent. Figure 11 shows this process. The Andes are an example of a **continental volcanic arc.** Such mountains are produced in part by the volcanic activity that is caused by the subduction of oceanic lithosphere.

Figure 11 Oceanic-Continental Convergent Boundary Oceanic lithosphere is subducted beneath a continental plate.
Inferring ***Why doesn't volcanic activity occur closer to the trench?***



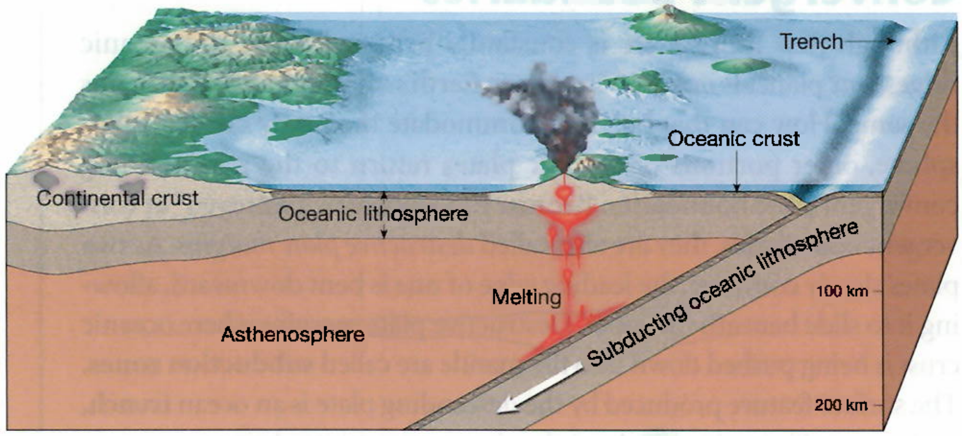


Figure 12 Oceanic-Oceanic Convergent Boundary One oceanic plate is subducted beneath another oceanic plate, forming a volcanic island arc. **Predicting** ***What would happen to the volcanic activity if the subduction stopped?***

Oceanic-Oceanic When two oceanic slabs converge, one descends beneath the other. This causes volcanic activity similar to what occurs at an oceanic-continental boundary. However, the volcanoes form on the ocean floor instead of on a continent, as shown in Figure 12. If this activity continues, it will eventually build a chain of volcanic structures that become islands. This newly formed land consisting of an arc-shaped chain of small volcanic islands is called a **volcanic island arc.** The Aleutian Islands off the shore of Alaska are an example of a volcanic island arc. Next to the Aleutians is the Aleutian trench.

Continental-Continental When an oceanic plate is subducted beneath continental lithosphere, a continental volcanic arc develops along the margin of the continent. However, if the subducting plate also contains continental lithosphere, the subduction eventually brings the two continents together, as shown in Figure 13. Continental lithosphere is buoyant, which prevents it from being subducted to any great depth. The result is a collision between the two continents, which causes the formation of complex mountains such as the Himalayas in South Asia.

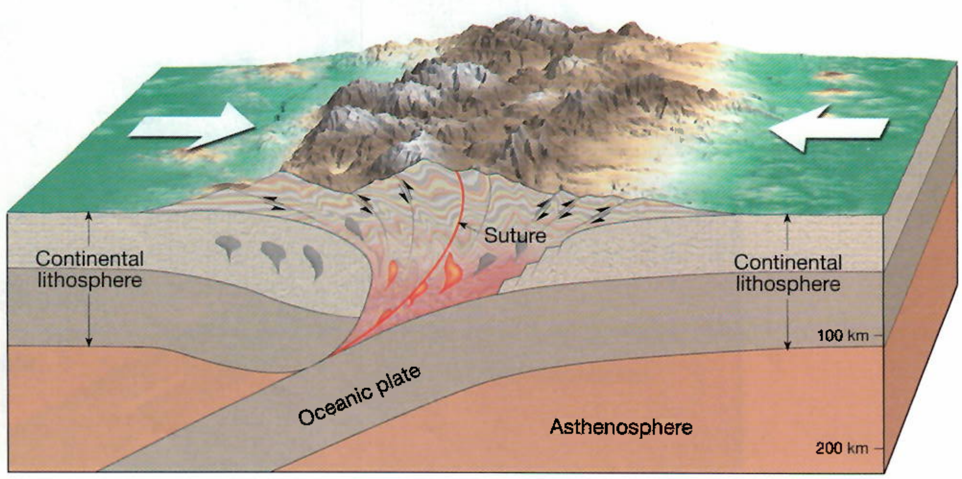


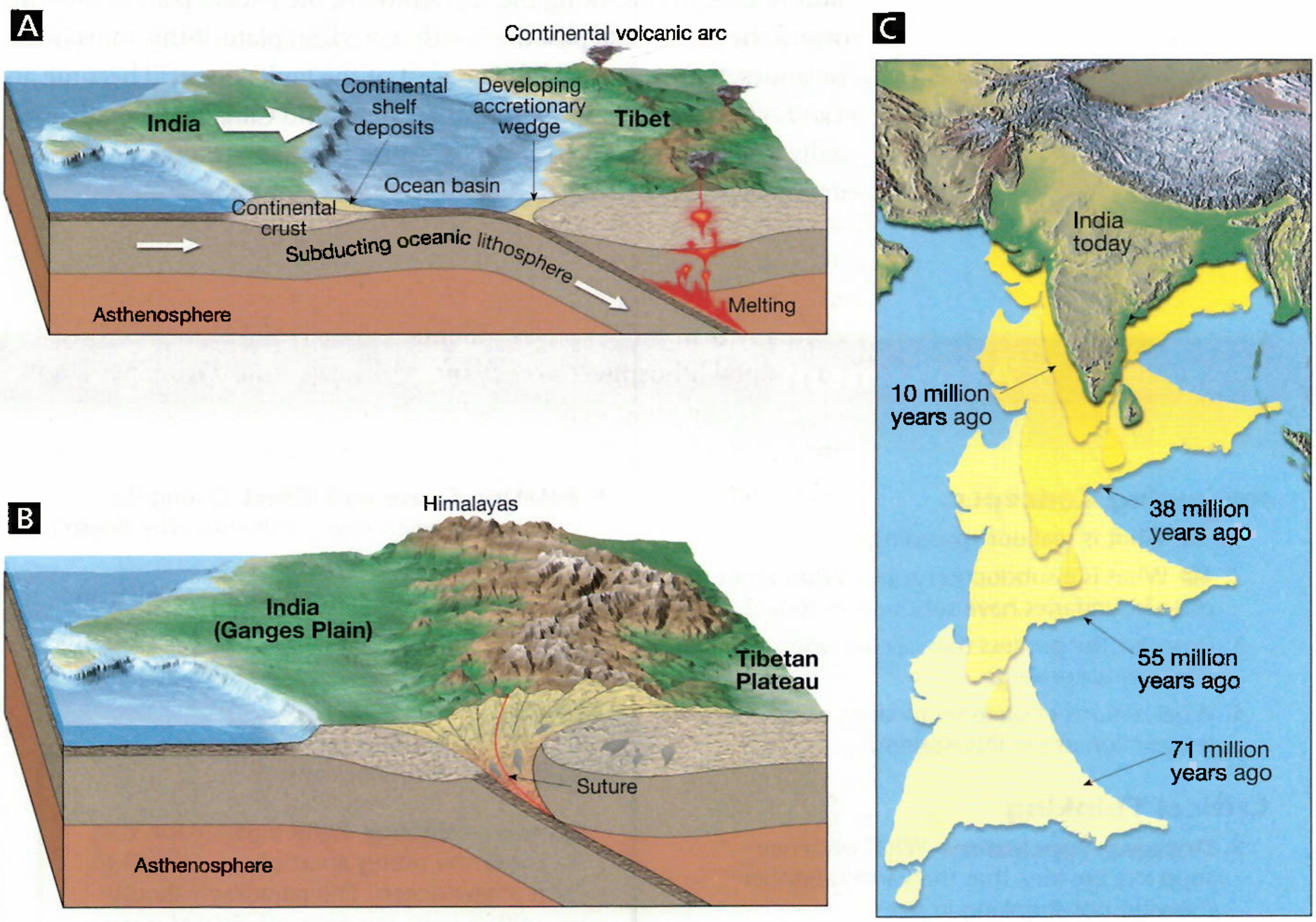
Figure 13 Continental-Continental Convergent Boundary Continental lithosphere cannot be subducted because it floats. The collision of two continental plates forms mountain ranges.

Before continents collide, the landmasses involved are separated by an ocean basin. As the continents move toward each other, the seafloor between them is subducted beneath one of the plates. When the continents collide, the collision folds and deforms the sediments along the margin as if they were placed in a giant vise. A new mountain range forms that is composed of deformed and metamorphosed sedimentary rocks, fragments of the volcanic arc, and possibly slivers of oceanic crust.

This kind of collision occurred when the subcontinent of India rammed into Asia and produced the Himalayas, as shown in Figure 14. During this collision, the continental crust buckled and fractured. Several other major mountain systems, including the Alps, Appalachians, and Urals, were also formed as a result of continental collisions.

Figure 14 A The leading edge of the plate carrying India is subducted beneath the Eurasian plate. **B** The landmasses collide and push up the crust. **C** India's collision with Asia continues today.

Collision of India and Asia



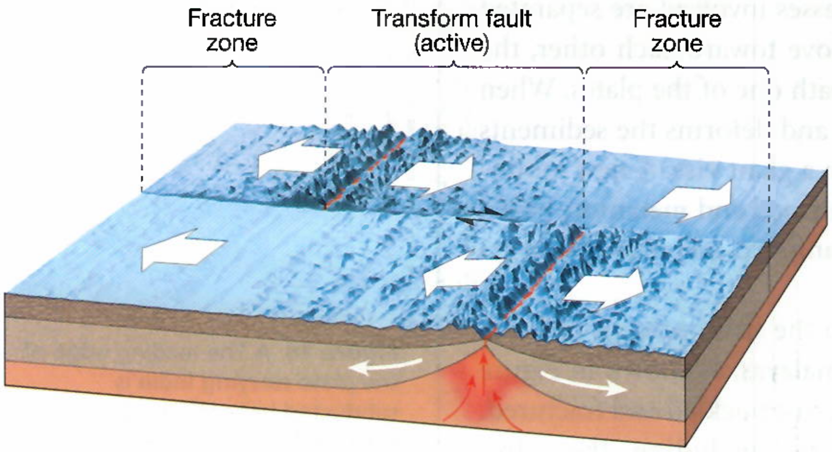


Figure 15 A transform fault boundary offsets segments of a divergent boundary at an oceanic ridge.

Transform Fault Boundaries

The third type of plate boundary is the transform fault boundary. **At a transform fault boundary, plates grind past each other without destroying the lithosphere.** Most transform faults join two segments of a mid-ocean ridge, as shown in Figure 15. These faults are present about every 100 kilometers along the ridge axis. Active transform faults lie between the two offset ridge segments. The seafloor produced at one ridge axis moves in the opposite direction as seafloor is produced at an opposing ridge segment. So between the ridge segments these slabs of oceanic crust are grinding past each other along a transform fault.

Although most transform faults are located within the ocean basins, a few cut through the continental crust. One example is the San Andreas Fault of California. Along the San Andreas, the Pacific plate is moving toward the northwest, past the North American plate. If this movement continues, that part of California west of the fault zone will become an island off the west coast of the United States and Canada. It could eventually reach Alaska. However, a more immediate concern is the earthquake activity triggered by movements along this fault system.

Section 9.3 Assessment

Reviewing Concepts

1. What is seafloor spreading?
2. What is a subduction zone? What types of plate boundaries have subduction zones?
3. Describe the process that occurs when continents converge.
4. What actions of plate boundaries cause the destruction of the lithosphere?

Critical Thinking

5. **Drawing Conclusions** What evidence supports the idea that the Earth is neither growing nor shrinking in size?
6. **Relating Cause and Effect** During the collision between two continents, why doesn't a subduction zone form?
7. **Predicting** How will the angle at which an oceanic plate is subducted affect the distance from the volcanic arc to the trench?

Writing in Science

Creative Writing Write a paragraph that describes the rifting apart of a continent to form a new ocean. The paragraph should be written from the point of view of a person witnessing the events.

9.4 Testing Plate Tectonics

Reading Focus

Key Concepts

- What evidence supports the theory of plate tectonics?
- How does paleomagnetism support the theory of plate tectonics?

Vocabulary

- paleomagnetism
- normal polarity
- reverse polarity
- hot spot

Reading Strategy

Predicting Copy the table. Write a prediction of where earthquakes will occur. After you read, if your prediction was incorrect or incomplete, write where earthquakes actually occur.

Probable Locations	Actual Locations
a. ?	b. ?

Evidence for Plate Tectonics

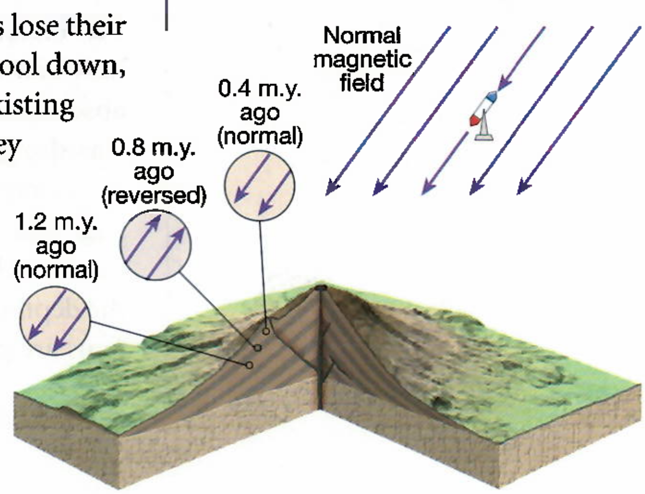
With the birth of the plate tectonics model, researchers from all of the Earth sciences began testing it. You have already seen some of the evidence supporting continental drift and seafloor spreading. Additional evidence for plate tectonics came as new technologies developed.

Paleomagnetism If you have ever used a compass to find direction, you know that the magnetic field has a north pole and a south pole. These magnetic poles align closely, but not exactly, with the geographic poles.

In many ways, Earth's magnetic field is much like that produced by a simple bar magnet. Invisible lines of force pass through Earth and extend from one pole to the other. A compass needle is a small magnet that is free to move about. The needle aligns with these invisible lines of force and points toward the magnetic poles.

Certain rocks contain iron-rich minerals, such as magnetite. When heated above a certain temperature, these magnetic minerals lose their magnetism. However, when these iron-rich mineral grains cool down, they become magnetized in the direction parallel to the existing magnetic field. Once the minerals solidify, the magnetism they possess stays frozen in this position. So magnetized rocks behave much like a compass needle because they point toward the existing magnetic poles. If the rock is moved or if the magnetic pole changes position, the rock's magnetism retains its original alignment. Rocks formed millions of years ago thus show the location of the magnetic poles at the time of their formation, as shown in Figure 16. These rocks possess **paleomagnetism.**

Figure 16 Paleomagnetism Preserved in Lava Flows As the lava cools, it becomes magnetized parallel to the magnetic field present at that time. When the polarity randomly reverses, a record of the paleomagnetism is preserved in the sequence of lava flows.



Polarity of Ocean Crust

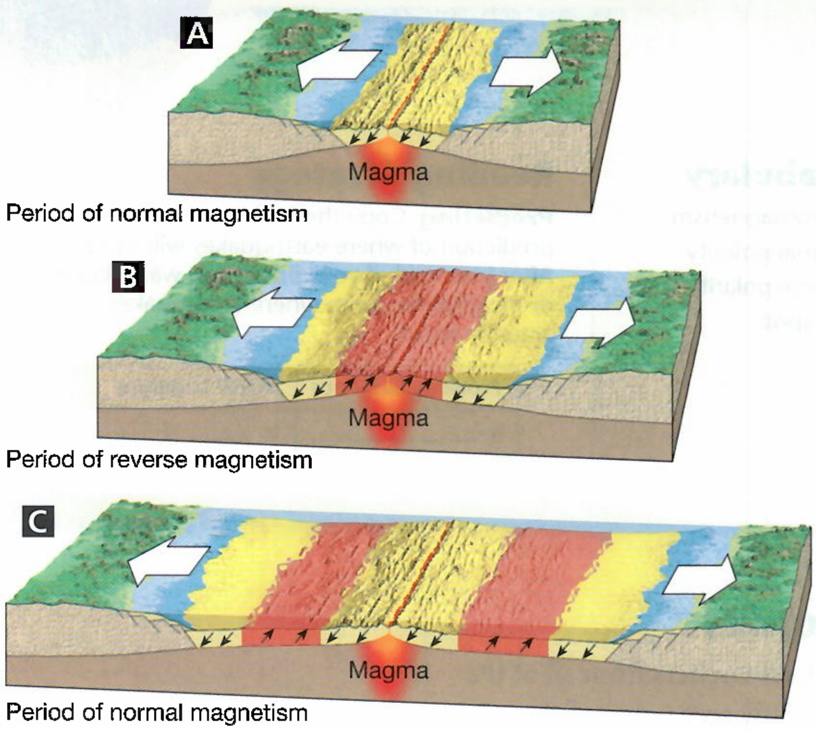


Figure 17 **A** As new material is added to the ocean floor at the oceanic ridges, it is magnetized according to Earth's existing magnetic field. **B** This process records each reversal of Earth's magnetic field. **C** Because new rock is added in approximately equal amounts to the trailing edges of both plates, strips of equal size and polarity parallel both sides of the ocean ridges. **Applying Concepts** ***Why are the magnetized strips about equal width on either side of the ridge?***

Geophysicists learned that Earth's magnetic field periodically reverses polarity. The north magnetic pole becomes the south magnetic pole, and vice versa. A rock solidifying during one of the periods of reverse polarity will be magnetized with the polarity opposite that of rocks being formed today.

When rocks show the same magnetism as the present magnetic field, they are described as having **normal polarity.** Rocks that show the opposite magnetism are said to have **reverse polarity.** A relationship was discovered between the magnetic reversals and the seafloor-spreading hypothesis. Ships towed instruments called magnetometers across segments of the ocean floor. This research revealed alternating strips of high- and low-intensity magnetism that ran parallel to the ridges. The strips of high-intensity magnetism are regions where the paleomagnetism of the ocean crust is of the normal type. These positively magnetized rocks enhance the existing magnetic field. The low-intensity strips represent regions where the ocean crust is polarized in the reverse direction and, therefore, weaken the existing magnetic field. As new basalt is added to the ocean floor at the oceanic ridges, it becomes magnetized according to the existing magnetic field, as shown in Figure 17. **The discovery of strips of alternating polarity, which lie as mirror images across the ocean ridges, is among the strongest evidence of seafloor spreading.**

Earthquake Patterns **Scientists found a close link between deep-focus earthquakes and ocean trenches. Also, the absence of deep-focus earthquakes along the oceanic ridge system was shown to be consistent with the new theory.**

Compare the distribution of earthquakes shown in Chapter 8 on page 226 with the map of plate boundaries on pages 256–257. The close link between plate boundaries and earthquakes is obvious. When the depths of earthquake foci and their locations within the trench systems are plotted, a pattern emerges.

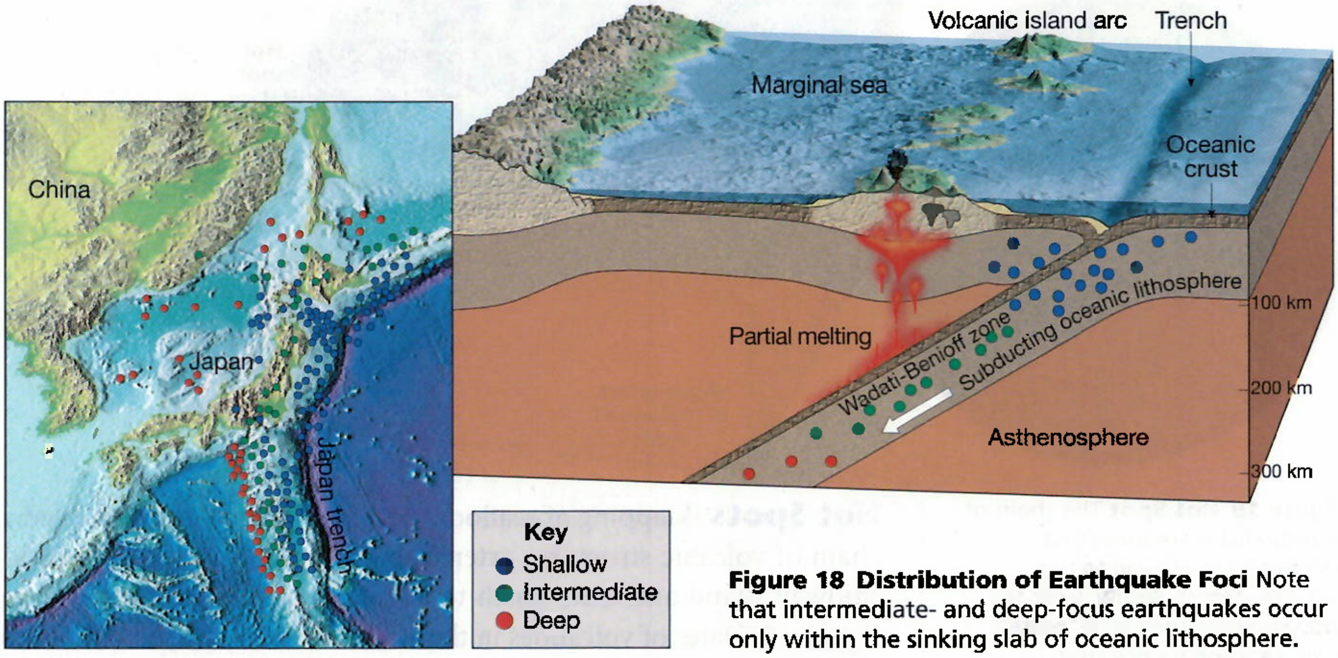


Figure 18 Distribution of Earthquake Foci Note that intermediate- and deep-focus earthquakes occur only within the sinking slab of oceanic lithosphere.

Look at Figure 18. It shows the distribution of earthquakes near the Japan trench. Here, most shallow-focus earthquakes occur within or adjacent to the trench. Intermediate- and deep-focus earthquakes occur toward the mainland.

In the plate tectonics model, deep-ocean trenches are produced where cool, dense slabs of oceanic lithosphere plunge into the mantle. Shallow-focus earthquakes are produced as the descending plate interacts with the lithosphere above it. As the slab descends farther into the mantle, deeper-focus earthquakes are produced. No earthquakes have been recorded below 700 kilometers. At this depth, the slab has been heated enough to soften.

Ocean Drilling Some of the most convincing evidence confirming the plate tectonics theory has come from drilling directly into ocean-floor sediment. The Deep Sea Drilling Project from 1968 to 1983 used the drilling ship *Glomar Challenger* to drill hundreds of meters into the sediments and underlying crust.

When the oldest sediment from each drill site was plotted against its distance from the ridge crest, it was revealed that the age of the sediment increased with increasing distance from the ridge. **The data on the ages of seafloor sediment confirmed what the seafloor-spreading hypothesis predicted. The youngest oceanic crust is at the ridge crest and the oldest oceanic crust is at the continental margins.**

The data also reinforced the idea that the ocean basins are geologically young. No sediment older than 180 million years was found. By comparison, some continental crust has been dated at 4.0 billion years.

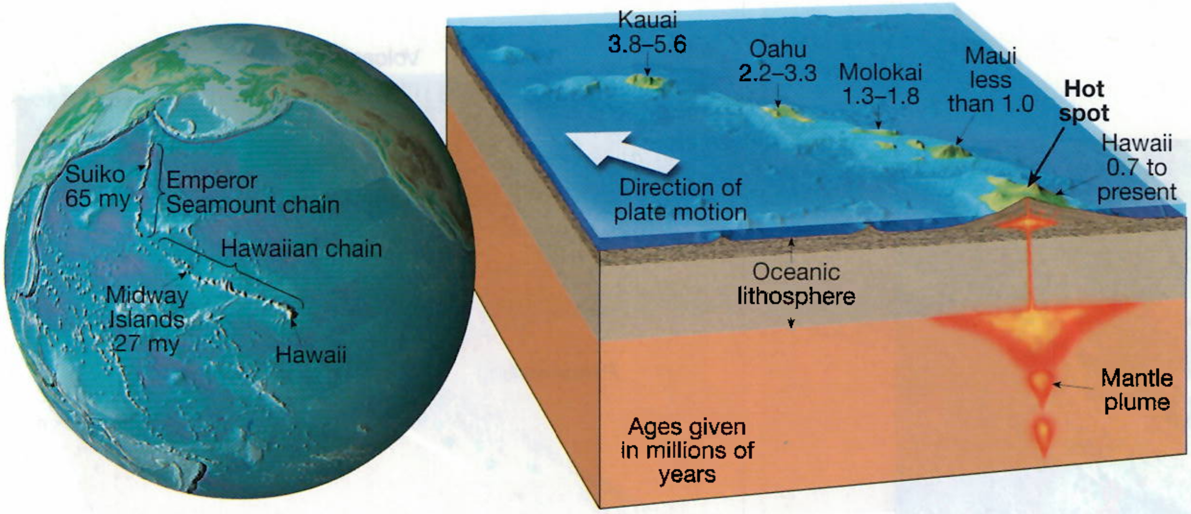


Figure 19 Hot Spot The chain of islands and seamounts that extends from Hawaii to the Aleutian trench results from the movement of the Pacific plate over a stationary hot spot. **Predicting** ***Where will a new Hawaiian island be located?***

Hot Spots Mapping of seafloor volcanoes in the Pacific revealed a chain of volcanic structures extending from the Hawaiian Islands to Midway Island and then north to the Aleutian trench, as shown in Figure 19. Dates of volcanoes in this chain showed that the volcanoes increase in age with increasing distance from Hawaii. Suiko Seamount is 65 million years old. Midway Island is 27 million years old. The island of Hawaii formed less than a million years ago and is still forming today.

A rising plume of mantle material is located below the island of Hawaii. Melting of this hot rock as it nears the surface creates a volcanic area, or **hot spot.** As the Pacific plate moves over the hot spot, successive volcanic mountains have been created. The age of each volcano indicates the time when it was situated over the hot spot. Kauai is the oldest of the large islands in the Hawaiian chain. Its volcanoes are extinct. The youthful island of Hawaii has two active volcanoes—Mauna Loa and Kilauea. **Hot spot evidence supports the idea that the plates move over Earth's surface.**

Section 9.4 Assessment

Reviewing Concepts

1. List and describe the evidence for the plate tectonics theory.
2. Define the term *paleomagnetism.*
3. What is the age of the oldest ocean crust? How do the ages of the ocean crust compare to the age of continental rocks?
4. What is a hot spot?

Critical Thinking

5. **Applying Concepts** How do hot spots and the plate tectonics theory account for the different ages of the Hawaiian Islands?
6. **Predicting** Would earthquakes occur at depths of over 700 kilometers? Why or why not?

Writing in Science

Explanatory Paragraph Write a paragraph explaining why the age pattern of the ocean floor supports seafloor spreading.

9.5 Mechanisms of Plate Motion

Reading Focus

Key Concepts

- What are the mechanisms of plate motion?
- What causes plate motion?

Vocabulary

- convective flow
- slab-pull
- ridge-push
- mantle plume

Reading Strategy

Identifying Main Ideas Copy the table. As you read, write the main ideas for each topic.

Topic	Main Idea
Slab-pull	a. ___?___
Ridge-push	b. ___?___
Mantle convection	c. ___?___

Causes of Plate Motion

Scientists generally agree that convection occurring in the mantle is the basic driving force for plate movement. During convection, warm, less dense material rises and cooler, denser material sinks. The motion of matter resulting from convection is called **convective flow.** The slow movements of the plates and mantle are driven by the unequal distribution of Earth's heat. The heat is generated by the radioactive decay of elements, such as uranium, found within Earth's mantle and crust.

Slab-Pull and Ridge-Push Several mechanisms produce forces that cause plate motion. One mechanism, called **slab-pull,** occurs because old oceanic crust, which is relatively cool and dense, sinks into the asthenosphere and "pulls" the trailing lithosphere along. **Slab-pull is thought to be the primary downward arm of convective flow in the mantle.** By contrast, **ridge-push** results from the elevated position of the oceanic ridge system. **Ridge-push causes oceanic lithosphere to slide down the sides of the oceanic ridge.** The downward slide is the result of gravity acting on the oceanic lithosphere. Ridge-push, although active in some spreading centers, is probably less important than slab-pull.

Mantle Convection Most models suggest that hot plumes of rock are the upward flowing arms in mantle convection. These rising **mantle plumes** sometimes show themselves on Earth's surface as hot spots and volcanoes.

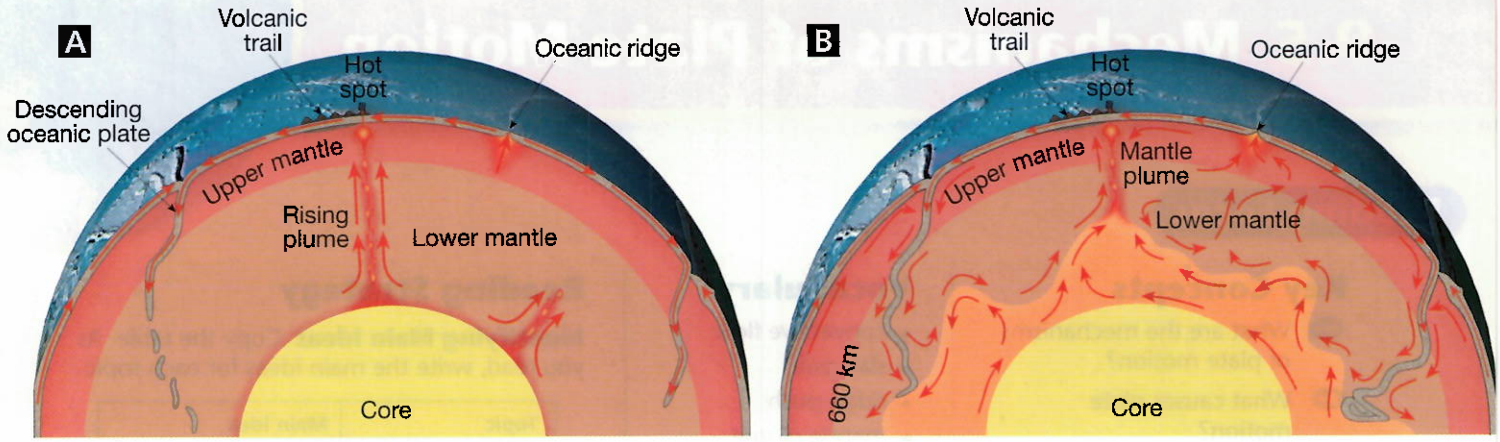


Figure 20 Mantle Convection Models A In the whole-mantle convection model, cold oceanic lithosphere descends into the mantle. Hot mantle plumes transport heat toward the surface. **B** The deep-layer model suggests that Earth's heat causes these layers of convection to slowly swell and shrink in complex patterns. Some material from the lower layer flows upward as mantle plumes.

One recent model is called whole-mantle convection. In this model, slabs of cold oceanic lithosphere descend into the lower mantle. This process provides the downward arm of convective flow, as shown in Figure 20A. At the same time, hot mantle plumes originating near the mantle-core boundary move heat toward the surface. Another model is the deep-layer model. You might compare this model to a lava lamp on a low setting. As shown in Figure 20B, the lower mantle is like the colored fluid in the bottom layer of a lava lamp. Like a lava lamp, heat from Earth's interior causes the two layers to slowly swell and shrink in complex patterns without much mixing. A small amount of material from the lower layer flows upward as mantle plumes, creating hot-spot volcanism at the surface.

There is still much to be learned about the mechanisms that cause plates to move. But one thing is clear. **The unequal distribution of heat within Earth causes the thermal convection in the mantle that ultimately drives plate motion.** Exactly how this convection operates is still being debated.

Section 9.5 Assessment

Reviewing Concepts

1. Describe the mechanisms of plate motion.
2. What drives the slow movement of the plates and the convection in the mantle?
3. What is the main source of heat in Earth's interior?

Critical Thinking

4. **Relating Cause and Effect** How is the theory of plate tectonics related to the radioactive decay of elements within Earth's interior?
5. **Calculating** If Africa and Australia are moving apart at a rate of 4.4 centimeters per year, approximately how long will it take for the ocean between the two continents to increase by 1000 kilometers?

Connecting Concepts

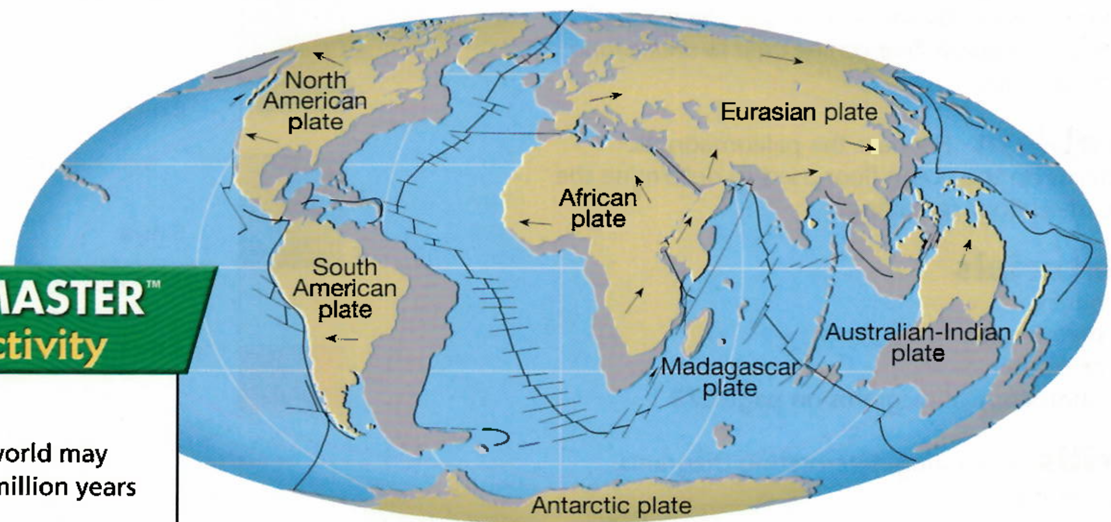
Heat Flow Review Section 9.1. How would the flow of heat generated by radioactive decay benefit the theory of continental drift?

understanding EARTH

Plate Tectonics into the Future

Two geologists, Robert Dietz and John Holden, used present-day plate movements to predict the locations of landmasses in the future. The map below shows where they predict Earth's landmasses will be 50 million years from now if plate movements remain at their present rates.

Future Continent Positions



MAP MASTER™ Skills Activity

Figure 21

Location The world may look like this 50 million years from now.

Identify Effects What could happen to Los Angeles and San Francisco if this proposed movement occurs?

L.A. on the Move

In North America, the Baja Peninsula and the portion of southern California that lies west of the San Andreas Fault will have slid past the North American plate. If this northward motion takes place, Los Angeles and San Francisco will pass each other in about 10 million years. In about 60 million years Los Angeles will begin to descend into the Aleutian trench.

New Sea in Africa

Major changes are seen in Africa, where a new sea emerges as East Africa is ripped away from the mainland. In addition, Africa will have moved slowly into Europe, perhaps creating the next major mountain-building stage on Earth. Meanwhile, the Arabian Peninsula continues to move away from Africa, allowing the Red Sea to widen and close the Persian Gulf.

Atlantic Ocean Grows

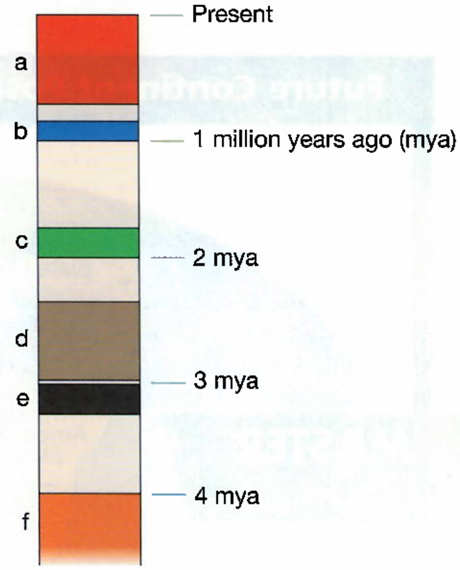
In other parts of the world, Australia will be located across the equator and, along with New Guinea, will be on a collision course with Asia. Meanwhile, North and South America will begin to separate, while the Atlantic and Indian oceans will continue to grow as the Pacific Ocean shrinks.

These projections into the future, although interesting, must be viewed with caution because many assumptions must be correct for these events to occur. We can be sure that large changes in the shapes and positions of continents will occur for millions of years to come.

Exploration Lab

Paleomagnetism and the Ocean Floor

In the continental drift hypothesis, the ocean floors were not really involved. The continents were proposed to move through the oceans like icebreaking ships plowing through ice. Later studies of the oceans provided one of the keys to the plate tectonic theory. You will observe how the magnetic rocks on the ocean floor can be used to understand plate tectonics.



Problem

How are the paleomagnetic patterns on the ocean floor used to determine the rate of seafloor spreading?

Materials

- pencil
- metric ruler
- calculator
- photocopy of diagrams on page 273

Skills

Measuring, Interpreting Diagrams, Calculating

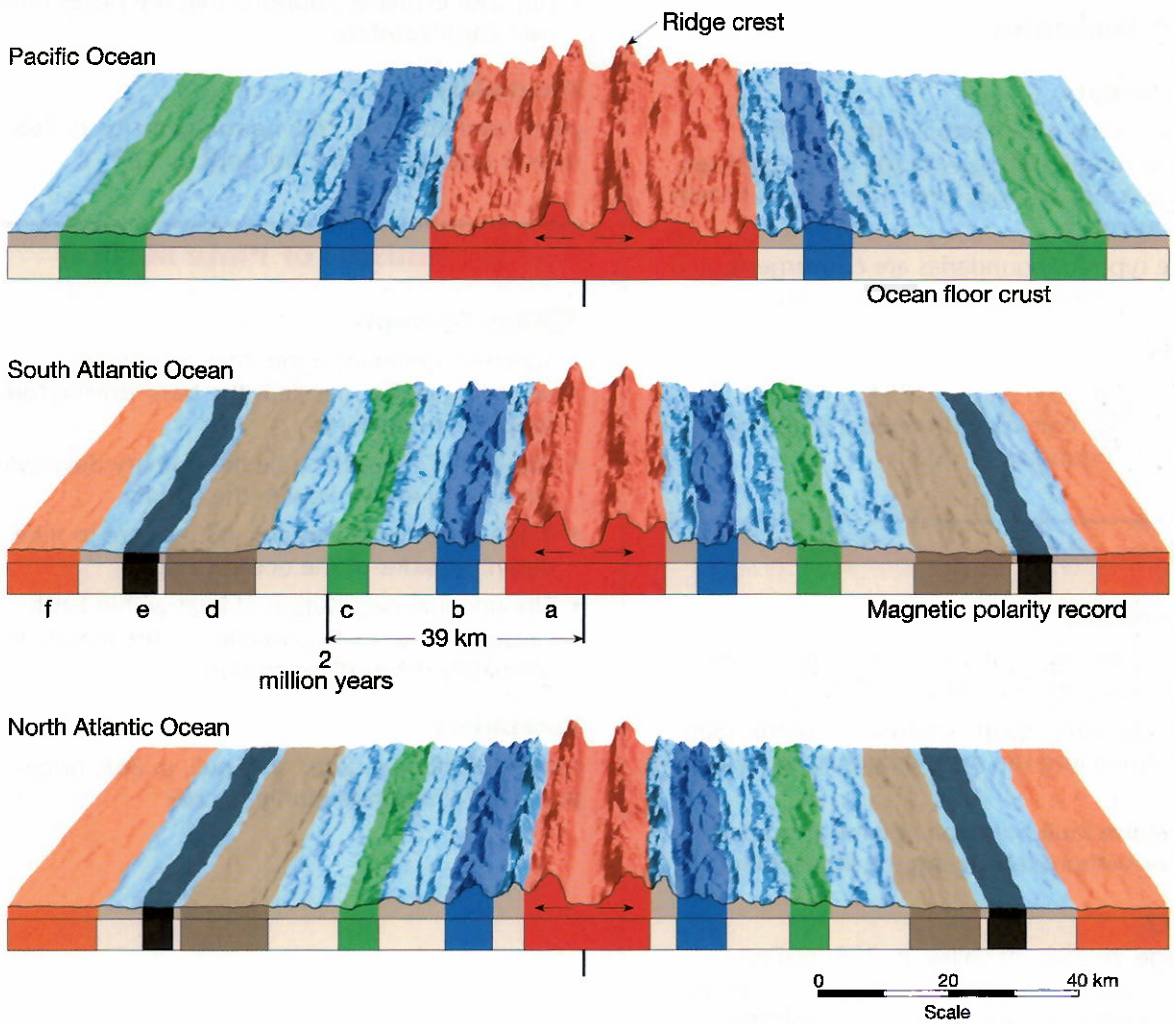
Procedure

1. Scientists have reconstructed Earth's magnetic polarity reversals over the past several million years. A record of these reversals is shown above. Periods of normal polarity, when a compass would have pointed north as it does today, are shown in color. Periods of reverse polarity are shown in white. Record the number of times Earth's magnetic field has had reversed polarity in the last 4 million years.
2. The three diagrams on the next page illustrate the magnetic polarity reversals across sections of the mid-ocean ridges in the Pacific, South Atlantic, and North Atlantic oceans. Periods of normal polarity are shown in color and match the colors in the illustration above. Observe that the patterns of polarity in the rock match on either side of the ridge for each ocean basin.
3. On the photocopy of the three ocean-floor diagrams, identify and mark the periods of normal polarity with the letters *a–f*. Begin at the ridge crest and label along both sides of each ridge. (*Hint:* The left side of the South Atlantic has already been done and can act as a guide.)
4. Using the South Atlantic as an example, label the beginning of the normal polarity period c, "2 million years ago," on the left sides of the Pacific and North Atlantic diagrams.
5. Using the distance scale shown with the ocean floor diagrams, determine which ocean basin has spread the greatest distance during the last 2 million years.
6. Refer to the distance scale. Notice that the left side of the South Atlantic basin has spread approximately 39 kilometers from the center of the ridge crest in 2 million years.

Analyze and Conclude

1. **Analyzing Data** How many kilometers has the left side of the Pacific basin spread in 2 million years?
2. **Analyzing Data** How many kilometers has the left side of the North Atlantic basin spread in 2 million years?
3. **Inferring** How many kilometers has each ocean basin opened in the past 2 million years?
4. **Calculating** If both the distance that each ocean basin has opened and the time it took to open that distance are known, the rate of seafloor spreading can be calculated. Determine the rate of seafloor spreading for the South Atlantic Ocean basin in centimeters per year. (*Hint:* To determine the rate of spreading in centimeters per year for each ocean basin, first convert the distance from kilometers to centimeters and then divide this distance by the time, 2 million years.)
5. **Calculating** Determine the rate of seafloor spreading for the North Atlantic and Pacific Ocean basins.
6. **Drawing Conclusions** Which ocean basin is spreading the fastest? The slowest?
7. **Inferring** Do ocean basins spread uniformly over the entire basin? Explain.

Go Further Use the library or the Internet to research the spreading rates for other divergent plate boundaries on Earth. Where is the fastest spreading rate? The slowest spreading rate?



CHAPTER 9

Study Guide

9.1 Continental Drift

Key Concepts

- Wegener's continental drift hypothesis stated that the continents had once been joined to form a single supercontinent.
- Fossil evidence for continental drift includes several fossil organisms found on different landmasses.
- Rock evidence for continental drift exists in the form of several mountain belts that end at one coastline, only to reappear on a landmass across the ocean.

Vocabulary

continental drift, *p. 248;* Pangaea, *p. 248*

9.2 Plate Tectonics

Key Concepts

- According to the plate tectonics theory, the uppermost mantle, along with the overlying crust, behaves as a strong, rigid layer. This layer is known as the lithosphere.
- The three types of boundaries are convergent, divergent, and transform fault boundaries.

Vocabulary

plate tectonics, *p. 254;* plate, *p. 254;* divergent boundary, *p. 255;* convergent boundary, *p. 255;* transform fault boundary, *p. 255*

9.3 Actions at Plate Boundaries

Key Concepts

- Seafloor spreading is the process by which plate tectonics produces new oceanic lithosphere.
- A subduction zone occurs when one oceanic plate is forced down into the mantle beneath a second plate.
- At a transform fault boundary, plates grind past each other without destroying the lithosphere.

Vocabulary

oceanic ridge, *p. 258;* rift valley, *p. 258;* seafloor spreading, *p. 259;* subduction zone, *p. 261;* trench, *p. 261;* continental volcanic arc, *p. 261;* volcanic island arc, *p. 262*

9.4 Testing Plate Tectonics

Key Concepts

- The discovery of strips of alternating polarity, which lie as mirror images across the ocean ridges, is among the strongest evidence of seafloor spreading.
- Scientists found a close link between deep-focus earthquakes and ocean trenches. Also, the absence of deep-focus earthquakes along the oceanic ridge system was shown to be consistent with the new theory.
- The data on the ages of seafloor sediment confirmed what the seafloor-spreading hypothesis predicted. The youngest oceanic crust is at the ridge crest and the oldest oceanic crust is at the continental margins.
- Hot spot evidence supports that the plates move over Earth's surface.

Vocabulary

paleomagnetism, *p. 265;* normal polarity, *p. 266;* reverse polarity, *p. 266;* hot spot, *p. 268*

9.5 Mechanisms of Plate Motion

Key Concepts

- Scientists generally agree that convection occurring in the mantle is the basic driving force for plate movement.
- Slab-pull is thought to be the primary downward arm of convective flow in the mantle.
- Ridge-push causes oceanic lithosphere to slide down the sides of the oceanic ridge.
- The unequal distribution of heat within Earth causes the thermal convection in the mantle that ultimately drives plate motion.

Vocabulary

convective flow, *p. 269;* slab-pull, *p. 269;* ridge-push, *p. 269;* mantle plume, *p. 269*

Assessment

Interactive textbook with assessment at PHSchool.com

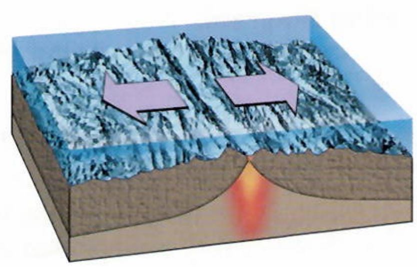
Reviewing Content

Choose the letter that best answers the question or completes the statement.

1. What is the weaker, hotter zone beneath the lithosphere that allows for motion of Earth's rigid outer shell?
   - a. crust
   - b. asthenosphere
   - c. outer core
   - d. inner core
2. Most of Earth's earthquakes, volcanoes, and mountain building occur
   - a. in the center of continents.
   - b. in the Himalayas.
   - c. at plate boundaries.
   - d. at volcanic island arcs.
3. Alfred Wegener is best known for what hypothesis?
   - a. plate tectonics
   - b. seafloor spreading
   - c. continental drift
   - d. subduction
4. Complex mountain systems such as the Himalayas are the result of
   - a. oceanic-oceanic convergence.
   - b. hot spots.
   - c. continental volcanic arcs.
   - d. continental-continental convergence.
5. The best approximation of the true outer boundary of the continents is the seaward edge of
   - a. continental shelf.
   - b. mid-ocean ridge.
   - c. present-day shorelines.
   - d. ocean trenches.
6. What is the name given by Wegener to the supercontinent he proposed existed before the current continents?
   - a. Euroamerica
   - b. Atlantis
   - c. Pangaea
   - d. Panamerica
7. Which of the following mountain ranges was NOT the result of continental-continental convergence?
   - a. Himalayas
   - b. Alps
   - c. Appalachians
   - d. Andes
8. What is the type of plate boundary where two plates move together, causing one of the slabs of lithosphere to descend into the mantle beneath an overriding plate?
   - a. oceanic-continental convergent
   - b. divergent
   - c. transform fault
   - d. continental-continental convergent
9. Most deep-focus earthquakes are linked to
   - a. hot spots.
   - b. ocean trenches.
   - c. ocean ridges.
   - d. transform fault boundaries.
10. One of the main objections to Wegener's hypothesis of continental drift was that he was unable to provide an acceptable
    - a. rate of continental drift.
    - b. date of continental drift.
    - c. mechanism of continental drift.
    - d. direction of continental drift.

Understanding Concepts

11. What are the three types of convergent plate boundaries?
12. Briefly explain the theory of plate tectonics.
13. How have earthquake patterns been used to support the theory of plate tectonics?
14. What type of plate boundary is shown? What types of lithosphere are involved?



15. At what location is most lithosphere created? At what location is most lithosphere destroyed?
16. What feature produces volcanoes that do not occur at plate boundaries?
17. At what types of boundaries do subduction zones form?

Assessment *continued*

Critical Thinking

18. **Drawing Conclusions** In the Atlantic Ocean basin, where would the oldest oceanic lithosphere be found?

19. **Summarizing** Describe the evidence that supported the hypothesis of continental drift.

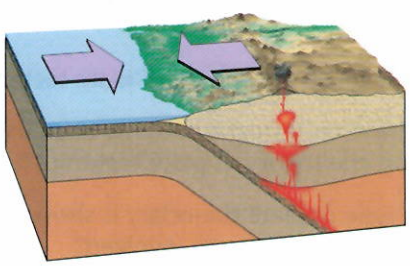
20. **Applying Concepts** Some people predict that California will sink into the ocean. Does this idea fit with the theory of plate tectonics? Explain.

21. **Inferring** Why did the discovery of *Mesosaurus*, in both South America and Africa but nowhere else, support the hypothesis of continental drift?

22. **Comparing and Contrasting** What is the difference between the collision of an oceanic plate with a continental plate and the collision of two continental plates?

Analyzing Data

Use the diagram below to answer Questions 23–25.



23. **Interpreting Diagrams** What type of boundary is shown? What types of lithosphere are involved?

24. **Inferring** What process is triggered as the slab descends beneath the other plate?

25. **Drawing Conclusions** How would the foci of earthquakes change if they were plotted in the diagram?

Concepts in Action

26. **Inferring** If the spreading rate at an ocean ridge increased, how would that affect the width of the paleomagnetic strips found on the ocean floor?

27. **Classifying** What type of plate boundary is formed when two plates grind past each other? Give an example of this type of boundary.

28. **Formulating Hypotheses** Form a hypothesis to explain what you think would happen if the direction of motion between India and Asia would change and India began to move in a southward direction.

29. **Calculating** How much wider would the Atlantic Ocean become in 10 million years if the spreading rate at the Mid-Atlantic Ridge was 2.5 cm/yr? Give your answer in kilometers.

30. **Connecting Concepts** What relationship exists between the ages of the Hawaiian Islands, hot spots, and plate tectonics?

31. **Writing in Science** Write a paragraph explaining why it is less likely that there will be a large earthquake in a location in the middle of North America, such as in Chicago, Illinois.

Performance-Based Assessment

Classifying Use a world map to choose ten different locations around the world. Then use Figure 8 on pages 256–257 to find the plate boundary nearest each location. Classify each boundary.

Standardized Test Prep

Test-Taking Tip

Eliminating Unreasonable Answers

When you answer a multiple-choice question, you can often eliminate at least one answer choice because it is clearly incorrect. If you eliminate one or more choices, you increase your odds of choosing the correct answer.

In the question below, you can immediately eliminate choice B because the outer core is located deep in Earth's interior. The mantle, answer choice A, is another layer that is found in Earth's interior. So you can eliminate A. You have narrowed your choices down to either C, the lithosphere, or D, the asthenosphere. The asthenosphere is not rigid. It is a weak layer over which the plates move. The remaining choice, C, must be the correct answer.

What is Earth's strong, rigid outer layer called?

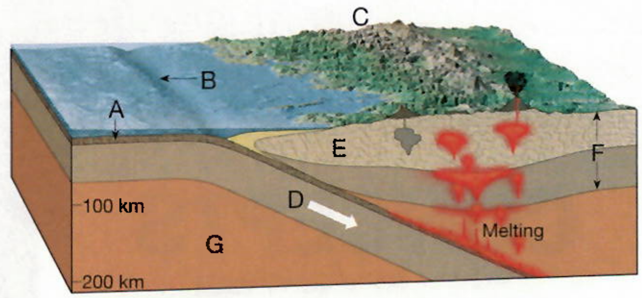
(A) the mantle
(B) the outer core
(C) the lithosphere
(D) the asthenosphere

Choose the letter that best answers the question or completes the statement.

1. Which one of the following was NOT used as support of Wegener's continental drift hypothesis?
   (A) fossil evidence
   (B) paleomagnetism
   (C) the fit of South America and Africa
   (D) ancient climates

2. At what type of plate boundary do plates move apart, resulting in the upwelling of material from the mantle to create new seafloor?
   (A) divergent
   (B) convergent
   (C) transform fault
   (D) subduction

Use the diagram below to answer Questions 3 and 4.



3. What feature is labeled F?
   (A) a continental volcanic arc
   (B) a subduction zone
   (C) continental lithosphere
   (D) an ocean ridge

4. The process occurring at the location labeled D is
   (A) oceanic lithosphere being created.
   (B) continental lithosphere being created.
   (C) a continental-continental collision occurring.
   (D) oceanic lithosphere being subducted.

Answer the following questions in complete sentences.

5. How does the age of the ocean lithosphere and deepest sediment in an ocean basin change with increasing distance from the oceanic ridge?

6. Why is Earth not getting larger even though new lithosphere is constantly being added at the oceanic ridges?

7. Describe two events that occur on Earth that you would not expect to find on Mars because of the lack of plate movements.

8. At some time in the distant future, Earth's interior will cool to the point that plate movement will stop. Describe how Earth would be different form that point onward.

CHAPTER 10
Volcanoes and Other Igneous Activity

CONCEPTS in Action

Quick Lab
Why are some volcanoes explosive?

Exploration Lab
Melting Temperatures of Rocks

How the Earth Works
Effects of Volcanoes

GEODe EARTH SCIENCE Forces Within
↳ Igneous Activity

Discovery CHANNEL SCHOOL **Video Field Trip**
Death and Destruction

Take a field trip to the ancient city of Pompeii with Discovery Channel and find out how the eruption of Mount Vesuvius destroyed a civilization. Answer the following questions after watching the video.

1. Judging from its eruption, what type of volcano is Vesuvius?
2. Are the cities near Vesuvius any safer today than they were in 79 A.D.? Why or why not?

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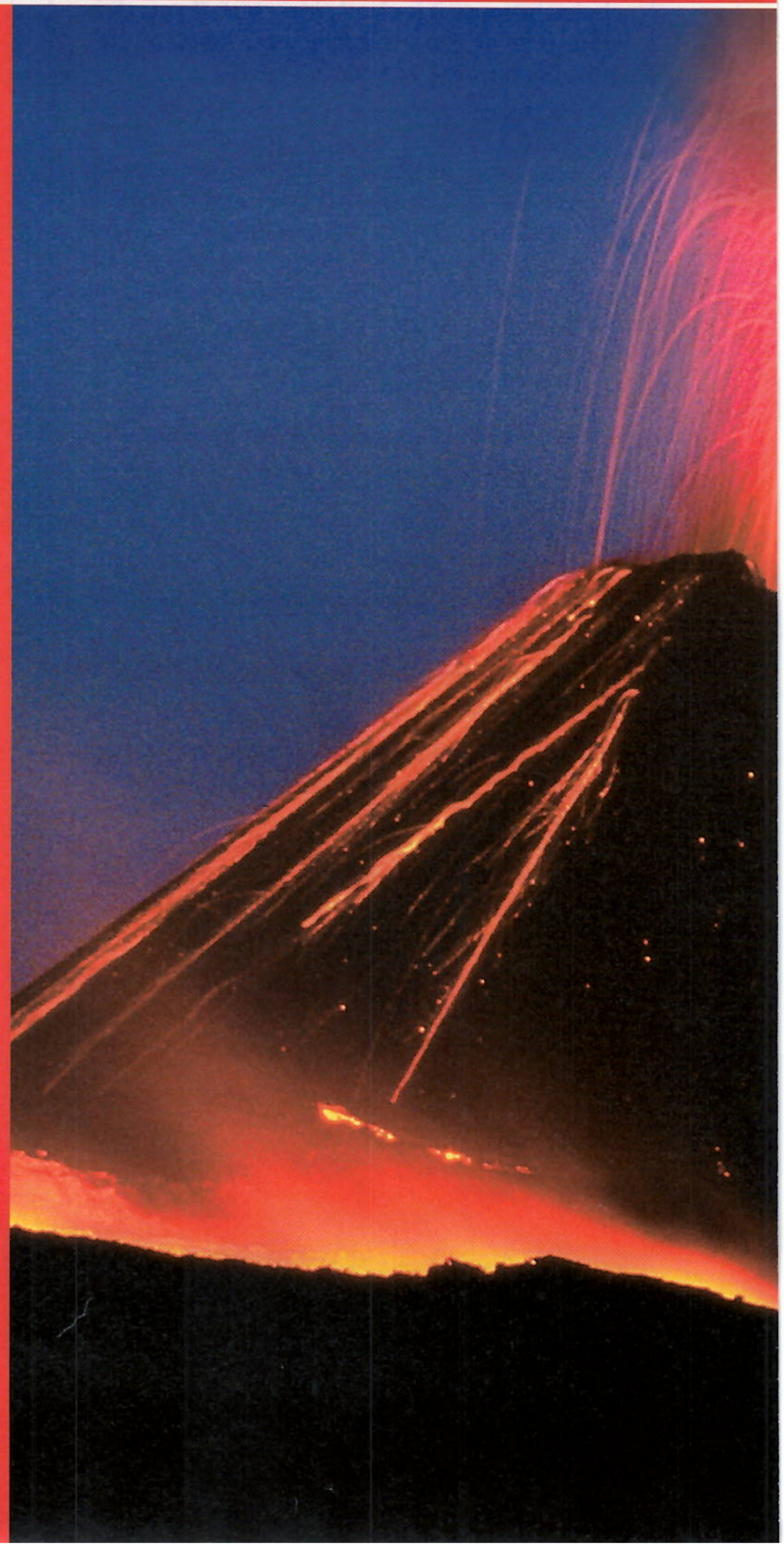

This photograph shows a recent eruption ▶ of Italy's Mount Etna.

Chapter Preview

Inquiry Activity

Where Are Volcanoes Located?

Procedure

1. Use the Internet and library resources to locate at least 15 active volcanoes and 10 historical volcanic eruptions.
2. Plot the locations of these volcanoes on a copy of a world map or on an overlay for a world atlas.
3. Neatly label the volcanoes on the map or overlay.
4. Compare your volcano map with the map of earthquake epicenters in Figure 9 on page 226 and the map of plate boundaries in Figure 8 on pages 256 and 257.

Think About It

1. **Observing** What is the relationship between the locations of the volcanoes you plotted and the earthquake epicenters and plate boundaries on the maps?
2. **Inferring** If there have been numerous volcanic eruptions in an area, would the area be a likely place for earthquakes to occur? Explain your answer.
3. **Predicting** Use your volcano map to predict if a volcanic eruption would be likely or not likely in each of the following areas: eastern coast of North America, Spain, eastern coast of South America, Italy, and Japan.

10.1 The Nature of Volcanic Eruptions

Reading Focus

Key Concepts

- What determines the type of volcanic eruption?
- What materials are ejected from volcanoes?
- What are the three main types of volcanoes?
- What other landforms are associated with volcanic eruptions?

Vocabulary

- viscosity
- vent
- pyroclastic material
- volcano
- crater
- shield volcano
- cinder cone
- composite cone
- caldera

Reading Strategy

Previewing Copy the table. Before you read the section, rewrite the green topic headings as questions. As you read, write the answers to the questions.

The Nature of Volcanic Eruptions	
What factors affect an eruption?	a. ___?___

Volcanic eruptions are more than spectacular sights. They are windows to Earth's interior. Because volcanoes eject molten rock that formed at great depth, they provide opportunities to observe the processes that occur deep beneath Earth's surface.

On May 18, 1980, one of the largest volcanic eruptions to occur in North America changed a scenic volcano into the smoldering wreck shown in Figure 1. On this date, Mount St. Helens erupted with tremendous force. The blast blew out the entire north flank of the volcano, leaving a gaping hole. The eruption ejected nearly a cubic kilometer of ash and rock debris. The air over Yakima, Washington, 130 kilometers to the east, was so filled with ash that noon became almost as dark as midnight. Why do volcanoes like Mount St. Helens erupt explosively, while others like Kilauea in Hawaii are relatively quiet?

Figure 1 A Mount St. Helens before the May 18, 1980, eruption. **B** After the eruption, Spirit Lake filled with debris.

Table 1 Magma Composition

Composition	Silica Content	Viscosity	Gas Content	Tendency to Form Pyroclastics (ejected rock fragments)	Volcanic Landform
Basaltic	Least (~50%)	Least	Least (1–2%)	Least	Shield Volcanoes Basalt Plateaus Cinder Cones
Andesitic	Intermediate (~60%)	Intermediate	Intermediate (3–4%)	Intermediate	Composite Cones
Rhyolitic	Most (~70%)	Greatest	Most (4–6%)	Greatest	Pyroclastic Flows Volcanic Domes

Factors Affecting Eruptions

The primary factors that determine whether a volcano erupts violently or quietly include magma composition, magma temperature, and the amount of dissolved gases in the magma.

Viscosity **Viscosity** is a substance's resistance to flow. For example, maple syrup is more viscous than water and flows more slowly. Magma from an explosive eruption may be thousands of times more viscous than magma that is extruded quietly.

The effect of temperature on viscosity is easy to see. If you heat maple syrup, it becomes more fluid and less viscous. In the same way, the mobility of lava is strongly affected by temperature. As a lava flow cools and begins to harden, its viscosity increases, its mobility decreases, and eventually the flow halts.

The chemical composition of magmas has a more important effect on the type of eruption. The viscosity of magma is directly related to its silica content. In general, the more silica in magma, the greater is its viscosity. Because of their high silica content, rhyolitic lavas are very viscous and don't flow easily. Basaltic lavas, which contain less silica, tend to be more fluid.

Dissolved Gases During explosive eruptions, the gases trapped in magma provide the force to eject molten rock from **the vent,** an opening to the surface. These gases are mostly water vapor and carbon dioxide. As magma moves nearer the surface, the pressure in the upper part of the magma is greatly reduced. The reduced pressure allows dissolved gases to be released suddenly.

Very fluid basaltic magmas allow the expanding gases to bubble upward and escape relatively easily. Therefore, eruptions of fluid basaltic lavas, such as those that occur in Hawaii, are relatively quiet. At the other extreme, highly viscous magmas slow the upward movement of expanding gases. The gases collect in bubbles and pockets that increase in size until they explosively eject the molten rock from the volcano. The result is a Mount St. Helens.

Quick Lab

Why are some volcanoes explosive?

Procedure

1. Obtain two bottles of noncarbonated water and two bottles of club soda.
2. Open one bottle of the noncarbonated water and one bottle of the club soda. Record your observations.
3. Gently shake each of the remaining unopened bottles. **CAUTION:** *Wear safety goggles and point the bottles away from everyone.*
4. Carefully open each bottle over a sink or outside. Record your observations.

Analyze and Conclude

1. **Observing** What happened when the bottles were opened?
2. **Inferring** Which bottle represents lava with the most dissolved gas?

Figure 2 Lava Flows A Typical pahoehoe (ropy) lava flow, Kilauea Hawaii. **B** Example of a slow-moving aa flow.
Drawing Conclusions ***Which of the flows has more viscous lava?***

Volcanic Material

Lava may appear to be the main material extruded from a volcano, but this is not always the case. Just as often, explosive eruptions eject huge quantities of broken rock, lava bombs, fine ash, and dust. All volcanic eruptions also emit large amounts of gas.

Lava Flows Hot basaltic lavas are usually very fluid because of their low silica content. Flow rates of 10 to 300 meters per hour are common. In contrast, the movement of silica-rich (rhyolitic) lava is often too slow to be visible. When fluid basaltic lavas harden, they commonly form a relatively smooth skin that wrinkles as the still-molten subsurface lava continues to move. These are known as pahoehoe (pah HOH ee hoh ee) flows and resemble the twisted braids in ropes, as shown in Figure 2. Another common type of basaltic lava called aa (AH ah) has a surface of rough, jagged blocks with dangerously sharp edges and spiny projections.

Gases Magmas contain varied amounts of dissolved gases held in the molten rock by confining pressure, just as carbon dioxide is held in soft drinks. As with soft drinks, as soon as the pressure is reduced, the gases begin to escape. The gaseous portion of most magmas is only about 1 to 6 percent of the total weight. The percentage may be small, but the actual quantity of emitted gas can exceed thousands of tons each day. Samples taken during a Hawaiian eruption consisted of about 70 percent water vapor, 15 percent carbon dioxide, 5 percent nitrogen, 5 percent sulfur, and lesser amounts of chlorine, hydrogen, and argon. Sulfur compounds are easily recognized because they smell like rotten eggs and readily form sulfuric acid, a natural source of air pollution. The composition of volcanic gases is important because they have contributed greatly to the gases that make up the atmosphere.

Pyroclastic Materials When basaltic lava is extruded, dissolved gases propel blobs of lava to great heights. Some of this ejected material may land near the vent and build a cone-shaped structure. The wind will carry smaller particles great distances. Viscous rhyolitic magmas are highly charged with gases. As the gases expand, pulverized rock and lava fragments are blown from the vent. **Pyroclastic material** is the name give to particles produced in volcanic eruptions. **The fragments ejected during eruptions range in size from very fine dust and volcanic ash (less than 2 millimeters) to pieces that weigh several tons.**

Particles that range in size from small beads to walnuts (2–64 millimeters) are called lapilli or more commonly cinders. Particles larger than 64 millimeters in diameter are called blocks when they are made of hardened lava and bombs when they are ejected as glowing lava. Because bombs are semimolten upon ejection, they often take on a streamlined shape as they hurtle through the air.

Reading Checkpoint ***What is a volcanic bomb?***

Go Online
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For: Links on volcanic eruptions
Visit: www.SciLinks.org
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Types of Volcanoes

Volcanic landforms come in a wide variety of shapes and sizes. Each structure has a unique eruptive history. **The three main volcanic types are shield volcanoes, cinder cones, and composite cones.**

Anatomy of a Volcano Volcanic activity often begins when a fissure, or crack, develops in the crust as magma is forced toward the surface. The gas-rich magma moves up this fissure, through a circular pipe, ending at a vent, as shown in Figure 3. Repeated eruptions of lava or pyroclastic material often separated by long inactive periods eventually build the mountain called a **volcano.** Located at the summit of many volcanoes is a steep-walled depression called a **crater.**

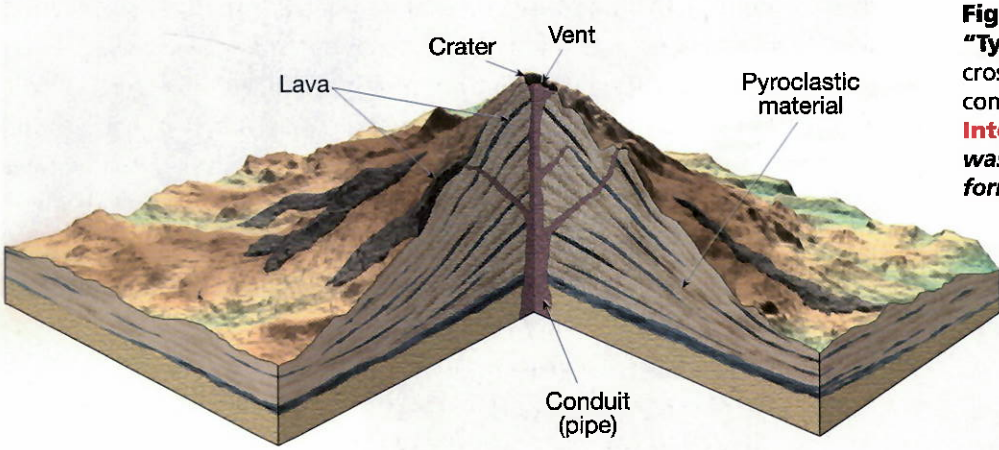


Figure 3 Anatomy of a "Typical" Volcano This cross section shows a typical composite cone.
Interpreting Diagrams ***How was the volcano in the diagram formed?***

The form of a volcano is largely determined by the composition of the magma. As you will see, fluid lavas tend to produce broad structures with gentle slopes. More viscous silica-rich lavas generate cones with moderate to steep slopes.

Shield Volcanoes **Shield volcanoes** are produced by the accumulation of fluid basaltic lavas. Shield volcanoes have the shape of a broad, slightly domed structure that resembles a warrior's shield, as shown in Figure 4. Most shield volcanoes have grown up from the deep-ocean floor to form islands. Examples of shield volcanoes include the Hawaiian Islands and Iceland.

Cinder Cones Ejected lava fragments the size of cinders, which harden in the air, build a **cinder cone.** These fragments range in size from fine ash to bombs but consist mostly of lapilli, or cinders. Cinder cones are usually a product of relatively gas-rich basaltic magma. Although cinder cones are composed mostly of loose pyroclastic material, they sometimes extrude lava.

Cinder cones have a very simple shape as shown in Figure 5A. The shape is determined by the steep-sided slope that loose pyroclastic material maintains as it comes to rest. Cinder cones are usually the product of a single eruption that sometimes lasts only a few weeks and rarely more than a few years. Once the eruption ends, the magma in the pipe connecting the vent to the magma chamber solidifies, and the volcano never erupts again. Because of this short life span, cinder cones are small, usually between 30 meters and 300 meters and rarely exceed 700 meters in height.

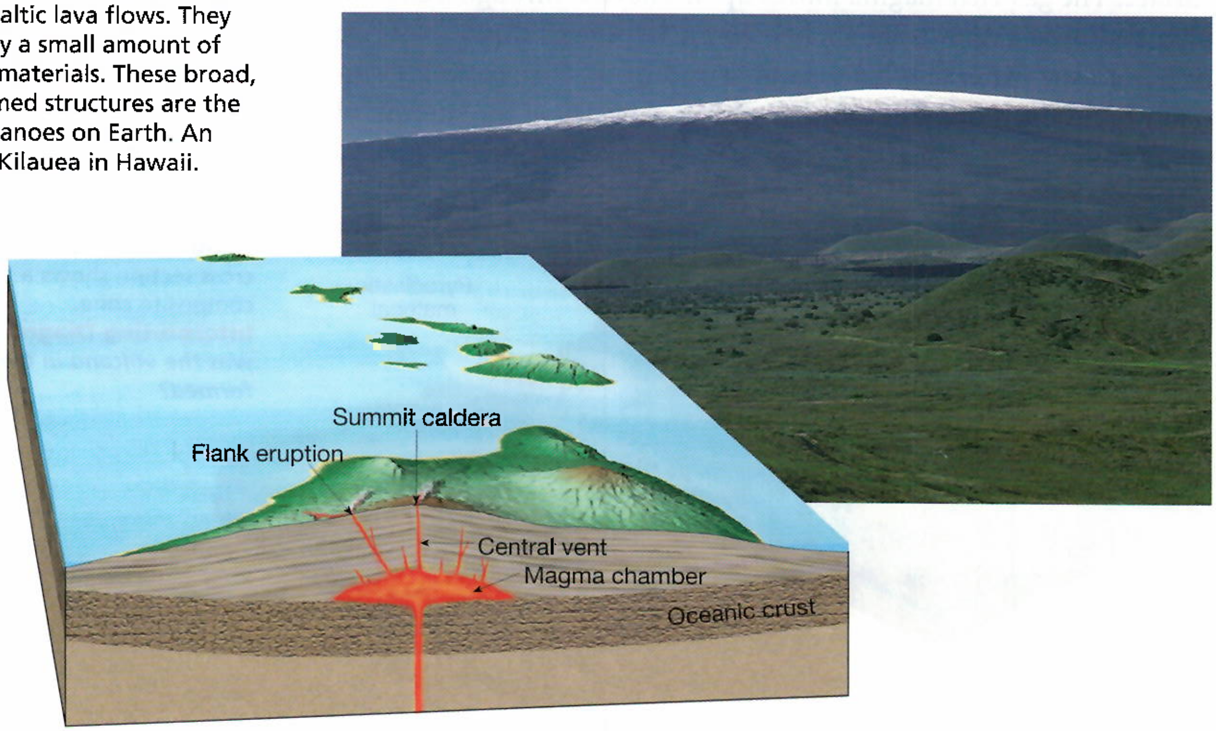
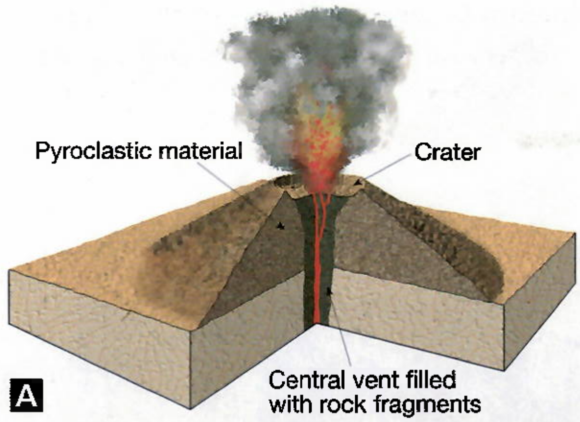


Figure 4 Shield Volcanoes Shield volcanoes are built mainly of fluid basaltic lava flows. They contain only a small amount of pyroclastic materials. These broad, slightly domed structures are the largest volcanoes on Earth. An example is Kilauea in Hawaii.



Cinder cones are found by the thousands all around Earth. Some, like the one shown in Figure 5B, near Flagstaff, Arizona, are located in volcanic fields. This field consists of about 600 cones. Others form on the sides of larger volcanoes. Mount Etna, for example, has dozens of cinder cones dotting its flanks.

Figure 5 Cinder Cones
A A typical cinder cone has steep slopes of 30–40 degrees. **B** This photograph shows SP Crater, a cinder cone north of Flagstaff, Arizona.
Inferring ***What feature is shown in the lower part of the photograph?***

Composite Cones Earth's most beautiful and potentially dangerous volcanoes are composite cones, or stratovolcanoes. Most are located in a relatively narrow zone that rims the Pacific Ocean, appropriately called the Ring of Fire. The Ring of Fire includes the large cones of the Andes in South America and the Cascade Range of the western United States and Canada. The Cascade Range includes Mount St. Helens, Mount Rainier, and Mount Garibaldi. The most active regions in the Ring of Fire are located along curved belts of volcanic islands next to the deep ocean trenches of the northern and western Pacific. This nearly continuous chain of volcanoes stretches from the Aleutian Islands to Japan, the Philippines, and New Zealand.

A **composite cone** is a large, nearly symmetrical structure composed of layers of both lava and pyroclastic deposits. For the most part, composite cones are the product of gas-rich magma having an andesitic composition. The silica-rich magmas typical of composite cones generate viscous lavas that can only travel short distances. Composite cones may generate the most explosive eruptions that eject huge quantities of pyroclastic material. Compare the shape and height of composite cones with other types of volcanoes in Figure 6.

Figure 6 Profiles of Volcanic Landforms A Profile of Mauna Loa, Hawaii, the largest shield volcano in the Hawaiian chain. **B** Profile of Mount Rainier, Washington, a large composite cone. **C** Profile of Sunset Crater, Arizona, a typical steep-sided cinder cone.

Figure 7 Composite Cone Mount Shasta, California, is one of the largest composite cones in the Cascade Range. Shastina is the smaller cone that formed on the left flank of Mt. Shasta.

Fujiyama in Japan and Mount Shasta in California show the classic shape you would expect of a composite cone, with its steep summit and gently sloping flanks, as shown in Figure 7. About 50 such volcanoes have erupted in the United States in the past 200 years. On a global scale, numerous destructive eruptions of composite cones have occurred during the past few thousand years. A few of these have had a major influence on human civilization.

Dangers from Composite Cones One of the most devastating features associated with composite cones are pyroclastic flows. They consist of hot gases, glowing ash, and larger rock fragments. The most destructive of these fiery flows are capable of racing down steep volcanic slopes at speeds of nearly 200 kilometers per hour. Some pyroclastic flows result when a powerful eruption blasts material out the side of a volcano. Usually they form from the collapse of tall eruption columns that form over a volcano during an explosive event. Once gravity overcomes the upward thrust provided by the escaping gases, the material begins to fall. Massive amounts of hot fragments, ash, and gases begin to race downhill under the influence of gravity.

Large composite cones may also generate mudflows called lahars. These destructive mudflows occur when volcanic debris becomes saturated with water and rapidly moves down steep volcanic slopes, often following stream valleys. Some lahars are triggered when large volumes of ice and snow melt during an eruption. Others are generated when heavy rainfall saturates weathered volcanic deposits. Lahars can occur even when a volcano is not erupting.

Reading Checkpoint *What is a lahar?*

Caldera Formation

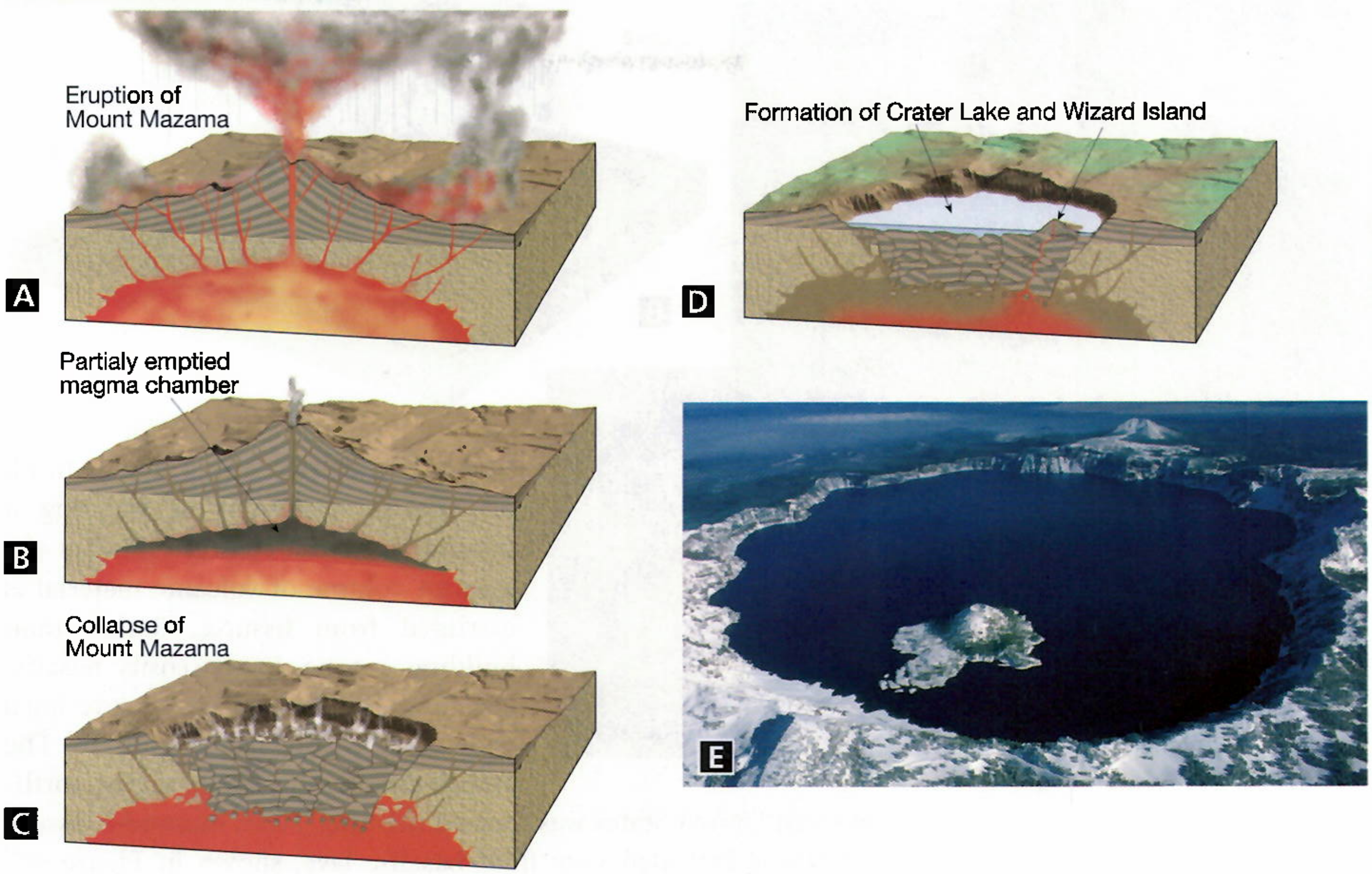


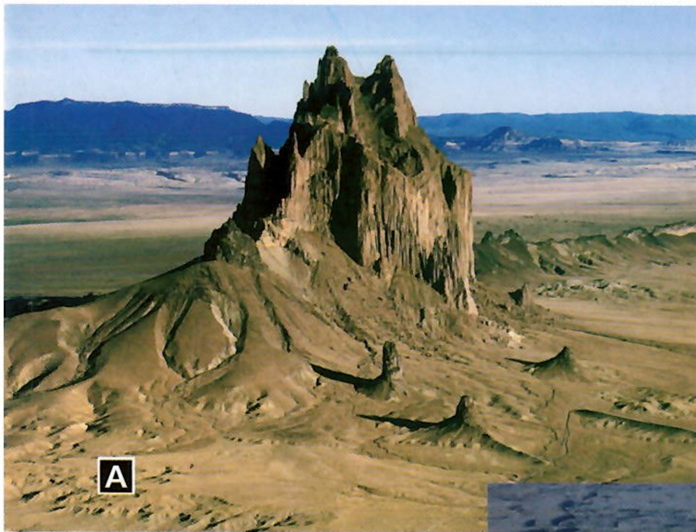
Figure 8 Crater Lake in Oregon occupies a caldera about 10 kilometers in diameter. About 7000 years ago, the summit of former Mount Mazama collapsed following a violent eruption that partly emptied the magma chamber. Rainwater then filled the caldera. Later eruptions produced the cinder cone called Wizard Island.

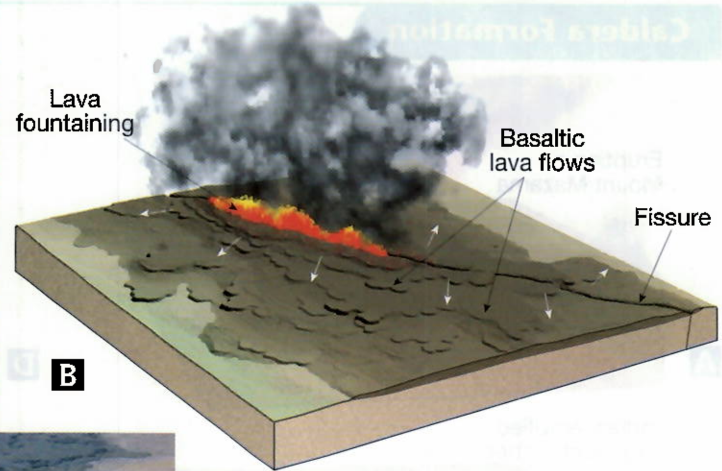
Other Volcanic Landforms

Calderas **A caldera is a large depression in a volcano.** Most calderas form in one of two ways: by the collapse of the top of a composite volcano after an explosive eruption, or from the collapse of the top of a shield volcano after the magma chamber is drained. Crater Lake, Oregon, is located in a caldera. This caldera formed about 7000 years ago when a composite cone, Mount Mazama, violently erupted and collapsed, as shown in Figure 8.

Necks and Pipes **Most volcanoes are fed magma through conduits, called pipes, connecting a magma chamber to the surface.** Volcanoes are always being weathered and eroded. Cinder cones are easily eroded because they are made up of loose materials. When the rock in the pipe is more resistant and remains standing above the surrounding terrain after most of the cone has been eroded, the structure is called a volcanic neck, as shown in Figure 9A on page 288.

The best-known volcanic pipes are the diamond-bearing pipes of South Africa. The rocks filling these pipes formed at depths of at least 150 kilometers, where pressure is high enough to form diamonds. The process of moving unaltered magma through 150 kilometers of solid rock is unusual, resulting in the rarity of diamonds.





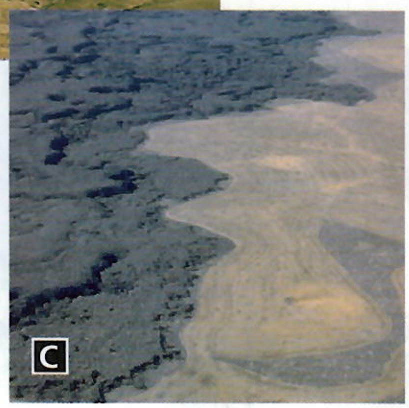


Figure 9 Other Volcanic Landforms A Ship Rock, New Mexico, is a volcanic neck. Ship Rock consists of igneous rock that crystallized in the pipe of a volcano that then was eroded away. **B** Lava erupting from a fissure forms fluid lava flows called flood basalts. **C** These dark-colored basalt flows are near Idaho Falls, Idaho.

Lava Plateaus You probably think of volcanic eruptions as building a mountain from a central vent. But the greatest volume of volcanic material is extruded from fissures. Rather than building a cone, low-viscosity basaltic lava flows from these fissures, covering a wide area, as shown in Figure 9B. The extensive Columbia Plateau in the northwestern United States was formed this way. Here, numerous fissure eruptions extruded very fluid basaltic lava, shown in Figure 9C. Successive flows, some 50 meters thick, buried the landscape, building a lava plateau nearly 1.6 kilometers thick.

Section 10.1 Assessment

Reviewing Concepts

1. What factors determine the type of volcanic eruption?
2. List the materials ejected from volcanoes.
3. Describe the three types of volcanoes.
4. What is a caldera?

Critical Thinking

5. **Comparing and Contrasting** Compare the formation of a lava plateau with the formation of a cinder cone.
6. **Applying Concepts** What type of eruption produces a viscous magma containing 53 percent silica and a gas content of 2 percent?
7. **Calculating** If a pyroclastic flow was traveling 145 kilometers per hour, how long would it take to reach a town 2.5 kilometers from the volcano's crater?

Writing in Science

Summary Research a volcanic eruption. Write a paragraph describing the eruption. Make sure to classify what type of volcano erupted.

10.2 Intrusive Igneous Activity

Reading Focus

Key Concepts

- How are intrusive igneous features classified?
- What are the major intrusive igneous features?
- What is the origin of magma?

Vocabulary

- pluton
- sill
- laccolith
- dike
- batholith
- geothermal gradient
- decompression melting

Reading Strategy

Comparing and Contrasting After you read the section, compare the types of plutons by completing the table.

Types of Plutons	Description
Sill	a. ___?___
Laccolith	b. ___?___
Dike	c. ___?___
Batholith	d. ___?___

Although volcanic eruptions are among the most violent and spectacular events in nature, most magma cools deep within Earth. The structures that result form the roots of mountain ranges and some of the most familiar features in the landscape.

Plutons

The structures that result from the cooling and hardening of magma at depth are called **plutons.** Because all plutons form beneath Earth's surface, they can be studied only after uplift and erosion have exposed them. Plutons occur in a great variety of sizes and shapes. **Intrusive igneous bodies, or plutons, are generally classified according to their shape, size, and relationship to the surrounding rock layers.**

Sills and Laccoliths

Sills and laccoliths are plutons that form when magma is intruded close to the surface. Sills and laccoliths differ in shape and often differ in composition. A **sill** forms when magma is injected along sedimentary bedding surfaces, parallel to the bedding planes. Horizontal sills, like the one shown in Figure 10, are the most common.

For a sill to form, the overlying sedimentary rock must be lifted to a height equal to the thickness of the sill. Although this is a not an easy task, at shallow levels it often requires less energy than forcing the magma up to the surface. Because of this, sills form only at shallow depths, where the pressure exerted by the weight of overlying rock layers is low. As shown in Figure 11A on page 290, sills look like buried lava flows.

Figure 10 Sills This dark, horizontal band is a sill of basalt that intruded into horizontal layers of sedimentary rock in Salt River Canyon, Arizona.
Inferring ***How could you determine if a horizontal igneous rock layer was a lava flow or a sill?***

Types of Igneous Plutons

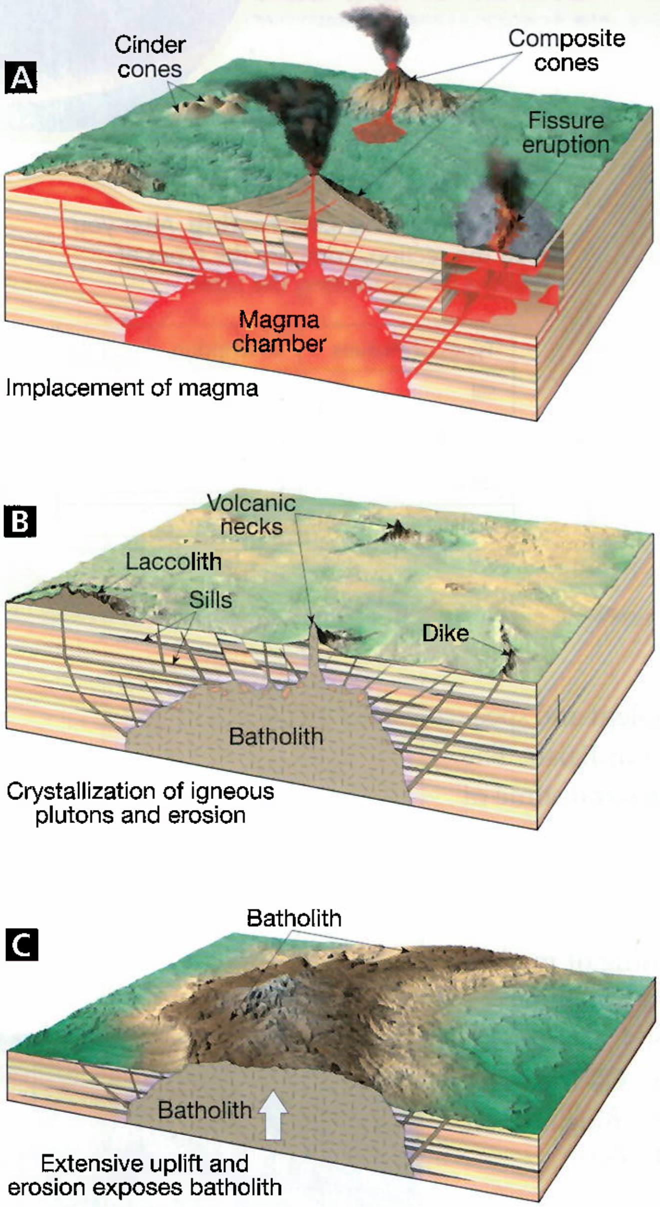


Figure 11 **A** This diagram shows the relationship between volcanism and intrusive igneous activity. **B** This view shows the basic intrusive igneous structures, some of which have been exposed by erosion long after their formation. **C** After millions of years of uplift and erosion, a batholith is exposed at the surface.

Laccoliths are similar to sills because they form when magma is intruded between sedimentary layers close to the surface. However, the magma that generates laccoliths is more viscous. This less-fluid magma collects as a lens-shaped mass that pushes the overlying strata upward. Most laccoliths are not much wider than a few kilometers.

Reading Checkpoint ***Compare and contrast sills and laccoliths.***

Dikes Some plutons form when magma is injected into fractures, cutting across preexisting rock layers. Such plutons are called **dikes,** as in Figure 11B. These sheetlike structures have thicknesses ranging from less than a centimeter to more than a kilometer. Most dikes, however, are a few meters thick and extend laterally for no more than a few kilometers.

Some dikes radiate, like spokes on a wheel, from an eroded volcanic neck. The movement of magma probably formed fissures in the volcanic cone from which the magma flowed to form the dikes. **Many dikes form when magma from a large magma chamber invades fractures in the surrounding rocks.**

Batholiths The largest intrusive igneous bodies are **batholiths.** The Idaho batholith, for example, covers an area of more than 40,000 square kilometers and consists of many individual plutons. Indirect evidence from gravity and seismic studies indicates that batholiths are also very thick, possibly extending dozens of kilometers into the crust.

An intrusive igneous body must have a surface exposure greater than 100 square kilometers to be considered a batholith. Smaller plutons are called stocks. Many stocks appear to be portions of batholiths that are not yet fully exposed. Batholiths may form the core of mountain ranges, as shown in Figure 12. In this case, uplift and erosion have removed the surrounding rock, exposing the batholith.

Figure 12 Batholiths Mount Whitney in California makes up just a tiny portion of the Sierra Nevada batholith, a huge structure that extends for approximately 400 kilometers.

Origin of Magma

The origin of magma has been controversial in geology for a long time. Based on available scientific evidence, Earth's crust and mantle are composed primarily of solid, not molten, rock. Although the outer core is a fluid, its iron-rich material is very dense and stays deep within Earth. What is the source of magma that produces igneous activity? **Geologists conclude that magma originates when essentially solid rock, located in the crust and upper mantle, partially melts. The most obvious way to generate magma from solid rock is to raise the temperature above the level at which the rock begins to melt.**

Role of Heat What source of heat is sufficient to melt rock? Workers in underground mines know that temperatures get higher as they go deeper. The rate of temperature change averages between 20°C and 30°C per kilometer in the upper crust. This change in temperature with depth is known as the **geothermal gradient.** Estimates indicate that the temperature at a depth of 100 kilometers ranges between 1400°C and 1600°C. At these high temperatures, rocks in the lower crust and upper mantle are near, but not quite at their melting point temperatures. So they are very hot but still essentially solid.

There are several ways that enough additional heat can be generated within the crust or upper mantle to produce some magma. First, at subduction zones, friction generates heat as huge slabs of crust slide past each other. Second, crustal rocks are heated as they descend into the mantle during subduction. Third, hotter mantle rocks can rise and intrude crustal rocks. All of these processes only form relatively small amounts of magma. As you'll see, the vast bulk of magma forms without an additional heat source.

Reading Checkpoint *What is a geothermal gradient?*

Figure 13 Basaltic Magma at the Surface Lava extruded along the East Rift Zone, Kilauea, Hawaii.
Observing ***Does this lava appear to have a high viscosity or a low viscosity? Explain.***

Role of Pressure If temperature were the only factor that determined whether or not rock melts, Earth would be a molten ball covered with a thin, solid outer shell. This is not the case because pressure also increases with depth. Melting, which causes an increase in volume, occurs at higher temperatures at depth because of greater confining pressure. In this way, an increase in confining pressure causes an increase in the rock's melting temperature. The opposite is also true. Reducing confining pressure lowers a rock's melting temperature. When confining pressure drops enough, **decompression melting** is triggered. This process generates magma beneath Hawaii where plumes of hot rock melt as they rise toward the surface.

Role of Water Another important factor affecting the melting temperature of rock is its water content. Water causes rock to melt at lower temperatures. Because of this, "wet" rock buried at depth has a much lower melting temperature than does "dry" rock of the same composition and under the same pressure. Laboratory studies have shown that the melting point of basalt can be lowered by up to 100°C by adding only 0.1 percent water. In addition to a rock's composition, its temperature, depth (confining pressure), and water content determine if it is a solid or liquid.

In summary, magma can be formed in three ways. First, heat may be added when a magma body from a deeper source intrudes and melts crustal rock. Second, a decrease in pressure (without the addition of heat) can result in decompression melting. Third, water can lower the melting temperature of mantle rock enough to form magma.

Section 10.2 Assessment

Reviewing Concepts

1. How are intrusive features classified?
2. List the major intrusive igneous bodies.
3. What are the three major ways that magma forms?
4. What is a pluton?

Critical Thinking

5. **Comparing and Contrasting** Describe the difference between a sill and a dike.
6. **Relating Cause and Effect** What effect does a decrease in confining pressure have on the melting temperature of rocks in the upper mantle?

Connecting Concepts

Convection Currents Recall what you learned about convection currents in Chapter 9. Explain how convection currents could affect the depth at which molten rocks are found.

10.3 Plate Tectonics and Igneous Activity

Reading Focus

Key Concepts

- What is the relationship between plate boundaries and igneous activity?
- Where does intraplate volcanism occur?

Vocabulary

- intraplate volcanism

Reading Strategy

Outlining After you read, make an outline of the most important ideas in the section.

I. **Plate Tectonics and Igneous Activity**
   A. Convergent Plate Boundaries
      1. ___?___
      2. ___?___

More than 800 active volcanoes have been identified worldwide. Most of them are located along the margins of the ocean basins, mainly within the circum-Pacific belt known as the Ring of Fire. A second group of volcanoes is found in the deep-ocean basins, including on Hawaii and Iceland. A third group includes volcanic structures that are irregularly distributed in the interiors of the continents. Until the late 1960s, geologists had no explanation for the distribution of volcanoes. With the development of the theory of plate tectonics, the picture became clearer.

Convergent Plate Boundaries

The basic connection between plate tectonics and volcanism is that plate motions provide the mechanisms by which mantle rocks melt to generate magma. At convergent plate boundaries, slabs of oceanic crust are pushed down into the mantle. As a slab sinks deeper into the mantle, the increase in temperature and pressure drives water from the oceanic crust. Once the sinking slab reaches a depth of about 100 to 150 kilometers, the fluids reduce the melting point of hot mantle rock enough for melting to begin. The magma formed slowly migrates upward forming volcanoes such as Mount St. Helens shown here. As you read about the relationships between plate tectonics and igneous activity, refer to Figure 17 on pages 296–297, which summarizes the relationships.

Figure 14 Convergent Boundary Volcano Mount St. Helens emitting volcanic ash on July 22, 1980, two months after the huge May eruption. Mount St. Helens is located at a convergent boundary between the Juan de Fuca plate and the North American plate.

MAP MASTER™ Skills Activity

Major Volcanoes

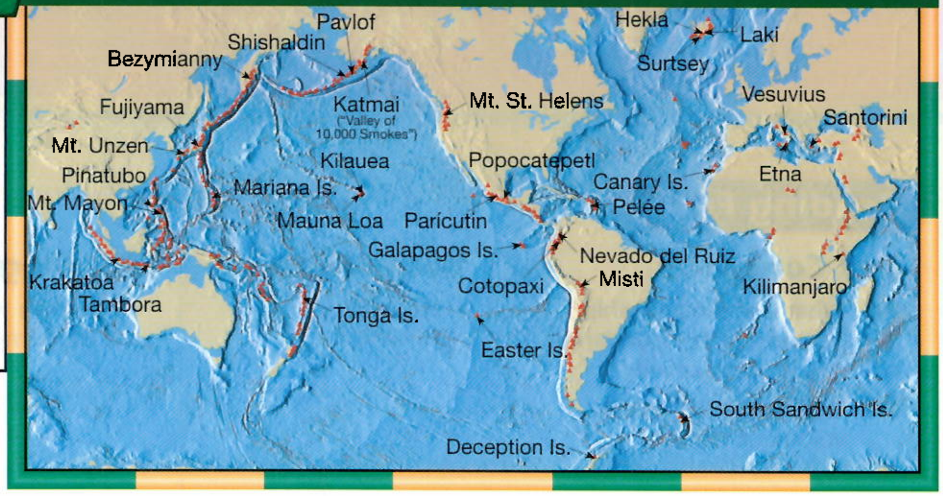


Figure 15

Location Note the concentration of volcanoes encircling the Pacific basin, known as the Ring of Fire. **Inferring** How are the volcanoes in the middle of the Atlantic Ocean related to a plate boundary?

Ocean-Ocean Volcanism at a convergent plate where one oceanic slab descends beneath another results in the formation of a chain of volcanoes on the ocean floor. Eventually, these volcanic structures grow large enough to rise above the surface and are called volcanic island arcs. Several volcanic island arcs border the Pacific basin, including the Aleutians.

Ocean-Continent Volcanism associated with convergent plate boundaries may also develop where slabs of oceanic lithosphere are subducted under continental lithosphere to produce a continental volcanic arc. The mechanisms are basically the same as those at island arcs. The major difference is that continental crust is much thicker and is composed of rocks with a higher silica content than oceanic crust. As the silica-rich crustal rocks melt, the magma may change composition as it rises through continental crust. The volcanoes of the Andes Mountains along the western edge of South America are an example of a continental volcanic arc, as shown in Figure 15.

Divergent Plate Boundaries

Most magma is produced along the oceanic ridges during seafloor spreading. Below the ridge axis where the plates are being pulled apart, the solid yet mobile mantle rises upward to fill in the rift where the plates have separated. As rock rises, confining pressure decreases. The rock undergoes decompression melting, producing large amounts of magma. This newly formed basaltic magma is less dense than the mantle rock from which it was formed, so it buoyantly rises.

Partial melting of mantle rock at spreading centers produces basaltic magma. Although most spreading centers are located along the axis of an oceanic ridge, some are not. The East African Rift in Africa is a site where continental crust is being rifted apart.

Go Online SciLinks™ NSTA

For: Links on predicting volcanic activity
Visit: www.SciLinks.org
Web Code: cjn-3103

Intraplate Igneous Activity

Kilauea is Earth's most active volcano, but it is in the middle of the Pacific plate, thousands of kilometers from a plate boundary. **Intraplate volcanism** occurs within a plate, not at a plate boundary. Another site of intraplate volcanism is Yellowstone National Park.

Most intraplate volcanism occurs where a mass of hotter than normal mantle material called a mantle plume rises toward the surface. Most mantle plumes appear to form deep within Earth at the core-mantle boundary. These plumes of hot mantle rock rise toward the surface in a way similar to the blobs that form within a lava lamp. Once the plume nears the top of the mantle, decompression melting forms basaltic magma. The result may be a small volcanic region a few hundred kilometers across called a hot spot. More than 40 hot spots have been identified, and most have lasted for millions of years. By measuring the heat flow at hot spots, geologists found that the mantle beneath some hot spots may be 100–150°C hotter than normal.

The volcanic activity on the island of Hawaii, shown in Figure 16, is the result of a hot spot. Where a mantle plume has persisted for long periods of time, a chain of volcanoes may form as the overlying plate moves over it. Mantle plumes are also thought to cause the vast outpourings of lava that create large lava plateaus such as the Columbia Plateau in the northwestern United States.

Figure 16 Intraplate Volcano An eruption of Hawaii's Kilauea volcano. The Hawaiian hot spot activity is currently centered beneath Kilauea and is an example of intraplate volcanic activity.

Section 10.3 Assessment

Reviewing Concepts

1. How are the locations of volcanoes related to plate boundaries?
2. What causes intraplate volcanism?
3. Where is most of the magma produced on Earth on a yearly basis?
4. What is the Ring of Fire?

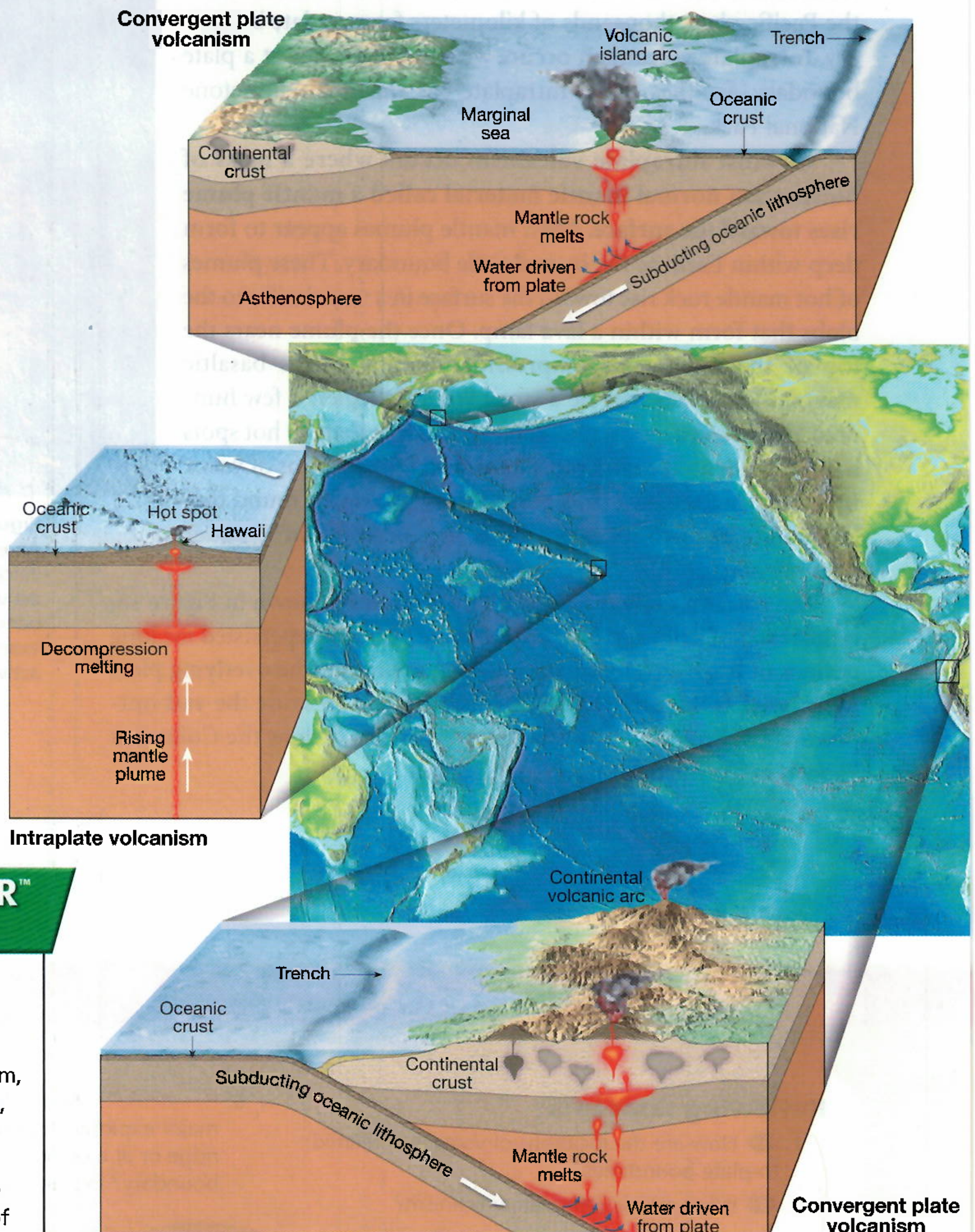
Critical Thinking

5. **Comparing and Contrasting** What are the differences between volcanic island arcs and continental volcanic arcs?
6. **Predicting** Would it be more likely for a major explosive eruption to occur at an ocean ridge or at a convergent ocean-continental boundary? Explain your answer.

Writing in Science

Explanatory Paragraph Write a paragraph to explain how magma is formed in the crust without adding heat.

Three Zones of Volcanism

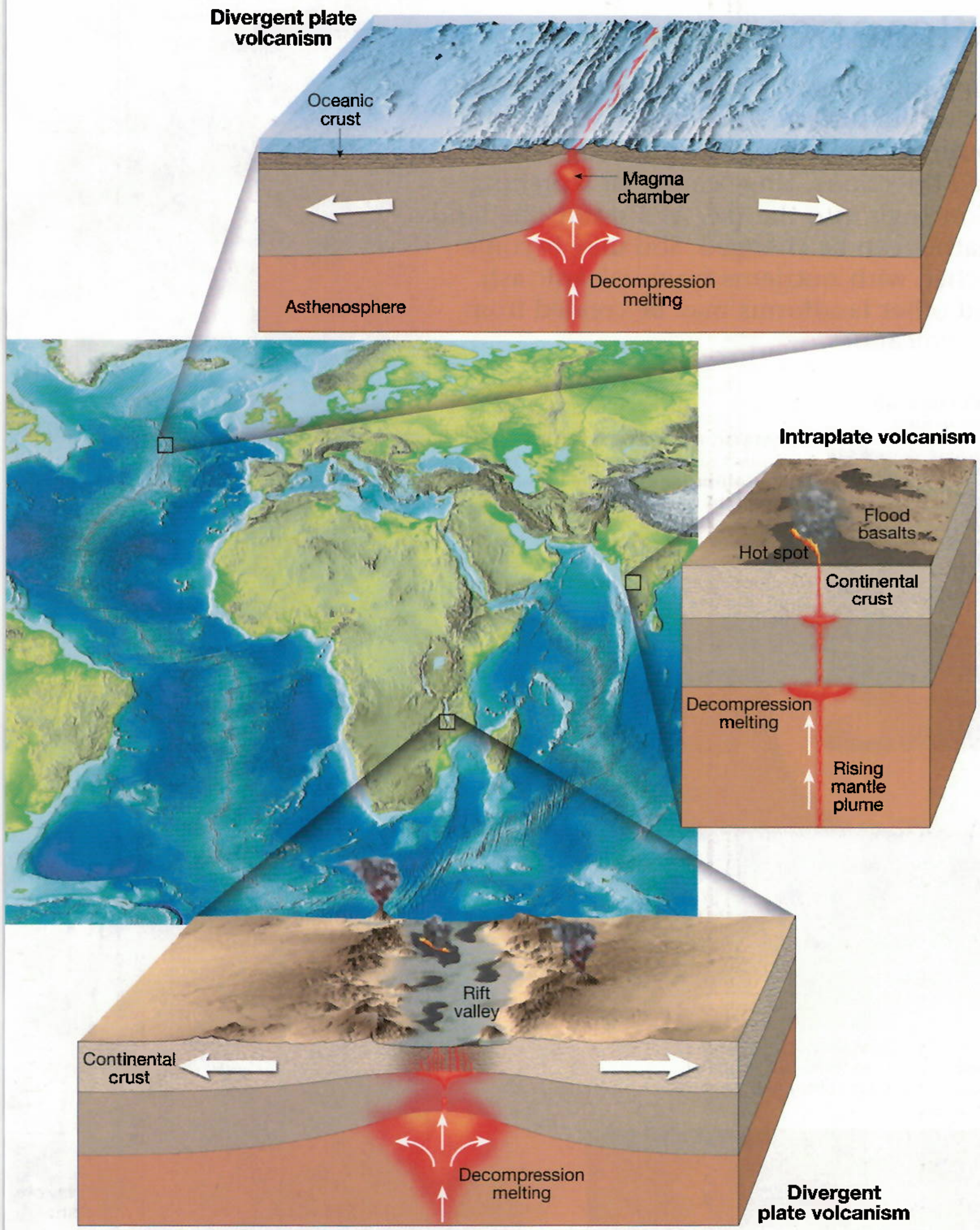


MAP MASTER™ Skills Activity

Figure 17

Regions The three zones of volcanism are convergent plate volcanism, divergent plate volcanism, and intraplate volcanism. Two of these zones are plate boundaries, and the third is the interior area of the plates.

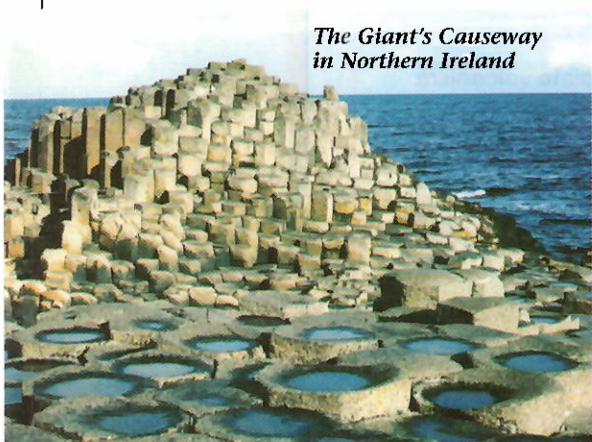
Drawing Conclusions In which zones do volcanoes occur on both continental plates and oceanic plates?


Divergent plate volcanism
Oceanic crust
Magma chamber
Asthenosphere
Decompression melting
Intraplate volcanism
Flood basalts
Hot spot
Continental crust
Decompression melting
Rising mantle plume
Rift valley
Continental crust
Decompression melting
Divergent plate volcanism

How the Earth Works

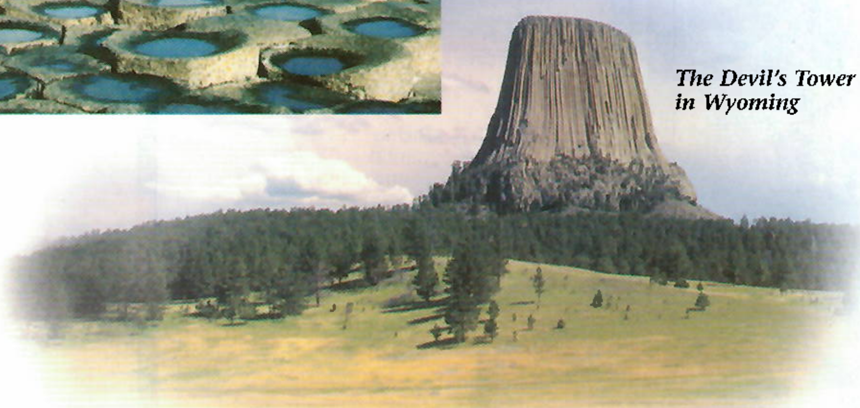
Effects of Volcanoes

A **volcano** is an opening in the Earth's crust from which **lava,** or molten rock, escapes to the surface. The impact of powerful volcanic eruptions is both immediate and long-lasting. Burning rocks are flung out in all directions. Huge clouds of scorching ash and fiery gases billow high into the sky. As a result, the landscape and even the weather can be changed. Soil may become more fertile when enriched with nutrients from volcanic ash. Islands, mountains, and other landforms may be created from the material emitted by volcanoes.



The Giant's Causeway in Northern Ireland

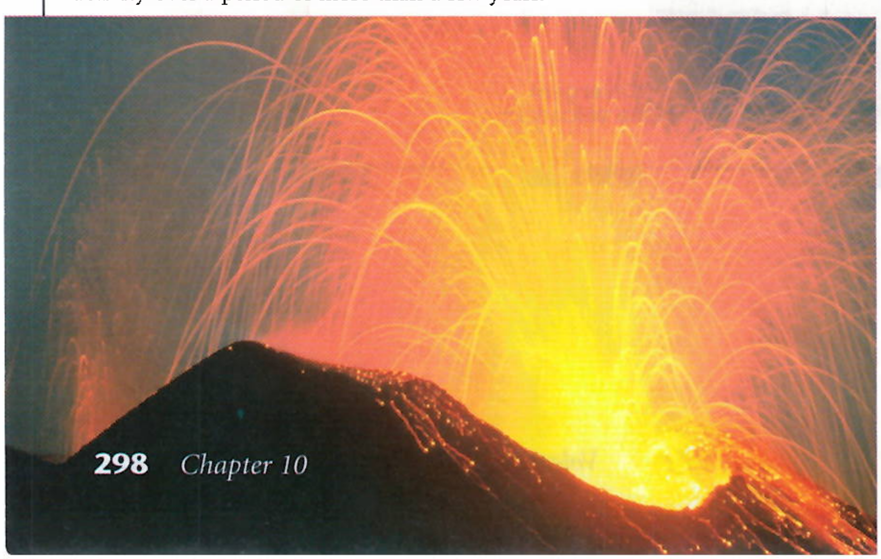
DRAMATIC ROCK FORMATIONS
Lava flows can form amazing rock formations. **Columnar rocks** are volcanic rocks that split into columns as the lava cools. The Devil's Tower in Wyoming (below) is one example of a columnar rock. Another example is the Giant's Causeway (left). This rock formation in Northern Ireland is the result of a lava flow that erupted millions of years ago.



The Devil's Tower in Wyoming

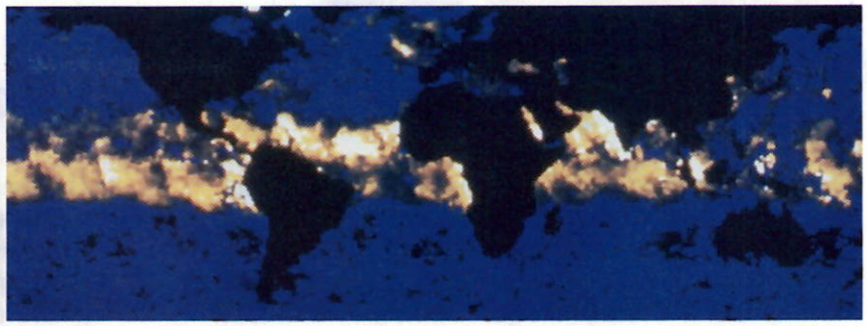
DUST AND GAS
Explosive volcanoes, like Mount St. Helens in Washington (right), spit clouds of ash and fumes into the sky. The debris can completely cover human communities. Another hazard is that volcanic gases may be deadly poisons.

ERUPTING LAVA
Red-hot lava is hurled into the air during an eruption of a volcano on Stromboli, an island off the coast of southern Italy. The Stromboli volcano is one of only a few volcanoes to display continuous eruptive activity over a period of more than a few years.



AFFECTING THE WORLD'S WEATHER

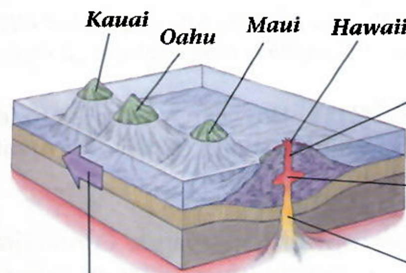
Powerful eruptions emit gas and dust that can rise high into the atmosphere and travel around the world. Volcanic material can reduce average temperatures in parts of the world by filtering out some of the sunlight that warms the Earth.



A satellite image shows the global spread of emissions from the 1991 eruptions of Mount Pinatubo in the Philippines.

A STRING OF ISLANDS

The Hawaiian Islands are the tops of volcanic mountains. They have developed over millions of years as a **plume,** or a very hot spot in the Earth's mantle, erupted great amounts of lava. As the Pacific Plate moves over the stationary plume, it carries older islands in the chain to the northwest. Today, active volcanoes are found on the island of Hawaii and the newly forming island of Loihi.



A crater lake in Iceland

A CRATER LAKE

A **crater lake** is a body of water that occupies a bowl-shaped depression around the opening of an extinct or dormant volcano. An eruption can hurl the water out of the crater. The water can then mix with hot rock and debris and race downhill in a deadly mudslide.

LIFE RETURNS TO THE LAVA

In time, plant life grows on lava. Lichen and moss often appear first. Grass and larger plants slowly follow. The upper surface of the rock is gradually weathered, and the roots of plants help break down the rock to form soil. After many generations, the land may become lush and fertile again.

A few lichens find a home on the lava.

Plants take root in the beginnings of topsoil.

ASSESSMENT

1. **Key Terms** Define **(a)** volcano, **(b)** lava, **(c)** columnar rock, **(d)** plume, **(e)** crater lake.
2. **Natural Resources** How can soil become more fertile as a result of volcanic eruptions?
3. **Environmental Change** **(a)** How can volcanic activity create new landforms? **(b)** How can explosive volcanic eruptions affect the atmosphere and weather around the world?
4. **Natural Hazards** What are some of the ways in which a volcanic eruption can devastate nearby human settlements?
5. **Critical Thinking** **Sequencing** Study the diagram of the Hawaiian Islands and the caption that accompanies it. **(a)** Which island on the diagram is probably the oldest? Why do you think so? **(b)** What will happen to the volcanoes on the island of Hawaii as a result of plate movement?

Exploration Lab

Melting Temperatures of Rocks

Measurements of temperatures in wells and mines have shown that Earth's internal temperatures increase with depth. Recall that this rate of temperature increase is called the geothermal gradient. Although the geothermal gradient varies from place to place, it is possible to calculate an average. In this lab, you will investigate Earth's internal temperatures and the temperatures at which rocks melt. You will also investigate the effect of water on the melting temperatures of rock.

Problem How can rocks melt to form magma in the crust and uppermost mantle?

Materials

- photocopy of Temperature Curves graph
- colored pencils (three different colors)
- ruler

Skills Analyzing Data, Graphing, Calculating

Procedure

1. Obtain a photocopy of the Temperature Curves graph on page 301. You will use it to plot the average temperature gradient for Earth's interior. Plot the temperature gradient on graph paper labeled like the graph shown.
2. Plot the temperature values from Table 1 on your graph. Then draw a single best-fit line through the points with a colored pencil. Extend your line from the surface to 200 kilometers. Label the line "Temperature Gradient."
3. The melting temperature of a rock changes as pressure increases deeper within Earth. The approximate melting points of the igneous rocks, granite and basalt, under various pressures (depths) have been determined in the laboratory and are shown in Table 2. Granite and basalt were used because they are common materials in the upper layer of Earth. Plot the melting temperatures from Table 2 on the same graph you made above. Use a different colored pencil to plot each set of points and draw the best-fit lines.
4. Label the two lines "Melting Curve for Wet Granite" and "Melting Curve for Basalt."

Table 1 Idealized Internal Temperatures of Earth

Depth (kilometers)	Temperature (°C)
0	20
25	600
50	1000
75	1250
100	1400
150	1700
200	1800

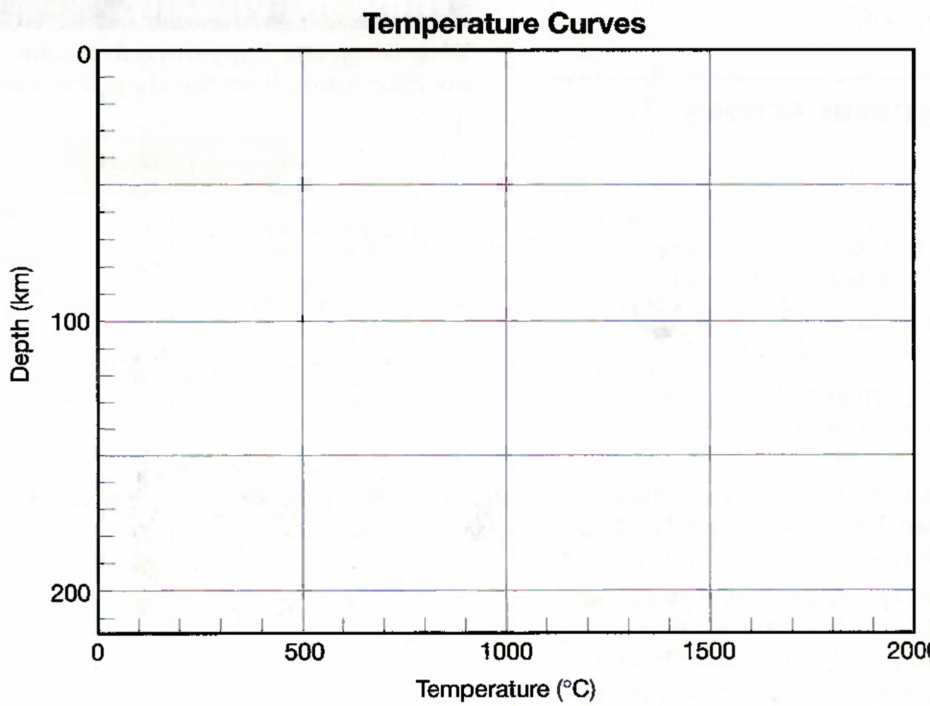
Table 2 Melting Temperatures of Granite (with water) and Basalt at Various Depths Within Earth

Granite (with water)		Basalt	
Depth (km)	Melting Temperature (°C)	Depth (km)	Melting Temperature (°C)
0	950	0	1100
5	700	25	1160
10	660	50	1250
20	625	100	1400
40	600	150	1600

Analyze and Conclude

1. **Using Graphs** Does the rate of increase of Earth's internal temperature stay the same or change with increasing depth?
2. **Using Graphs** Is the rate of temperature increase greater from the surface to 100 kilometers or below 100 kilometers?
3. **Interpreting Data** What is the temperature at 100 kilometers below the surface?
4. **Calculating** Use the data and your graph to calculate the average temperature gradient for the upper 100 kilometers of Earth in °C/100 kilometers and in °C/kilometer.
5. **Drawing Conclusions** Based on your data, at approximately what depth within Earth would wet granite reach its melting temperature and begin to form magma? Explain.
6. **Drawing Conclusions** Based on your data, at what depth will basalt have reached its melting temperature and begin to form magma?

Go Further What is the name of the layer within Earth's upper mantle that is below about 100 kilometers? Why do scientists theorize that this zone is capable of "flowing" more easily than other mantle rock, allowing the lithosphere to move across it?



CHAPTER 10

Study Guide

10.1 The Nature of Volcanic Eruptions

Key Concepts

- The primary factors that determine whether a volcano erupts violently or quietly include magma composition, magma temperature, and the amount of dissolved gases in the magma.
- The fragments ejected during eruptions range in size from very fine dust and volcanic ash (less than 2 millimeters) to pieces that weigh several tons.
- The three main volcanic types are shield volcanoes, cinder cones, and composite cones.
- A caldera is a large depression in a volcano.
- Most volcanoes are fed magma through conduits, called pipes, connecting a magma chamber to the surface.

Vocabulary

viscosity, *p. 281*; vent, *p. 281*; pyroclastic material, *p. 283;* volcano, *p. 283;* crater, *p. 283;* shield volcano, *p. 284;* cinder cone, *p. 284;* composite cone, *p. 285;* caldera, *p. 287*

10.2 Intrusive Igneous Activity

Key Concepts

- Intrusive igneous bodies, or plutons, are generally classified according to their shape, size and relationship to the surrounding rock layers.
- Sills and laccoliths are plutons that form when magma is intruded close to the surface.
- Many dikes form when magma from a large magma chamber invades fractures in the surrounding rocks.
- An intrusive igneous body must have a surface exposure greater than 100 square kilometers to be considered a batholith.
- Geologists conclude that magma originates when essentially solid rock, located in the crust and upper mantle, partially melts. The most obvious way to generate magma from solid rock is to raise the temperature above the level at which the rock begins to melt.

Vocabulary

pluton, *p. 289;* sill, *p. 289;* laccolith, *p. 290;* dike, *p. 290;* batholith, *p. 290;* geothermal gradient, *p. 291;* decompression melting, *p. 292*

10.3 Plate Tectonics and Igneous Activity

Key Concepts

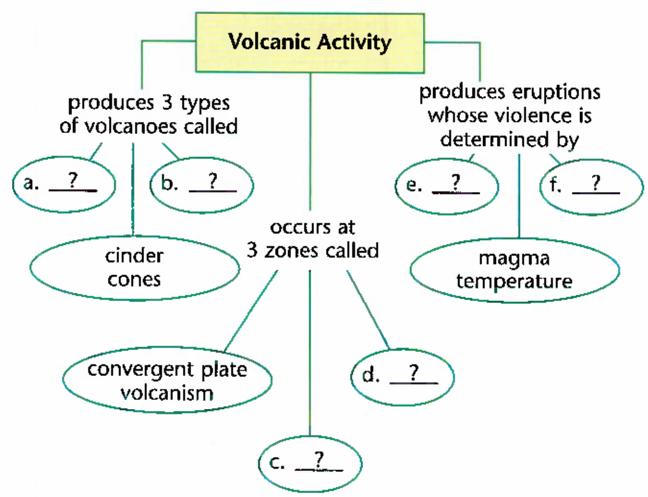
- The basic connection between plate tectonics and volcanism is that plate motions provide the mechanisms by which mantle rocks melt to generate magma.
- Most intraplate volcanism occurs where a mass of hotter than normal mantle material called a mantle plume rises toward the surface.

Vocabulary

intraplate volcanism, *p. 295*

Thinking Visually

Web Diagram Copy the web diagram below and use information from the chapter to complete it.



CHAPTER 10

Assessment

Interactive textbook with assessment at PHSchool.com

Reviewing Content

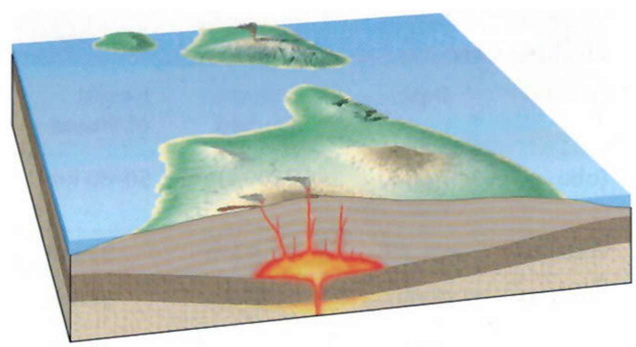
Choose the letter that best answers the question or completes the statement.

1. Underground igneous rock bodies are called
   a. lava flows. b. plutons.
   c. volcanoes. d. calderas.
2. The greatest volume of volcanic material is produced by
   a. eruptions of cinder cones.
   b. eruptions of composite cones.
   c. eruptions along ocean ridges.
   d. eruptions of shield volcanoes.
3. The most violent type of volcanic activity is associated with
   a. cinder cones. b. sills.
   c. composite cones. d. shield volcanoes.
4. A magma's viscosity is directly related to its
   a. depth. b. age.
   c. color. d. silica content.
5. What are the pulverized rock, lava, ash, and other fragments ejected from the vent of a volcano called?
   a. sills b. craters
   c. pahoehoes d. pyroclastic material
6. Which type of volcano consists of layers of lava flows and pyroclastic material?
   a. composite cone b. cinder cone
   c. shield volcano d. laccolith
7. Fluid basaltic lavas, like those in Hawaii, commonly form
   a. aa flows. b. pahoehoe flows.
   c. pyroclastic flows. d. lapilli flows.
8. What is the very large depression at the top of some volcanoes called?
   a. a vent b. a lava plateau
   c. a volcanic neck d. a caldera
9. When silica-rich magma is extruded, ash, hot gases, and larger fragments may be propelled from the vent at high speeds and produce which of the following?
   a. a lava plateau b. a lahar
   c. a pahoehoe flow d. a pyroclastic flow
10. What feature may form in an intraplate area over a rising plume of hot mantle material?
    a. a hot spot b. a dike
    c. a subduction zone d. an ocean ridge

Understanding Concepts

11. What is a volcanic neck and how does it form?
12. Describe the Ring of Fire.
13. The Hawaiian Islands and Yellowstone National Park are associated with which of the three zones of volcanism?
14. What is the chain of volcanoes called that forms at a convergent boundary between a subducting oceanic plate and a continental plate? What type of volcano commonly forms?
15. Explain how most magma is theorized to originate.

Use the diagram below to answer Questions 16 and 17.



16. Identify the type of volcano shown in the diagram.
17. What types of eruptions are commonly associated with this type of volcano?
18. How do hot spots form?
19. How are pyroclastic materials classified?
20. What is viscosity and how does it affect volcanic eruptions?
21. Give an example of each of the three types of volcanoes.
22. How do dikes form?

Assessment *continued*

Critical Thinking

23. **Applying Concepts** Why might a laccolith be detected at Earth's surface before being exposed by erosion?

24. **Inferring** Why is a volcano fed by a highly viscous magma likely to be a greater threat to people than a volcano fed by very fluid magma?

25. **Comparing and Contrasting** Compare pahoehoe lava flows and aa lava flows.

26. **Relating Cause and Effect** What is a lahar? Explain why a lahar can occur on a volcano without an eruption.

27. **Drawing Conclusions** Why are cinder cones usually small?

Analyzing Data

Use the data table below to answer Questions 28–31.

Notable Volcanic Eruptions

Volcano	Date	Volume Ejected	Height of Plume
Toba	74,000 years ago	2800 km^3	50–80 km
Vesuvius	A.D. 79	4 km^3	32 km
Tambora	1815	150 km^3	44 km
Krakatau	1883	21 km^3	36 km
Mount St. Helens	1980	1 km^3	19 km
Mount Pinatubo	1991	5 km^3	35 km

28. **Interpreting Data** What volcanic eruption listed in the data table produced the most pyroclastic material?

29. **Calculating** The volume of material ejected by the eruption of Tambora in 1815 was how many times larger than the volume of material ejected in 1883 by the eruption of Krakatau?

30. **Forming Hypotheses** Develop a hypothesis to explain why the eruption of Mount Vesuvius in A.D. 79 was more deadly than the eruption of Mount Pinatubo in 1991, even though the eruptions were approximately the same size.

31. **Calculating** Calculate how much higher the plume of volcanic debris was during the eruption of Tambora in 1815 compared to the plume from the 1980 eruption of Mount St. Helens. Calculate the increase in kilometers and in percentage of increase.

Concepts in Action

32. **Hypothesizing** Large volcanic eruptions eject large amounts of gas, dust, and ash into the atmosphere. This volcanic material can affect the world's climate by blocking incoming solar radiation. An eruption from what type of volcano is most likely to cause global climate changes? Explain your answer.

33. **Classifying** On the side of a composite cone you see a large area where there are no trees and the ground surface looks disturbed. What possible volcanic feature or event could have caused this?

34. **Applying Concepts** Would you be safer from a violent, explosive eruption while vacationing in Arizona near a cinder cone or while skiing in the Andes Mountains of South America? Explain.

35. **Writing in Science** Write a paragraph describing what an eruption of a nearby composite cone might be like.

Performance-Based Assessment

Making a Poster Make a poster illustrating the internal and external features that are typical of a composite cone. Include on your poster copies of photographs of some classic composite cones. Also explain some of the possible dangers associated with living near a composite cone.

Standardized Test Prep

Test-Taking Tip

Paying Attention to the Details
Sometimes two or more answers to a question may seem correct. If you do not read the question and answer choices carefully, you may select an incorrect answer by mistake. In the question below, two answer choices, (A) dissolved gases and (B) gravity, would seem to be possible correct answers to the question. However, the question asks what force extrudes magma from the vent, not down the slopes of the volcano. So only the answer choice, (A) dissolved gases, is correct.

What is the force that extrudes magma from a volcanic vent?
(A) dissolved gases
(B) gravity
(C) the magma's heat
(D) the volcano's slope

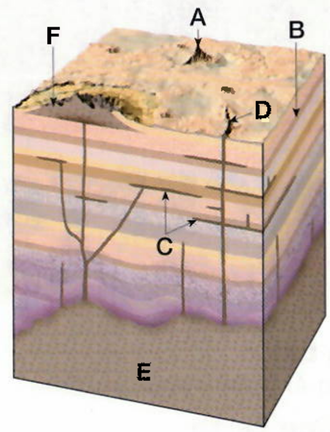
(Answer: A)

Choose the letter that best answers the question or completes the statement.

1. Which of the following is NOT a factor that determines if a volcano erupts violently or quietly?
   (A) temperature of the magma
   (B) size of the volcanic cone
   (C) the magma's composition
   (D) amount of dissolved gases in the magma

2. How does an increase in confining pressure affect a rock's melting temperature?
   (A) The melting temperature increases.
   (B) The melting temperature decreases.
   (C) The melting temperature is stabilized.
   (D) It has no effect on the melting temperature.

Use the diagram below to answer Questions 3 and 4.



3. What intrusive igneous feature in the diagram is labeled C?
   (A) a dike
   (B) a sill
   (C) a batholith
   (D) a laccolith

4. If the feature labeled E when exposed to erosion extended for over 100 square kilometers, what would it be classified as?
   (A) a dike
   (B) a stock
   (C) a laccolith
   (D) a batholith

Answer the following questions in complete sentences.

5. Briefly describe the relative sizes and shapes of the three types of volcanoes.

6. Explain how a volcanic eruption is affected by magma composition, magma temperature, and the amount of dissolved gases in the magma.

7. Most volcanic eruptions occur at tectonic plate boundaries, but some occur within a tectonic plate, far from plate boundaries.

   Part A Explain the tectonic setting of volcanoes that occur at plate boundaries.

   Part B Explain how volcanoes form in areas that are not associated with a plate boundary. Give an example.

CHAPTER

11 Mountain Building

CONCEPTS in Action

Exploration Lab
Investigating Anticlines and Synclines

Understanding Earth
Mountain Building away from Plate Margins

People and the Environment
The San Andreas Fault System

Problem Solving
Rates of Mountain Building

GEODe EARTH SCIENCE Forces Within
↳ Igneous Activity

Discovery Channel School **Video Field Trip**

Earthquake Zone

Take a field trip to the Himalayas with Discovery Channel and learn about the excitement and danger that surround the world's most dramatic mountain range. Answer the following questions after watching the video.

1. How were the Himalayas formed?
2. Why is the convergence of tectonic plates surrounding the Himalayas so dangerous?

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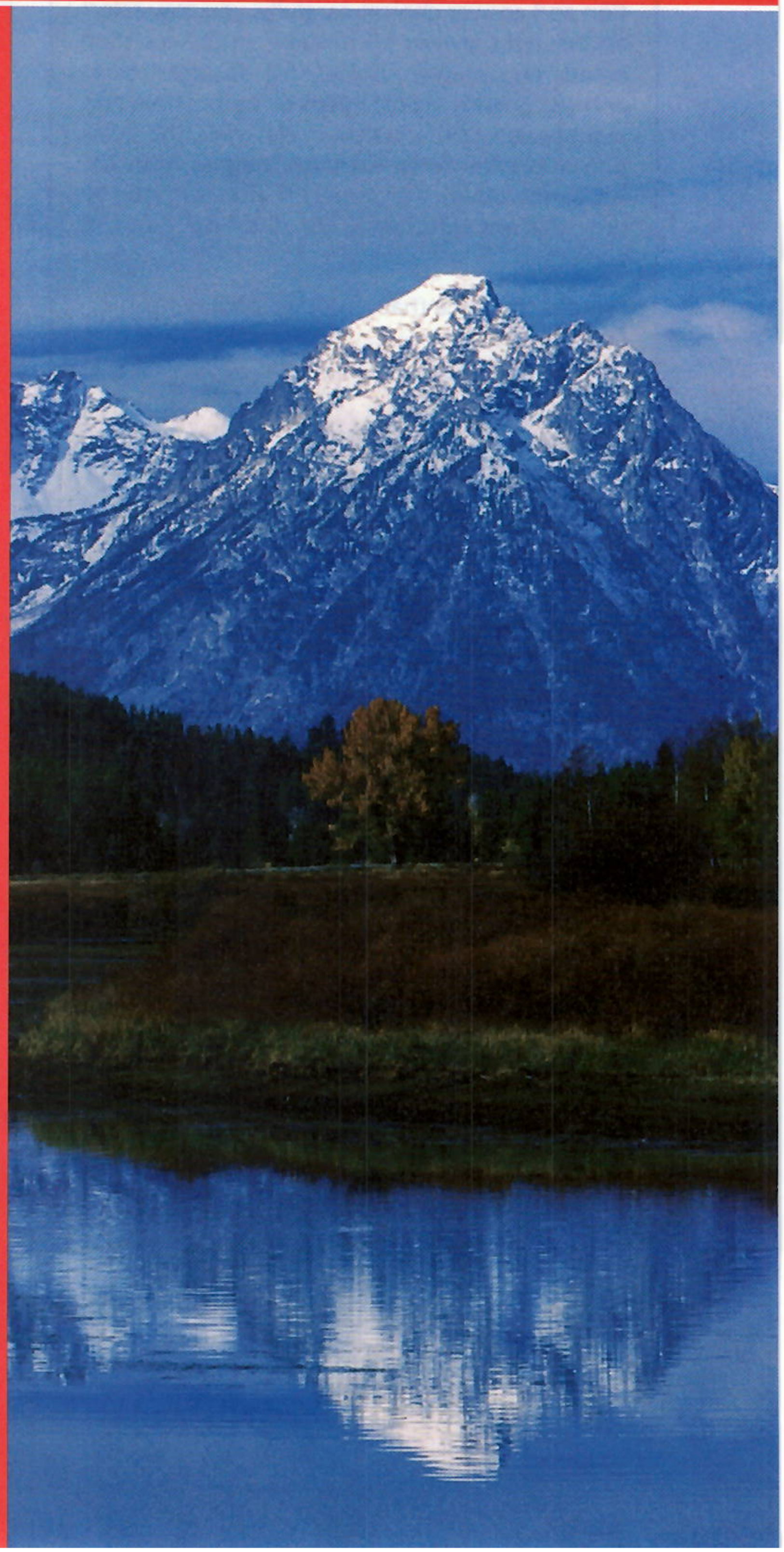
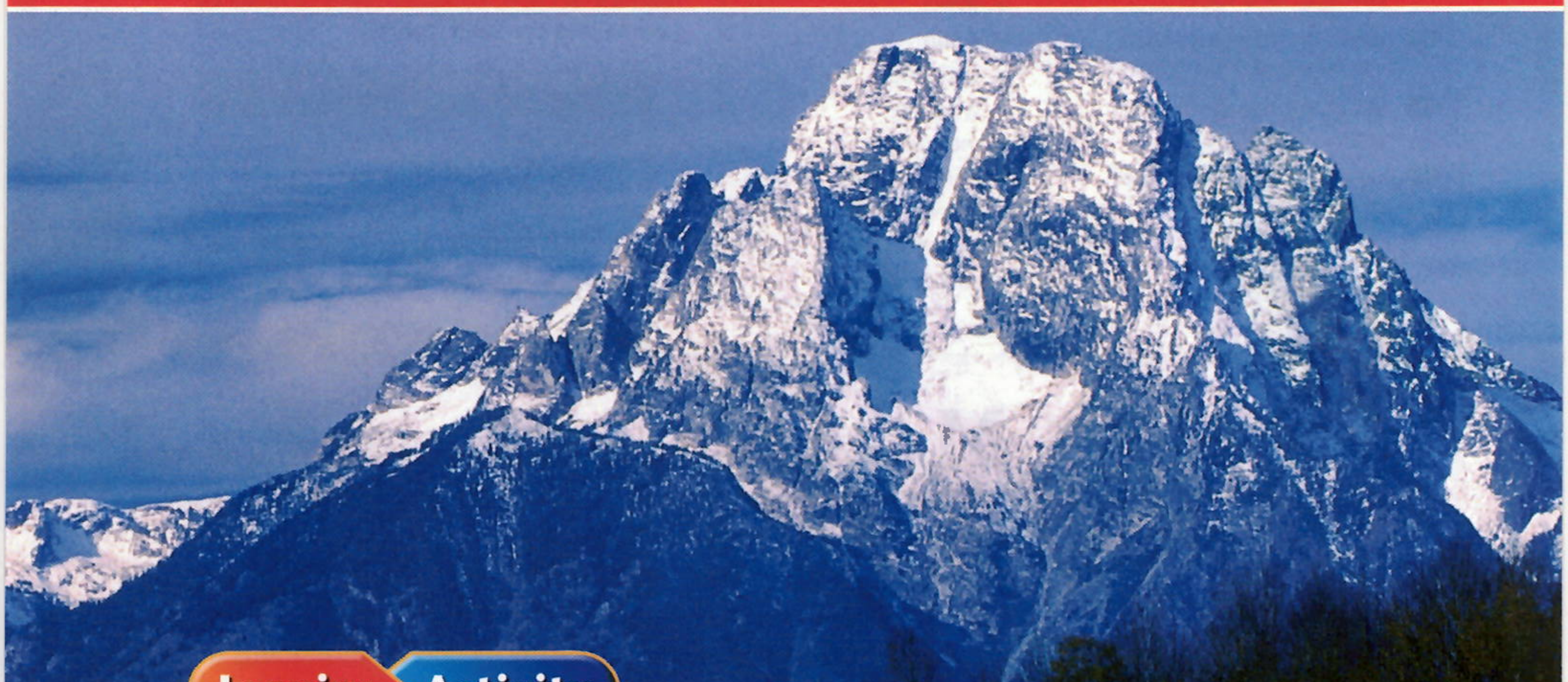


Mount Moran (on right) in Wyoming's Grand Teton National Park ▶

FORCES WITHIN

Chapter Preview



Inquiry Activity

Can You Model How Rocks Deform?

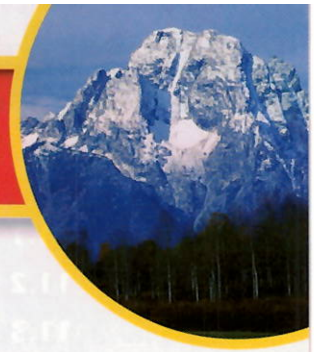
Procedure

1. Take a large, thick rubber band and stretch it out a few centimeters. Then let it relax. **CAUTION:** *Be sure to hold on to both ends of the rubber band so it does not snap your fingers. Record your observations.*
2. Take a chunk of plastic putty. Pull on the ends of the piece of putty rapidly. Record your observations.
3. Now take the chunk of plastic putty, and work it gently until it is warm and flexible. Slowly stretch it. Record your observations.
4. Take a straight, thin wooden stick about 25 centimeters long, and gently bend the ends of the stick until it breaks. **CAUTION:** *Be sure to wear safety goggles when bending the stick.* Record your observations.

Think About It

1. **Observing** Describe how the rubber band, plastic putty, and wooden stick behaved when you deformed them.
2. **Observing** Which item or items returned to the original shape and size after the force was removed?
3. **Drawing Conclusions** Which item was the easiest to deform? The hardest to deform?
4. **Inferring** Under what conditions do you think rocks are easier to bend? Under what conditions to you think rocks will break?

11.1 Rock Deformation



Reading Focus

Key Concepts

- What determines the strength of a rock?
- What are the types of stresses that affect rocks?
- What are the three main types of folds?
- What are the main types of faults?

Vocabulary

- deformation
- stress
- strain
- anticline
- syncline
- monocline
- normal fault
- reverse fault
- thrust fault
- strike-slip fault

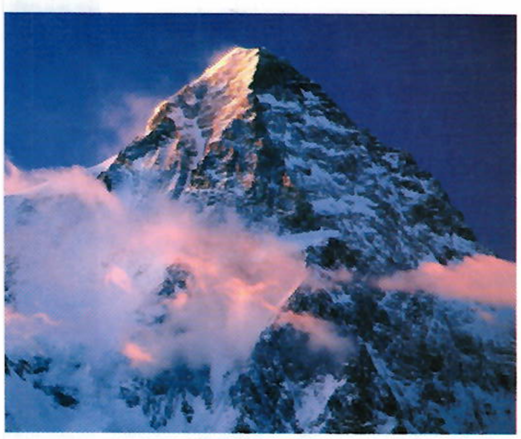
Reading Strategy

Comparing and Contrasting After you read the section, compare types of faults by completing the table below.

Types of Fault	Description
Normal fault	a. ___?___
b. ___?___	c. ___?___
d. ___?___	e. ___?___
f. ___?___	g. ___?___

Mountains, like those shown in Figure 1, provide some of the most spectacular scenery on our planet. It is theorized that all continents were once mountainous masses and grow by the addition of mountains to their edges. As geologists unravel the secrets of mountain formation, they also gain a deeper understanding of the evolution of Earth's continents. However, if continents do grow by adding mountains to their edges, then how do mountains exist in the interior of continents?

Figure 1 Mountain Ranges This peak is part of the Karakoram Range in Pakistan.



Factors Affecting Deformation

Every body of rock, no matter how strong, has a point at which it will bend or break. **Deformation** is a general term that refers to all changes in the original shape and/or size of a rock body. Most crustal deformation occurs along plate margins. Plate motions and interactions at plate boundaries create forces that cause rock to deform.

Stress is the force per unit area acting on a solid. When rocks are under stresses greater than their own strength, they begin to deform, usually by folding, flowing, or fracturing. The change in shape or volume of a body of rock as a result of stress is called **strain.** How can rock masses be bent into folds without being broken? When stress is gradually applied, rocks first respond by deforming elastically. Changes that result from elastic deformation are recoverable. Like a rubber band, the rock will return to almost its original size and shape once the force is removed. Once the elastic limit or strength of a rock is surpassed, it either flows or fractures. **The factors that influence the strength of a rock and how it will deform include temperature, confining pressure, rock type, and time.**

Temperature and Pressure **Rocks deform permanently in two ways: brittle deformation and ductile deformation.** Rocks near the surface, where temperatures and confining pressures are low, usually behave like brittle solids and fracture once their strength is exceeded. This type of deformation is called brittle failure or brittle deformation. You know that glass objects, wooden pencils, china plates, and even our bones show brittle failure once their strength is exceeded.

At depth, where temperatures and confining pressures are high, rocks show ductile behavior. Ductile deformation is a type of solid-state flow that produces a change in the size and shape of an object without fracturing the object. Objects that display ductile behavior include modeling clay, bee's wax, caramel candy, and most metals. For example, a copper penny placed on a railroad track will be flattened and deformed without breaking by the force applied by a passing train. Ductile deformation of a rock that is strongly aided by high temperature and high confining pressure is somewhat similar to the deformation of a penny flattened by a train.

Rock Type The mineral composition and texture of a rock also greatly affect how it will deform. Rocks like granite and basalt that are composed of minerals with strong internal molecular bonds usually fail by brittle fracture. Sedimentary rocks that are weakly cemented or metamorphic rocks that contain zones of weakness—such as foliation—are more likely to deform by ductile flow. Rocks that are weak and most likely behave in a ductile manner when under force include rock salt, gypsum, and shale. Limestone, schist, and marble are of intermediate strength and may also behave in a ductile manner.

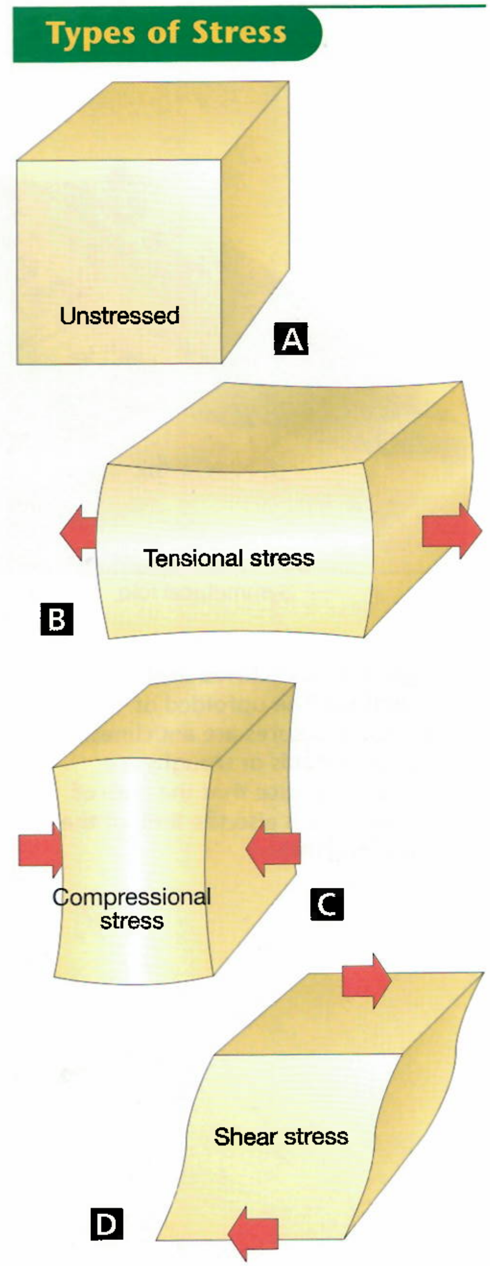
Time In nature small stresses applied over long time spans play an important role in the deformation of rock. You can see the effects of time on deformation in everyday settings. For example, marble benches have been known to sag under their own weight over a span of a hundred years or so. **Forces that are unable to deform rock when first applied may cause rock to flow if the force is maintained over a long period of time.**

Reading Checkpoint *What is brittle deformation?*

Types of Stress

Rocks are exposed to many different forces due to plate motions. **The three types of stresses that rocks commonly undergo are tensional stress, compressional stress, and shear stress.** Look at Figure 2. When rocks are squeezed or shortened the stress is compressional. Tensional stress is caused by rocks being pulled in opposite directions. Shear stress causes a body of rock to be distorted.

Figure 2 Undeformed material is changed as it undergoes different types of stress. The arrows show the direction of maximum stress. **A** Compressional stress causes a material to shorten. **B** Tensional stress causes a material to be stretched or to undergo extension. **C** Shear stress causes a material to be distorted with no change in volume.



Folds

During mountain building, flat-lying sedimentary and volcanic rocks are often bent into a series of wavelike ripples called folds. Folds in sedimentary strata are much like those that would form if you were to hold the ends of a sheet of paper and then push them together. In nature, folds come in a wide variety of sizes and shapes. **The three main types of folds are anticlines, synclines, and monoclines.**

Anticlines The two most common types of folds are anticlines and synclines. An **anticline** is most commonly formed by the upfolding, or arching, of rock layers, as shown in Figure 3.

Synclines Often found in association with anticlines are downfolds, or troughs, called **synclines.** Notice in Figure 3 that the limb of an anticline is also a limb of the adjacent syncline. Folds do not continue forever. Instead their ends die out much like the wrinkles in cloth.

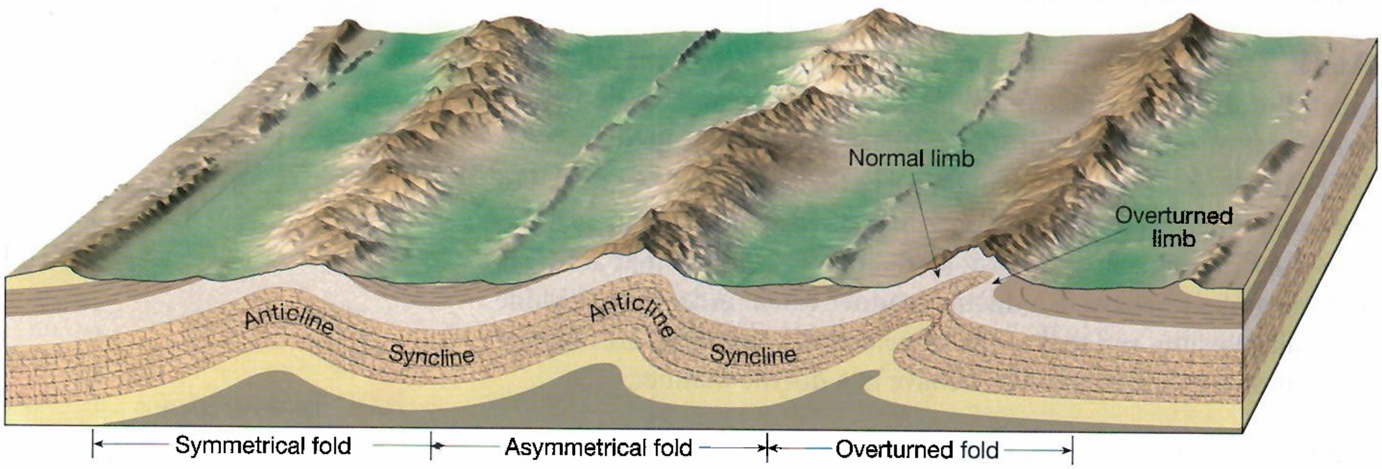


Figure 3 Anticlines and Synclines The upfolded or arched structures are anticlines. The downfolds or troughs are synclines. Notice that the limb of an anticline is also the limb of the adjacent syncline.

Monoclines Although we will discuss folds and faults separately, in the real world folds are generally closely associated with faults. Examples of this close association are broad, regional features called monoclines. **Monoclines** are large, step-like folds in otherwise horizontal sedimentary strata. Monoclines seem to occur as sedimentary layers have been folded over a large faulted block of underlying rock. Monoclines are prominent features of the Colorado Plateau area in Colorado, New Mexico, Utah, and Arizona, as shown in Figure 4 on the next page.

Reading Checkpoint *What is a syncline?*

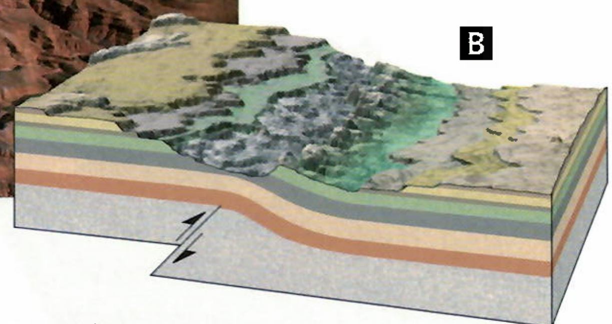


Figure 4 Monocline
A Monocline located near Mexican Hat, Utah. **B** This monocline consists of bent sedimentary beds that were deformed by faulting in the bedrock below.

Faults

Recall that faults are fractures in the crust along which movement has taken place. Small faults can be recognized in road cuts where sedimentary beds have been offset a few meters, as shown in Figure 5. Faults of this size usually occur as single breaks. By contrast, large faults, like the San Andreas fault in California, have displacements of hundreds of kilometers and consist of many interconnecting fault surfaces. These fault zones can be many kilometers wide and are often easier to identify from high-altitude photographs than at ground level.

The rock surface that is immediately above the fault is commonly called the hanging wall, and the rock surface below the fault is called the footwall. **The major types of faults are normal faults, reverse faults, thrust faults, and strike-slip faults.**

Figure 5 Normal Fault Faulting caused the vertical displacement of these beds located near Kanab, Utah. Arrows show the relative motion of rock units.
Observing ***Which side of the fault is the hanging wall?***

Normal Faults A **normal fault** occurs when the hanging wall block moves down relative to the footwall block. Most normal faults have steep dips of about 60°, as shown in Figure 6A on the next page. These dips often flatten out with depth. The movement in normal faults is mainly in a vertical direction, with some horizontal movement. Because of the downward motion of the hanging wall block, normal faults result in the lengthening, or extension, of the crust.

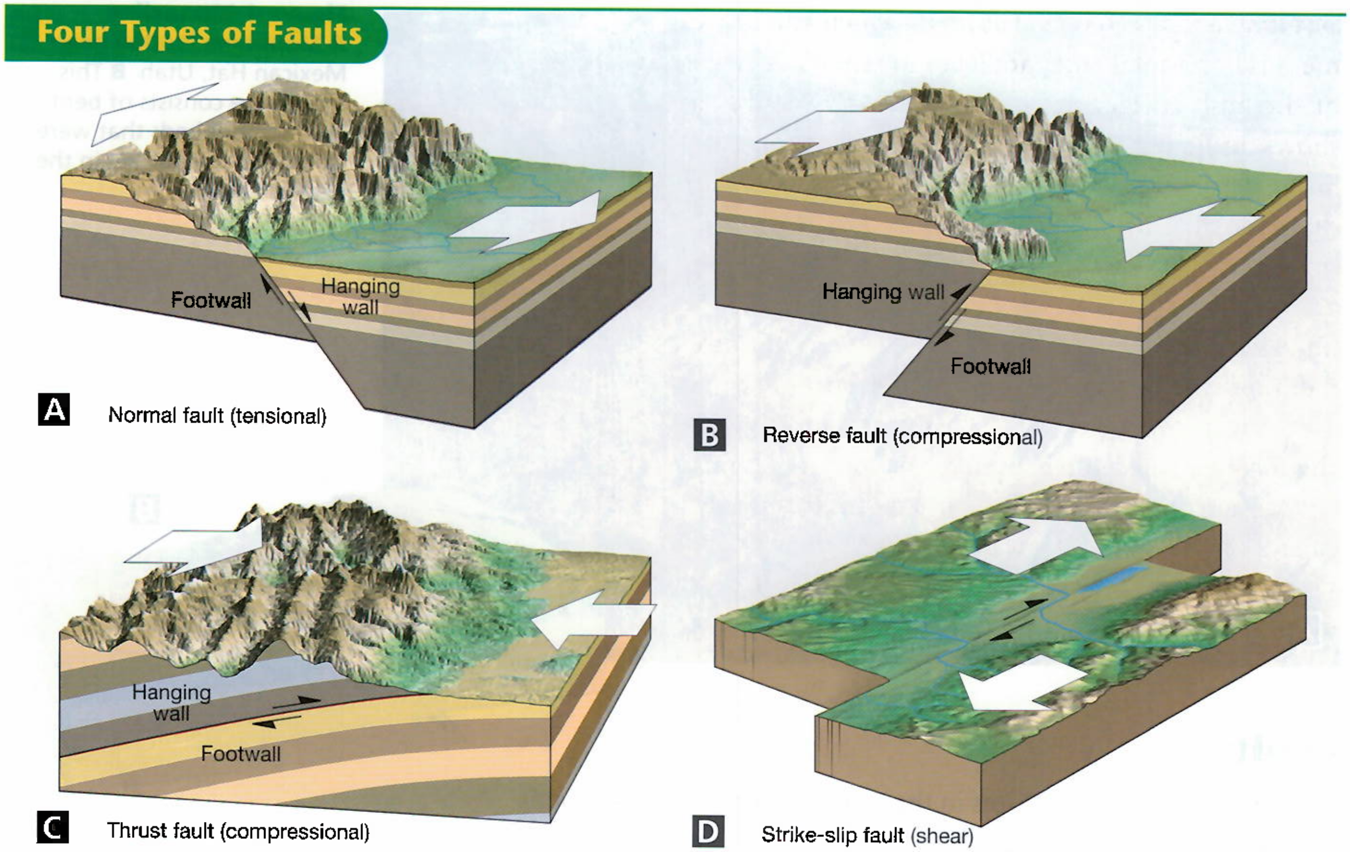


Figure 6 **A** Normal fault **B** Reverse fault **C** Thrust fault **D** Strike-slip fault
Interpreting Diagrams ***Which type of fault would cause extension in an area?***

Q&A

Q *How do you determine which side of a fault has moved?*

A For the fault shown in Figure 5, did the left side move down, or did the right side move up? Since the surface at the top of the photo has been eroded flat, either side could have moved, or both sides could have moved, with one side moving more than the other. That's why geologists talk about *relative* motion across faults. In this case, the left side moved down *relative* to the right side, and the right side moved up *relative* to the left side.

Reverse Faults and Thrust Faults A **reverse fault** is a fault in which the hanging wall block moves up relative to the footwall block. Reverse faults are high-angle faults with dips greater than 45°. **Thrust faults** are reverse faults with dips of less than 45°. Because the hanging wall block moves up and over the footwall block, reverse and thrust faults result in a shortening of the crust, as shown in Figure 6B and 6C.

Most high-angle reverse faults are small. They cause only local displacements in regions dominated by other types of faulting. Thrust faults, on the other hand, exist at all scales. In mountainous regions such as the Alps, northern Rockies, Himalayas, and Appalachians, thrust faults have displaced rock layers as far as 50 kilometers over adjacent rocks. The result of this large-scale movement is that older rocks end up on top of younger rocks.

Normal faults occur due to tensional stresses, and reverse and thrust faults result from compressional stresses. Compressional forces generally produce folds as well as faults. These compressional forces result in a thickening and shortening of the rocks.

Reading Checkpoint ***What are the major types of faults?***

Strike-Slip Faults Faults in which the movement is horizontal and parallel to the trend, or strike, of the fault surface are called **strike-slip faults,** as shown in Figure 6D. Because of their large size and linear nature, many strike-slip faults produce a trace that is visible over a great distance. Rather than a single fracture, large strike-slip faults usually consist of a zone of roughly parallel fractures. The zone may be up to several kilometers wide. The most recent movement, however, is often along a section only a few meters wide, which may offset features such as stream channels. Crushed and broken rocks produced during faulting are more easily eroded, often producing linear valleys or troughs that mark the locations of strike-slip faults. Scientific records of strike-slip faulting were made following surface ruptures that produced large earthquakes. Strike-slip faults are commonly caused by shear stress. The San Andreas fault in California and the Great Glen fault in Scotland are well-known examples of strike-slip faults.

Figure 7 Joints These joints are found in Arches National Park, near Moab, Utah. The joints in the sandstone stand out because chemical weathering is enhanced along them.

Joints Among the most common rock structures are fractures called joints. Unlike faults, joints are fractures along which no appreciable movement has occurred. Although some joints have a random orientation, most occur in roughly parallel groups, as shown in Figure 7. Joints usually form as the result of large-scale regional stresses.

Section 11.1 Assessment

Reviewing Concepts

1. What factors determine the strength of a rock?
2. In what ways do rocks deform? Explain the differences in these deformations.
3. Describe the different types of stress.
4. List the three types of folds.
5. Explain the direction of movement in the four types of faults.

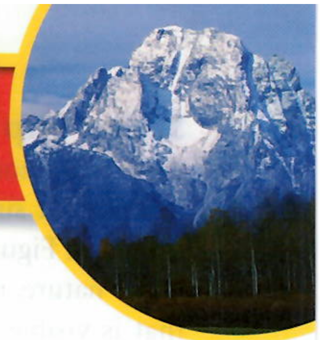
Critical Thinking

6. **Inferring** What type of deformation would a rock in the lower part of the mantle be more likely to undergo? Explain.
7. **Comparing and Contrasting** How is an anticline different from a syncline?
8. **Applying Concepts** What type of faults should be most common at a spreading ocean ridge? Explain.

Connecting Concepts

Compressional Stress Review the types of plate boundaries in Chapter 9. At which type of boundary would compressional stresses be the dominant force?

11.2 Types of Mountains



Reading Focus

Key Concepts

- How are mountains classified?
- What are the major types of mountains?

Vocabulary

- orogenesis
- folded mountain
- fault-block mountain
- graben
- horst

Reading Strategy

Previewing Make a table like the one below. Before you read the section, rewrite the green topic headings as questions. As you read, write answers to the questions.

Types of Mountains
What are folded mountains?
a. ___?___
b. ___?___
c. ___?___

Mountains are one of the most inspiring features on Earth. The collection of processes that produce a mountain belt is called **orogenesis.** The rocks in mountains provide striking evidence of the enormous compressional forces that have deformed and lifted Earth's crust. Folding is often the most obvious sign of these forces, but thrust faulting, metamorphism, and igneous activity are also important processes in mountain building. **Mountains are classified by the dominant processes that have formed them.**

Figure 8 Folded Mountains Folded sedimentary layers are exposed in the northern Rocky Mountains on the face of Mount Kidd, Alberta, Canada.

Folded Mountains

Many mountains contain huge spectacular folds of rocks, as shown in Figure 8. **Mountains that are formed primarily by folding are called folded mountains.** Compressional stresses are the major force that forms folded mountains.

Thrust faulting is also important in the formation of folded mountains, which are often called fold-and-thrust belts. Folded mountains often contain numerous stacked thrust faults that have displaced the folded rock layers many kilometers horizontally. The Appalachian Mountains, the northern Rocky Mountains, and the Alps in Europe are examples of folded mountain ranges.

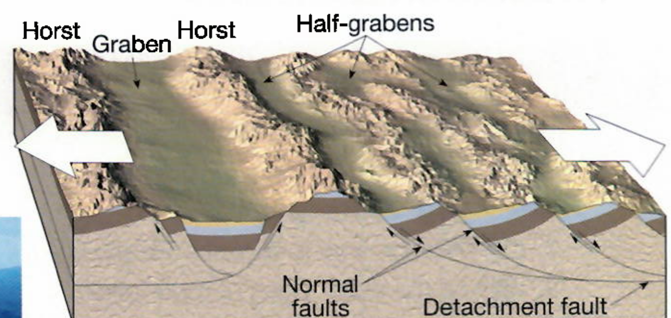
Fault-Block Mountains

Most normal faults are small and have displacements of only a meter or so. Others extend for tens of kilometers where they may outline the boundary of a mountain front. **Large-scale normal faults are associated with structures called fault-block mountains.** These mountains form as large blocks of crust are uplifted and tilted along normal faults.

In the western United States, examples of fault-block mountains include the Teton Range of Wyoming and the Sierra Nevada of California. Both are faulted along their eastern flanks, which were uplifted as the blocks tilted downward to the west. These steep mountain fronts were produced over a period of 5 million to 10 million years by many episodes of faulting. Each event produced just a few meters of displacement.

Normal faulting occurs where tensional stresses cause the crust to be stretched or extended. As the crust is stretched, a block called a **graben,** which is bounded by normal faults, drops down. *Graben* is the German word for ditch or trench. Grabens produce an elongated valley bordered by relatively uplifted structures called **horsts.** The Basin and Range Province of Nevada, Utah, and California, shown in Figure 9, is made of elongated grabens. Above the grabens, tilted fault-bound blocks or horsts produce linear fault-block mountains.

Reading Checkpoint ***What is a horst?***



B

A

Figure 9 Fault-Block Mountains A Part of the Basin and Range Province of Nevada, California, and Utah **B** Here, tensional stresses have elongated and fractured the crust into numerous blocks. Movement along these fractures has tilted the blocks producing parallel mountain ranges called fault-block mountains.

MAP MASTER™ Skills Activity

Domed Mountains

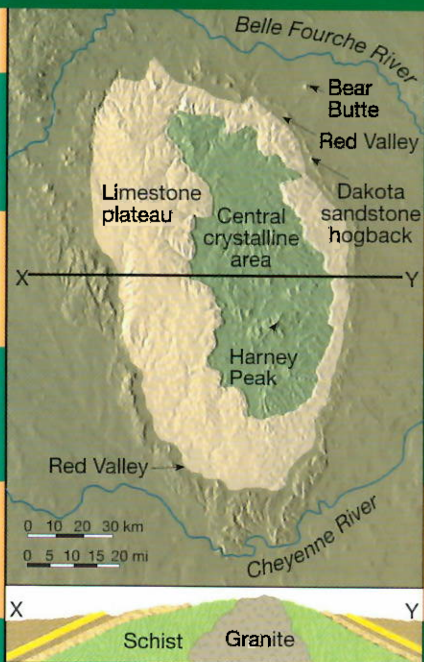


Figure 10

Regions The Black Hills of South Dakota is a large domed structure, exposing resistant igneous and metamorphic rocks in the center. **Identify** Locate the schist and granite core of the Black Hills, shown on the cross section.

Domes and Basins

The Black Hills of western South Dakota form a large domed structure thought to be formed by upwarping. Broad upwarping in basement rock may deform the overlying cover of sedimentary strata. This upwarping can generate large folds. **When upwarping produces a circular or elongated structure, the feature is called a dome.** Erosion has stripped away the highest portion of the sedimentary beds in the Black Hills, exposing older igneous and metamorphic rocks in the center. Look at the map in Figure 10. The remnants of the sedimentary layers surround the crystalline core of the mountains. The oldest rocks form the core.

Reading Checkpoint *Where are the oldest rocks found in a dome?*

Downwarped structures having a circular shape are called basins. Several large basins exist in the United States. The basins of Michigan and Illinois have very gently sloping beds similar to saucers. These basins are thought to be the result of large accumulations of sediment, whose weight caused the crust to subside.

Because large basins usually contain sedimentary beds sloping at very low angles, the basins are usually identified by the age of the rocks composing them. The youngest rocks are found near the center. The oldest rocks are at the flanks. A geologic map of lower Michigan, for example, looks somewhat like a bull's-eye. The oldest rocks are near the center of the state. Progressively younger rocks ring the center. This is just the opposite order of a domed structure, such as the Black Hills, where the oldest rocks form the core.

Section 11.2 Assessment

Reviewing Concepts

1. Describe how mountains are classified.
2. List the major types of mountains.
3. What is a graben? In what type of mountains are grabens most commonly found?
4. What is the dominant type of stress associated with folded mountains?

Critical Thinking

5. **Applying Concepts** In a mountain range, you observe a series of anticlines and synclines and numerous thrust faults. How would you classify the type of mountains in this mountain range?
6. **Comparing and Contrasting** Compare uplifted mountains and fault-block mountains.

Writing in Science

Descriptive Paragraph Write a paragraph describing a trip across an uplifted mountain. Describe the types of rocks and structures you might observe.

11.3 Mountain Formation

Reading Focus

Key Concepts

- What mountains are associated with convergent plate boundaries?
- What mountains are associated with divergent plate boundaries?
- How is isostatic adjustment involved in mountain formation?

Vocabulary

- accretionary wedge
- accretion
- terrane
- isostasy
- isostatic adjustment

Reading Strategy

Outlining As you read, make an outline of the important ideas in this section. Use the green topic headings as the main topics and the blue headings as subtopics.

I. Mountain Formation
  A. Mountain Building at Convergent Boundaries
    1. Ocean-Ocean Convergence
    2. a. ___?___
    3. b. ___?___
  B. Mountain Building at Divergent Boundaries

Mountain building still occurs in several places worldwide. For example, the Himalayas began to form 45 million years ago and are still rising. Older mountain ranges, such as the Appalachians in the eastern United States, are deeply eroded, but they have many features found in younger mountains.

Many hypotheses have been proposed to explain mountain formation. One early proposal suggested that mountains are wrinkles in Earth's crust, produced as the planet cooled from its early semi-molten state. People believed that as Earth cooled, it contracted and shrank. In this way, the crust was deformed the way an apple peel wrinkles as it dries out. However, this early hypothesis and many others were not able to withstand careful analysis and had to be discarded.

Figure 11 Young Mountains The Grand Tetons of Wyoming are an example of relatively young mountains.

Mountain Building at Convergent Boundaries

With the development of the theory of plate tectonics, a widely accepted model for orogenesis became available. **Most mountain building occurs at convergent plate boundaries. Colliding plates provide the compressional forces that fold, fault, and metamorphose the thick layers of sediments deposited at the edges of landmasses.** The partial melting of mantle rock also provides a source of magma that intrudes and further deforms these deposits.

Ocean-Ocean Convergence

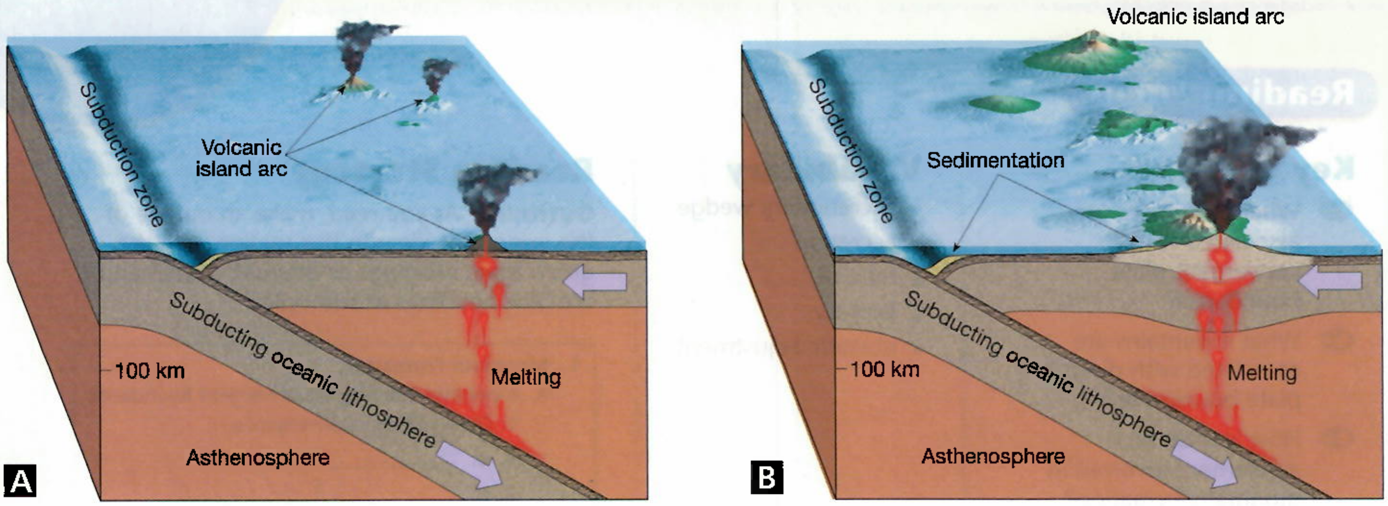


Figure 12 A A volcanic island arc develops due to the convergence of two oceanic plates. **B** Continued subduction along this type of convergent boundary results in the development of volcanic mountains.

Ocean-Ocean Convergence Ocean-ocean convergence occurs where two oceanic plates converge and one is subducted beneath the other, as shown in Figure 12. The converging plates result in partial melting of the mantle above the subducting plate and can lead to the growth of a volcanic island arc on the ocean floor. Because they are associated with subducting oceanic lithosphere, island arcs are typically found on the margins of a shrinking ocean basin, such as the Pacific. These features tend to be relatively long-lived. Here, somewhat sporadic volcanic activity, the depth of magma, as well as the accumulation of sediment that is scraped off the subducting plates, increases the volume of the crust. An example of an active island arc is the Aleutian arc, which forms the Aleutian Islands in Alaska. Some volcanic island arcs, such as Japan, appear to have been built up by two or three different periods of subduction. As shown by Japan, the continued development of a volcanic island arc can result in the formation of mountains made up of belts of igneous and metamorphic rocks. **Ocean-ocean convergence mainly produces volcanic mountains.**

Ocean-Continental Convergence Mountain building along continental margins involves the convergence of an oceanic plate and a plate whose leading edge contains continental crust. A good example is the west coast of South America. In this area, the Nazca plate is being subducted beneath the South American plate along the Peru-Chile trench. As shown by the Andes Mountains, ocean-continental convergence results in the formation of a continental volcanic arc inland of the continental margin.

The convergence of the continental block and the subduction of the oceanic plate leads to deformation and metamorphism of the continental margin. Partial melting of mantle rock above the subducting slab generates magma that migrates upward. This melting and fluid migration occurs once the oceanic plate moves down to about 100 kilometers. During the development of this continental volcanic arc, sediment derived from the land and scraped from the subducting plate is stuck against the landward side of the trench. This accumulation of different sedimentary and metamorphic rocks with some scraps of ocean crust is called an **accretionary wedge.** A long period of subduction can build an accretionary wedge of rock that is large enough to stand above sea level, as shown in Figure 13.

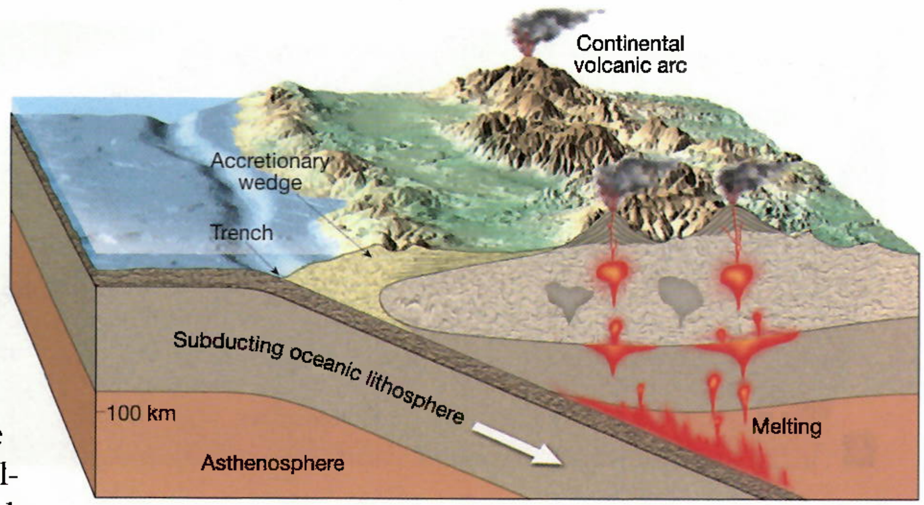


Figure 13 Ocean-Continental Convergence Plate convergence generates a subduction zone, and partial melting produces a continental volcanic arc. Continued convergence and igneous activity further deforms the crust and forms a roughly parallel folded mountain belt. **Observing** ***What type of mountains result from the partial melting?***

Ocean-continental convergence produces mountain ranges composed of two roughly parallel belts. The continental volcanic arc develops on the continental block. The arc consists of volcanoes and large intrusive bodies mixed with high-temperature metamorphic rocks. The seaward belt is the accretionary wedge. It consists of folded, faulted sedimentary and metamorphic rocks. **The types of mountains formed by ocean-continental convergence are volcanic mountains and folded mountains.**

Problem-Solving Activity

Rates of Mountain Building

The mighty Himalayas between India and Tibet are the tallest mountains on Earth, rising to more than 8 kilometers. These mountains are still rising at about 1 centimeter per year. Mount Everest is the tallest peak with an elevation of 8848 meters above sea level. The Himalayas formed as a result of India colliding with the Eurasian plate.

1. **Calculating** If you assume that the Himalayas will continue to be uplifted at the current rate of 1 centimeter per year, how long will it take the mountains to rise another 500 meters?
2. **Calculating** Assuming a rate of uplift of 1 centimeter per year, how much higher could the Himalayas be in one million years?
3. **Applying Concepts** If the convergence of tectonic plates is causing the Himalayas to rise in elevation, what common surface processes are working to decrease their elevations?
4. **Inferring** Do you think it is reasonable for the Himalayas to continue to rise in elevation indefinitely? Explain your answer.

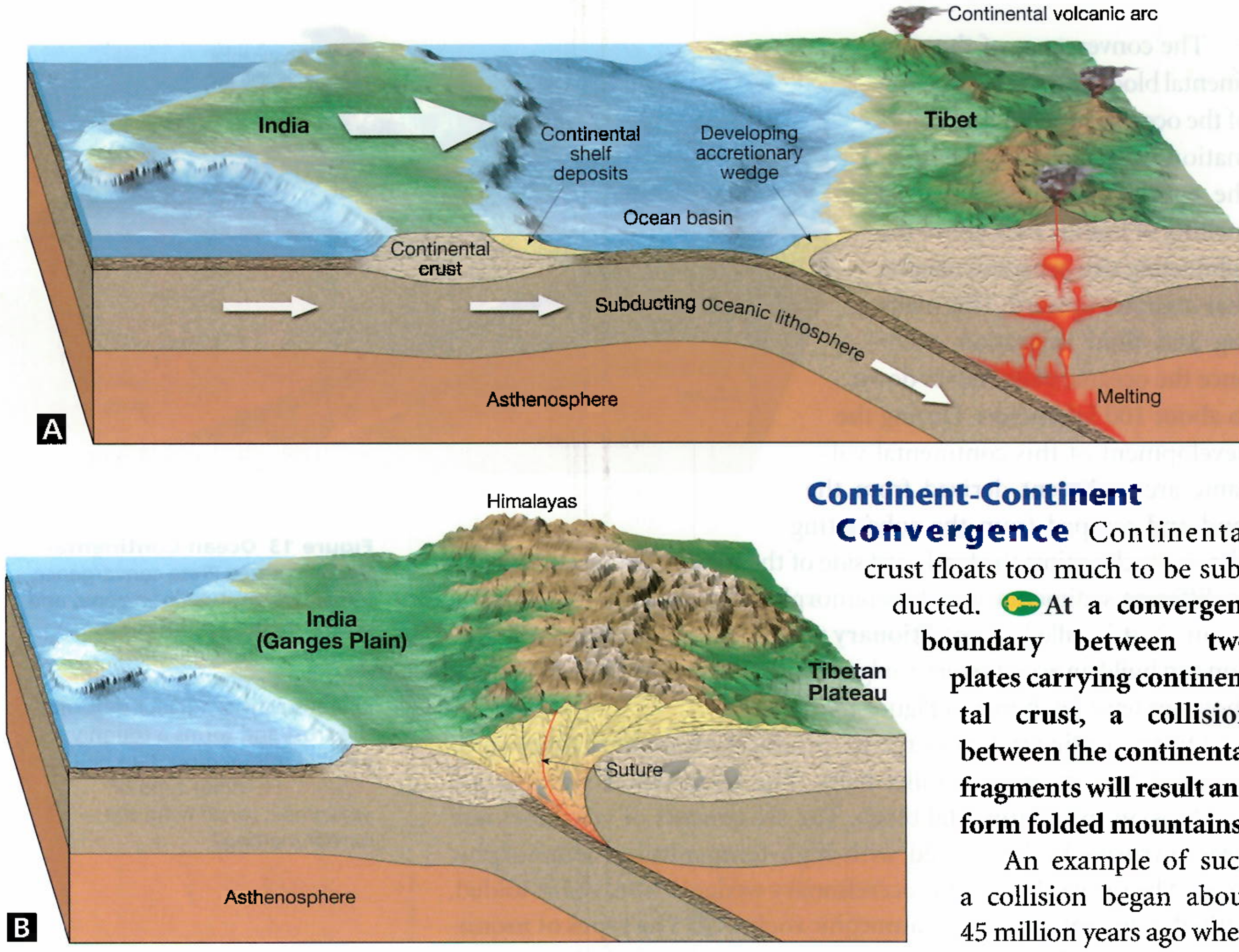


Figure 14 Continental-Continental Convergence The ongoing collision of India and Asia started about 45 million years ago and produced the majestic Himalayas. **A** Converging plates generated a subduction zone, producing a continental volcanic arc. **B** Eventually the two landmasses collided, which deformed and elevated the mountain range.

Continent-Continent Convergence Continental crust floats too much to be subducted. **At a convergent boundary between two plates carrying continental crust, a collision between the continental fragments will result and form folded mountains.**

An example of such a collision began about 45 million years ago when India collided with the Eurasian plate, as shown in Figure 14. Before this event, India was once part of Antarctica, and it had split from that continent over the course of millions of years. It slowly moved a few thousand kilometers due north. The result of the collision was the formation of the spectacular Himalaya Mountains and the Tibetan Plateau. Most of the oceanic crust that separated these landmasses before the collision was subducted, but some was caught up in the collision zone, along with the sediment along the shoreline. Today these sedimentary rocks and slivers of oceanic crust are elevated high above sea level.

A similar but much older collision is believed to have taken place when the European continent collided with the Asian continent to produce the Ural Mountains in Russia. Before the theory of plate tectonics, geologists had difficulty explaining mountain ranges such as the Urals, which are located far within continents.

Reading Checkpoint *Why can't continental crust be subducted?*

Mountain Building by Continental Accretion

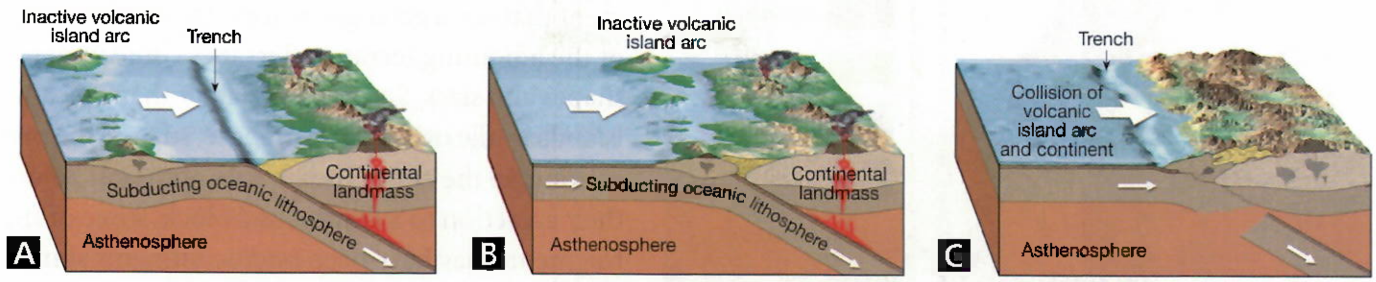


Figure 15 This sequence illustrates the collision of an inactive volcanic island arc with the margin of a continental plate. The island arc becomes embedded or accreted onto the continental plate.

Mountain Building at Divergent Boundaries

Most mountains are formed at convergent boundaries, but some are formed at divergent boundaries, usually on the ocean floor. These mountains form a chain that curves along the ocean floor at the ocean ridges. This mountain chain is over 65,000 kilometers long and rises to 2000 to 3000 meters above the ocean floor. **The mountains that form along ocean ridges at divergent plate boundaries are fault-block type mountains.** The mountain chain that makes up the Mid-Atlantic Ridge is an example.

Non-Boundary Mountains

Even though most mountains are formed at plate boundaries, some are found far from any boundaries. Some upwarped mountains, fault-block mountains, and volcanic mountains are not formed at plate boundaries. Volcanic mountains such as the Hawaiian Islands are formed at a hot spot, far from any plate boundary. Many fault-block mountains occur in areas that are undergoing regional extension or stretching. These areas may possibly become a plate boundary if the plate rifts apart.

Reading Checkpoint ***Where is the longest mountain range?***

Continental Accretion

Plate tectonics theory originally suggested two major mechanisms for orogenesis at convergent boundaries: continental collisions and subduction of oceanic lithosphere to form volcanic arcs. Further studies have lead to another mechanism in which smaller crustal fragments collide and merge with continental margins. When the fragments collide with a continental plate they become stuck to or embedded into the continent in a process called **accretion.** Many of the mountainous regions rimming the Pacific have been produced through the process of collision and accretion.

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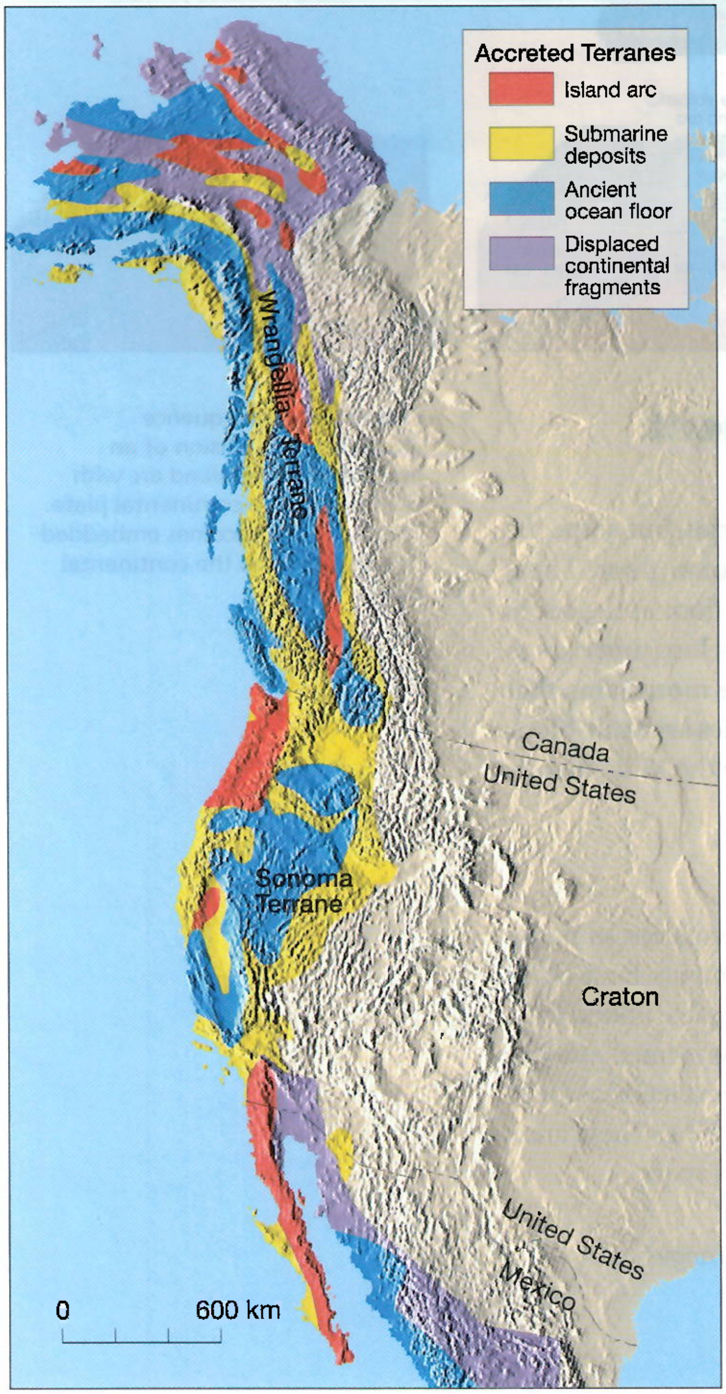


Figure 16 Accretion in Western North America These terranes are thought to have been added to western North America during the past 200 million years.
Interpreting Maps ***What do the areas in blue represent?***

Terranes Geologists refer to accreted crustal blocks as terranes. A **terrane** is any crustal fragment that has a geologic history distinct from that of the adjoining terranes. Terranes come in many shapes and sizes. Some are no larger than volcanic islands, while others are immense, such as the one making up the entire Indian subcontinent. Before their accretion to a continental block, some of the fragments may have been microcontinents similar to the present-day island of Madagascar, located in the Indian Ocean east of Africa. Many others were island arcs like Japan and the Philippines.

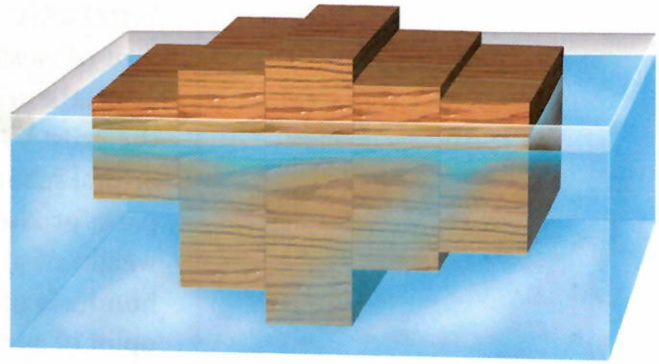
As oceanic plates move, they carry the embedded volcanic island arcs and microcontinents along with them. Eventually a collision between the crustal fragment and the continent occurs. Relatively small crustal pieces are peeled from the oceanic plate at a subduction zone, and thin sheets of the crustal fragment are thrust onto the continental block. This newly added material increases the width and thickness of the continental crust. The material may later be displaced farther inland by the addition of other fragments.

Mountains from Accretion The accretion of larger crustal fragments, such as a mature island arc, may result in a mountain range. These mountain ranges are much smaller than the ones that result from a continent–continent collision. Because of its buoyancy, or ability to float, an island arc will not subduct beneath the continental plate. Instead, it will plow into the continent and deform both blocks.

The idea that mountain building occurs in connection with the accretion of crustal fragments to a continental mass came mainly from studies in western North America. See Figure 16. Areas in the mountains of Alaska and western Canada were found to contain rocks, fossils, and structures that were different from those in surrounding areas. These areas have been accreted to the western margin of North America.

Reading Checkpoint *What is a terrane?*

Principle of Isostasy



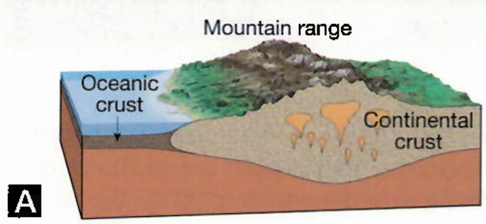
In addition to the horizontal movements of lithospheric plates, gradual up-and-down motions of the crust are seen at many locations around the globe. Although much of this vertical movement occurs along plate margins and is linked to mountain building, some of it is not. The up-and-down motions also occur in the interiors of continents far from plate boundaries.

Earth's crust floats on top of the denser and more flexible rocks of the mantle. The concept of a floating crust in gravitational balance is called **isostasy** (*iso* = equal and *stasis* = standing). One way to understand the concept of isostasy is to think about a series of wooden blocks of different heights floating in water, as shown in Figure 17. Note that the thicker wooden blocks float higher than the thinner blocks. In a similar way, many mountain belts stand high above the surface because they have buoyant (less dense) crustal "roots" that extend deep into the denser mantle. The denser mantle supports the mountains from below.

What would happen if another small block of wood were placed on top of one of the blocks in Figure 17? The combined block would sink until a new isostatic balance was reached. However, the top of the combined block would actually be higher than before, and the bottom would be lower. This process of establishing a new level of gravitational equilibrium is called **isostatic adjustment.**

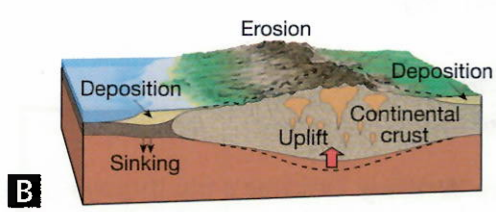
Figure 17 Isostatic Adjustment This drawing illustrates how wooden blocks of different thicknesses float in water. In a similar manner, thick sections of crustal material float higher than thinner crustal slabs. **Inferring** ***Would a denser wooden block float at a higher or lower level?***

Isostatic Adjustment in Mountains

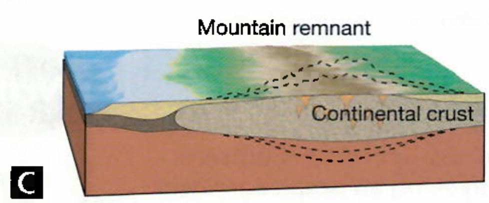


A When mountains are young, the continental crust is thickest.

Figure 18 This sequence illustrates how the combined effect of erosion and isostatic adjustment results in a thinning of the crust in mountainous regions.



B As erosion lowers the mountains, the crust rises in response to the reduced load.



C Erosion and uplift continue until the mountains reach "normal" crustal thickness.

Isostatic Adjustment for Mountains Applying the concept of isostasy, we should expect that when weight is added to the crust, the crust responds by subsiding. Also when weight is removed, the crust will rebound. Evidence of crustal subsidence followed by crustal rebound is provided by the continental ice sheets that covered parts of North America during the Pleistocene epoch. The added weight of a 3-kilometer-thick mass of ice depressed Earth's crust by hundreds of meters. In the 8000 years since the last ice sheet melted, uplift of as much as 330 meters has occurred in Canada's Hudson Bay region, where the ice was thickest.

Reading Checkpoint *How are ice sheets related to isostatic adjustment?*

Crustal buoyancy can account for considerable vertical movement. Most mountain building causes the crust to shorten and thicken. **Because of isostasy, deformed and thickened crust will undergo regional uplift both during mountain building and for a long period afterward.** As the crust rises, the processes of erosion increase, and the deformed rock layers are carved into a mountainous landscape.

As erosion lowers the summits of mountains, the crust will rise in response to the reduced load, as shown in Figure 18 on page 323. The processes of uplifting and erosion will continue until the mountain block reaches "normal" crustal thickness. When this occurs, the mountains will be eroded to near sea level, and the once deeply buried interior of the mountain will be exposed at the surface.

Section 11.3 Assessment

Reviewing Concepts

1. What types of mountains are associated with convergent plate boundaries?
2. What mountains are associated with divergent plate boundaries?
3. How is isostatic adjustment involved in mountain building?
4. How is accretion involved in mountain formation?

Critical Thinking

5. **Comparing and Contrasting** Compare mountain building along an ocean-continent convergent boundary and a continent-continent convergent boundary.
6. **Drawing Conclusions** How does the theory of plate tectonics help explain the existence of marine fossils in sedimentary rocks on top of the Himalayas?
7. **Applying Concepts** How would the accretion of a large microcontinent affect the isostatic adjustment of the region around a mountain range?

Writing in Science

Creative Writing Describe a trip through a mountain range like the Andes that has formed at an ocean-continent convergent boundary.

people and the ENVIRONMENT

The San Andreas Fault System

The San Andreas, the largest fault system in North America, first attracted attention after the 1906 San Francisco earthquake. But this dramatic event is just one of many thousands of earthquakes that have resulted from movements along the San Andreas over the last 29 million years.

The San Andreas fault system, as shown in the map, trends in a northwesterly direction for nearly 1300 kilometers through much of western California. In many places, a linear trough marks the trace of the San Andreas fault. From the air, linear scars, offset stream channels, and elongated ponds mark the location of the fault. On the ground, however, evidence of the fault is harder to find. Some of the most distinctive landforms include long, straight cliffs, narrow ridges, and sag ponds formed by the settling of blocks within the fault zone.

Transform Boundary Mountains

The San Andreas fault is a transform fault boundary separating two crustal plates that move very slowly. The Pacific plate, located to the west, moves northwestward in relation to the North American plate.

Some large blocks of crust within the fault zone are pushed up forming hills or mountains of various sizes. Other blocks are forced down and form depressions called sag ponds. The fault trace is not straight. It has many bends along its length. In one of these major bends, the force of the two sides of the fault moving past one another has caused the uplift of the San Gabriel Mountains north of Los Angeles.

Fault System

Different segments of the San Andreas behave differently. Some portions creep slowly with little noticeable seismic activity. Other segments regularly slip, producing small earthquakes. Still other segments seem to store elastic energy for hundreds of years and rupture in great earthquakes.

Because of the great length and complexity of the San Andreas fault, it is more appropriately referred to as a "fault system." This major fault system consists primarily of the San Andreas fault and several major branches, including the Hayward and Calaveras faults of central California and the San Jacinto and Elsinore faults. By matching rock units across the fault, geologists have determined that the total displacement from earthquakes and creep along the San Andreas is greater than 560 kilometers.

Exploration Lab

Investigating Anticlines and Synclines

The axial plane of a fold is an imaginary plane drawn through the long axis of a fold. The axial plane divides the fold into two halves called limbs as shown in Figure 1. In a symmetrical fold, the limbs are mirror images of each other and move away at the same angle. In an asymmetrical fold, the limbs dip or tilt at different angles. Folds do not continue forever. Where the fold axis dips and is no longer horizontal, the fold is said to be plunging, as shown in Figure 2. A geologic principle known as the principle of superposition states that in most situations with layered rocks, the oldest rocks are at the bottom of the sequence.

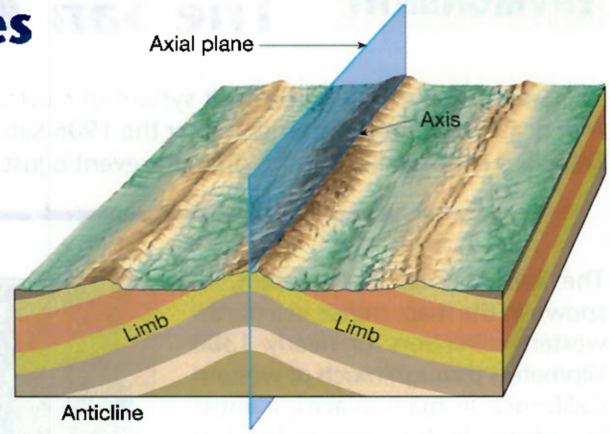


Figure 1 Horizontal Axis

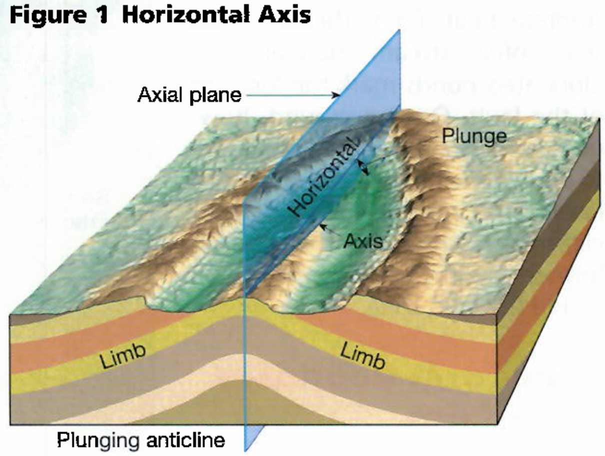


Figure 2 Plunging Axis

Problem

How are rocks oriented in anticlines and synclines?

Materials

- pencil
- protractor
- tracing paper

Skills

Observing, Measuring, Classifying, Interpreting Diagrams

Procedure

1. Study the two diagrams, labeled Fold A and Fold B in Figures 3 and 4.
2. Use a protractor to measure the angles of the rock layers in both limbs of Fold A. Repeat your measurements for both limbs of Fold B. For consistency, measure the angles on both folds at the surface between layers 3 and 4.
3. Use Figures 3 and 4 and Figure 3 on page 310 to determine what types of folds are shown by Fold A and Fold B.
4. Anticlines and synclines are linear features caused by compressional stresses. Two other types of folds—domes and basins—are often nearly circular and result from vertical displacement. Uplift produces domes like those shown in Figure 3. A basin is a downwarped structure, as shown in Figure 4.

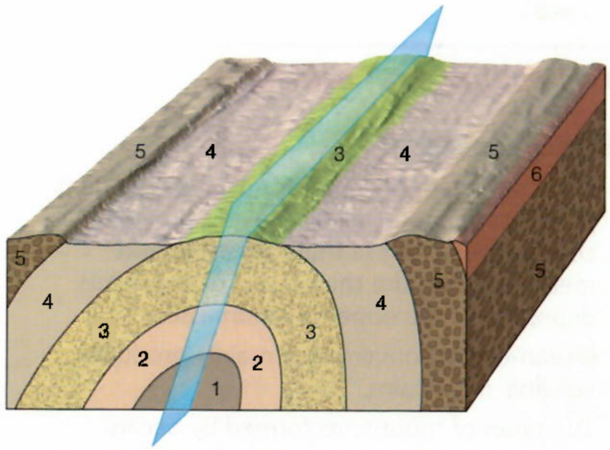


Figure 3 Fold A

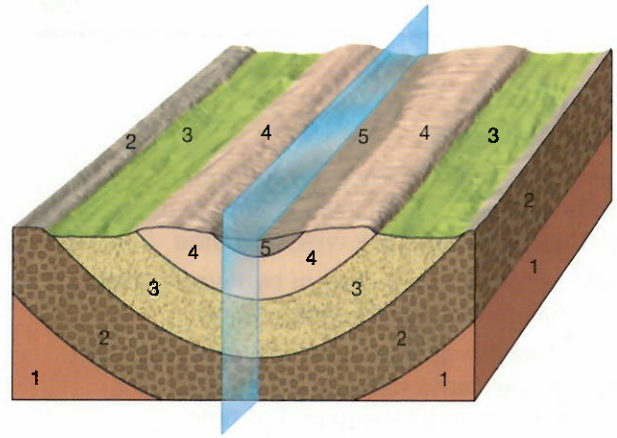
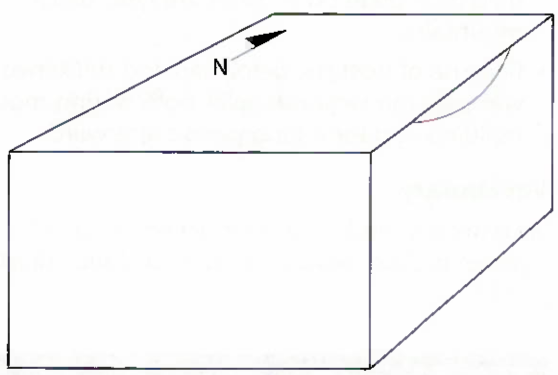


Figure 4 Fold B

5. Use tracing paper to make a copy of the blank block diagram shown below. Complete all three sides of the diagram to show an eroded fold consistent with the rock layer shown on the right side of the block.



Analyze and Conclude

1. **Interpreting Diagrams** What type of fold is shown by Fold A? In what direction do the limbs dip or tilt from the axial plane?
2. **Interpreting Diagrams** What type of fold is shown by Fold B? In what direction do the limbs dip or tilt from the axial plane?
3. **Drawing Conclusions** In Fold A, which rock layer is the oldest shown? Which rock layer is the youngest shown?
4. **Measuring** In Fold A, at what angle are the rock layers in both limbs dipping or tilted?
5. **Drawing Conclusions** In Fold B, which rock layer is the oldest shown? Which rock layer is the youngest shown?
6. **Measuring** In Fold B, at what angle are the rock layers in both limbs dipping or tilted?
7. **Classifying** What type of fold did you draw in the blank block diagram on your tracing paper?
8. **Observing** Is Fold A symmetrical or asymmetrical? Is Fold B symmetrical or asymmetrical?
9. **Observing** Is Fold A plunging or nonplunging? Is Fold B plunging or nonplunging?
10. **Applying Concepts** If you walk away from the axis on an eroded anticline, do the rocks get older or younger? How do the ages of the rocks change as you walk away from the axis in a syncline?

Go Further Use library or Internet sources to research the geologic terms "strike" and "dip." Draw a block diagram showing rocks layers that illustrate these terms. Give a presentation to the class, and explain the terms using your diagram as a visual aid.

CHAPTER 11

Study Guide

11.1 Rock Deformation

Key Concepts

- The factors that influence the strength of a rock and how it will deform include temperature, confining pressure, rock type, and time.
- Rocks deform permanently in two ways: brittle deformation and ductile deformation.
- Forces that are unable to deform rock when first applied may cause rock to flow if the force is maintained over a long period of time.
- The three types of stresses that deform rocks are tensional stress, compressional stress, and shear stress.
- The three main types of folds are anticlines, synclines, and monoclines.
- The major types of faults are normal faults, reverse faults, thrust faults, and strike-slip faults.

Vocabulary

deformation, *p. 308;* stress, *p. 308;* strain, *p. 308;* anticline, *p. 310;* syncline, *p. 310;* monocline, *p. 310;* normal fault, *p. 311;* reverse fault, *p. 312;* thrust fault, *p. 312;* strike-slip fault, *p. 313*

11.2 Types of Mountains

Key Concepts

- Mountains are classified by the dominant processes that have formed them.
- Mountains that are formed primarily by folding are called folded mountains.
- Large-scale normal faults are associated with structures called fault-block mountains.
- Mountains formed by the upwarping of a large block of basement rock are called domed mountains. Downwarped structures having a circular shape are called basins.

Vocabulary

orogenesis, *p. 314;* folded mountain, *p. 314;* fault-block mountain, *p. 315;* graben, *p. 315;* horst, *p. 315*

11.3 Mountain Formation

Key Concepts

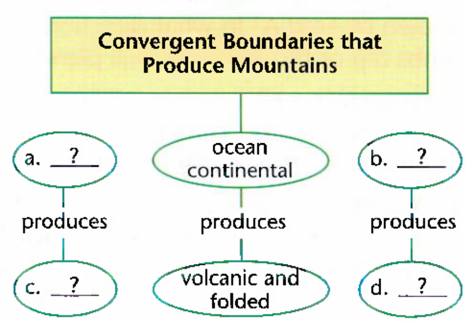
- Most mountain building occurs at convergent plate boundaries. Colliding plates provide the compressional forces that fold, fault, and metamorphose the thick layers of sediments deposited at the edges of landmasses.
- Ocean-ocean convergence mainly produces volcanic mountains.
- The types of mountains formed by ocean-continental convergence are volcanic mountains and folded mountains.
- At a convergent boundary between two continental plates, a collision between the continental fragments will result and form folded mountains.
- The mountains that form along ocean ridges at divergent plate boundaries are fault-block mountains.
- Because of isostasy, deformed and thickened crust will undergo regional uplift both during mountain building and for a long period afterward.

Vocabulary

accretionary wedge, *p. 319;* accretion, *p. 321;* terrane, *p. 322;* isostasy, *p. 323;* isostatic adjustment, *p. 323*

Thinking Visually

Concept Map Copy the concept map onto a sheet of paper. Use information from the chapter to complete it.



CHAPTER 11

Assessment

Interactive textbook with assessment at PHSchool.com

Reviewing Content

Choose the letter that best answers the question or completes the statement.

1. Which one of the following is NOT a form of rock deformation?
- **a.** elastic deformation
- **b.** ductile deformation
- **c.** brittle deformation
- **d.** oblique deformation

2. The two most common types of linear folds are
- **a.** anticlines and synclines.
- **b.** basins and monoclines.
- **c.** domes and synclines.
- **d.** thrusts and anticlines.

3. Orogenesis refers to those processes that produce
- **a.** spreading centers.
- **b.** earthquakes.
- **c.** mountains.
- **d.** subduction zones.

4. Which one of the following is NOT a factor that affects the strength of a rock?
- **a.** time
- **b.** age of the rock
- **c.** rock type
- **d.** temperature

5. The rock surface immediately above a fault surface is commonly called the
- **a.** anticline.
- **b.** foot wall.
- **c.** hanging wall.
- **d.** syncline.

6. Folding is usually the result of what type of stress?
- **a.** tensional stress
- **b.** compressional stress
- **c.** shear stress
- **d.** faulting

7. The collision and joining of crustal fragments to a continent is called
- **a.** subduction.
- **b.** isostasy.
- **c.** accretion.
- **d.** extension.

8. The San Andreas Fault is an example of what type of fault?
- **a.** normal fault
- **b.** strike-slip fault
- **c.** reverse fault
- **d.** thrust fault

9. What type of mountains form at convergent boundaries where two oceanic plates meet?
- **a.** volcanic mountains
- **b.** upwarped mountains
- **c.** folded mountains
- **d.** fault-block mountains

10. What is the most important difference between faults and joints?
- **a.** Joints occur along folds.
- **b.** Joints are often parallel.
- **c.** Joints have no displacement.
- **d.** Joints are always vertical.

Understanding Concepts

11. How does tensional stress deform a body of rock?

12. What is ductile deformation?

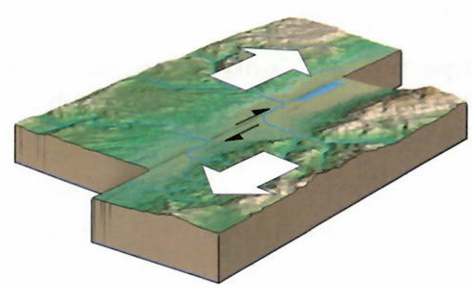
13. How is a syncline different from an anticline?

14. What types of faults are most commonly associated with fault-block mountains?

15. Define graben.

16. What types of faults are most commonly formed by compressional stresses?

Use the diagram below to answer Questions 17–18.



17. What type of fault is shown in the diagram?

18. What type of stress formed the fault shown in the diagram?

Assessment *continued*

19. In the plate tectonics theory, what type of plate boundary is associated with the formation of the Himalayas and Appalachians?

20. What is an accretionary wedge? Briefly describe its formation.

21. Define terrane.

22. Describe folded mountains. Give an example of folded mountains.

23. How do volcanic mountains form at locations that are not near plate boundaries? Give an example.

24. How do the ages of rock layers change as you go from the axial plane of an anticline outwards towards the limbs?

25. What type of stress is most common at divergent boundaries? What type of mountains are most often found at this type of boundary? Give an example.

Critical Thinking

26. **Applying Concepts** How would a period of major erosion affect the isostatic adjustment of a mountain range?

27. **Comparing and Contrasting** Compare normal faults and reverse faults.

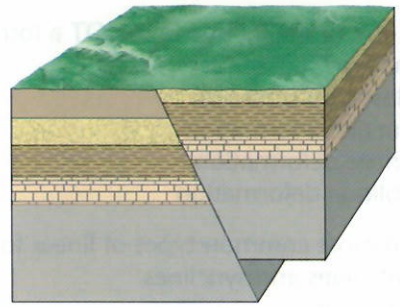
28. **Predicting** What would most likely happen if a continental fragment the size of Greenland was carried by an oceanic plate into a subduction zone along the margin of a continental plate?

29. **Inferring** Why don't anticlines always appear as hills, even though the rocks beneath the surface are folded upward?

30. **Comparing and Contrasting** How are a dome and a basin similar? How are they different?

Analyzing Data

Use the diagram below to answer Questions 31–34.



31. **Inferring** What is the block on the right side of the fault called?

32. **Observing** Describe the movement along the fault.

33. **Interpreting Diagrams** What type of fault is shown in the diagram?

34. **Drawing Conclusions** What type of stress was responsible for forming this fault?

Concepts in Action

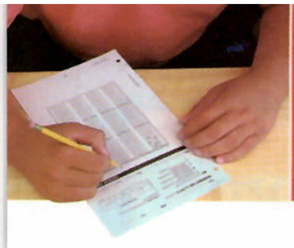
35. **Designing an Experiment** Put together an experiment that models the isostatic adjustment that results from a continent-continent collision and the erosion that takes place on the resulting mountain range.

36. **Hypothesizing** Explain how a slice of ocean crust could be found on top of a peak in the Himalayas.

37. **Writing in Science** Write a paragraph briefly describing the development of volcanic mountains at an oceanic-oceanic convergent boundary.

Performance-Based Assessment

Classifying Use a world physiographic map or a world atlas and Figure 8 in Chapter 9 to classify the following mountains or mountain ranges: Mount Baker in Washington State, the Zagros Mountains in Iran, Mount Fuji in Japan, and the mountains in western Egypt.



Standardized Test Prep

Test-Taking Tip

Avoiding Careless Mistakes
Students often make mistakes when they fail to examine a test question and possible answers thoroughly. Always read a question carefully and underline key words, such as NOT, EXCEPT, or EXCLUDING. After choosing an answer, reread the question to check your selection.

Which of the following is NOT caused by compressional stresses?

(A) thrust faults
(B) anticlines
(C) reverse faults
(D) normal faults

(Answer: D)

Choose the letter that best answers the question or completes the statement.

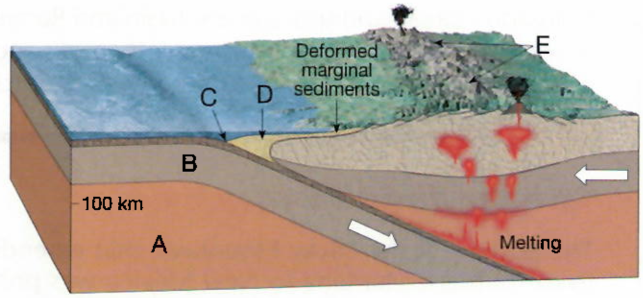
1. A fracture with horizontal displacement parallel to its surface trend is called a
(A) joint.
(B) normal fault.
(C) strike-slip fault.
(D) reverse fault.

2. Compared to the elevation of a thin piece of continental crust, the highest elevation of a thick piece in isostatic balance will be
(A) the same.
(B) higher.
(C) lower.
(D) older.

3. The removal of material by erosion will cause the crust to
(A) subduct.
(B) fold.
(C) rise.
(D) subside.

4. Which of the following are NOT generally associated with convergent margins?
(A) volcanic mountains
(B) folded mountains
(C) thrust faulted mountains
(D) fault-block mountains

Use the diagram below to answer Questions 5–6.



5. What feature is illustrated at the area labeled D in the diagram?
(A) accretionary wedge
(B) subducting continental lithosphere
(C) ocean trench
(D) continental volcanic arc

6. What types of mountains can form at the type of plate boundary illustrated in the diagram?
(A) upwarped mountains and volcanic mountains
(B) volcanic mountains and fault-block mountains
(C) volcanic mountains and folded mountains
(D) folded mountains and upwarped mountains

7. Describe the concept of isostasy.

8. Briefly describe what grabens and horsts are and how they form.

9. What type of tectonic settings are grabens and horsts commonly associated with? Give an example of an area where these structures are found.

understanding EARTH

Mountain Building away from Plate Margins

In the American West, extending from the Front Range of the southern Rocky Mountains across the Colorado Plateau and through the Basin and Range Province, the topography consists of lofty peaks and elevated plateaus. According to the plate tectonics model, you would expect mountain belts to be produced along continental margins and convergent plate boundaries. But this mountainous region extends inland almost 1600 kilometers, far from the nearest plate boundary.

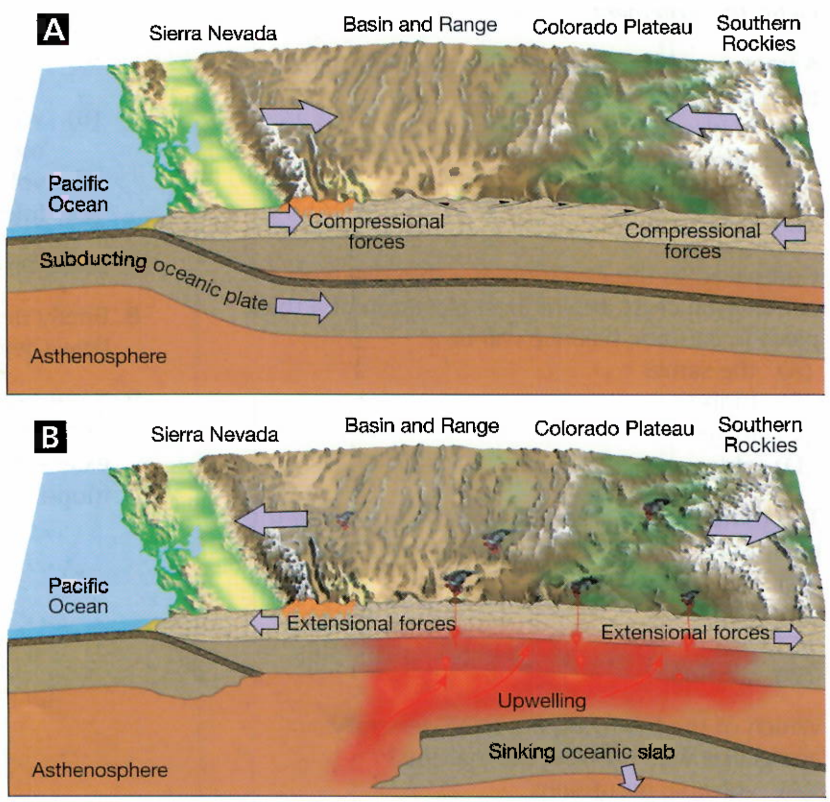
The Laramide Orogeny

The portion of the Rocky Mountains that extends from southern Montana to New Mexico was produced by a period of uplift known as the Laramide Orogeny. This event, which created some of the most picturesque scenery in the United States, peaked about 60 million years ago.

The event that may have triggered the Laramide Orogeny started with the nearly horizontal subduction of the Farallon plate eastward beneath North America. As the diagrams show, this plate extended inland as far as the Black Hills of South Dakota. As the subducted slab scraped beneath the continent, compressional forces started a period of tectonic activity. About 65 million years ago the Farallon plate began to sink into the mantle. As this relatively cool plate gradually separated from the lithosphere above, it was replaced by hot rock that upwelled from the mantle. Thus, according to this scenario, the hot mantle provided the buoyancy to raise the southern Rockies, as well as the Colorado Plateau and the Basin and Range Province.

Basin and Range

In the southern Rockies this event uplifted large blocks of ancient basement rocks along high-angle faults. This produced mountains separated by large basins that became filled with sediment as the mountains eroded. The upwelling that is associated with the Basin and Range Province started about 50 million years ago and remains active today. Here the buoyancy of the warm material caused upwarping and rifting that elongated the overlying crust by 200 to 300 kilometers. The lower crust is ductile and easily stretched. The upper crust, on the other hand, is brittle and deforms by faulting. The extension and faulting broke the uplifted crust, causing individual blocks to shift. The high portions of these tilted blocks make up the mountain ranges, whereas their low areas form the basins, now partially filled with sediment.



A Nearly horizontal subduction of an oceanic plate initiated a period of tectonic activity. **B** Sinking of this oceanic slab allowed for upwelling of hot mantle material that buoyantly raised the crust.

people and the ENVIRONMENT

Damaging Earthquakes East of the Rockies

When you think of earthquakes, you probably think of California and Japan. However, six major earthquakes have occurred in the central and eastern United States since colonial times. Three of these had estimated moment magnitudes of 7.3, 7.0, and 7.5, and they were centered near the Mississippi River Valley in southeastern Missouri. Occurring on December 16, 1811, January 23, 1812, and February 7, 1812, these earthquakes, plus numerous smaller tremors, destroyed the town of New Madrid, Missouri, triggered massive landslides, and caused damage over a six-state area. The course of the Mississippi River was altered, and Tennessee's Reelfoot Lake was enlarged. Chimneys toppled in Cincinnati, Ohio, and Richmond, Virginia, while Boston residents, located 1770 kilometers away, felt the tremor.

Damage to Charleston, South Carolina, caused by the August 31, 1886 earthquake.

Memphis, Tennessee, the largest population center in the New Madrid area today, is located on unconsolidated floodplain deposits. Therefore, buildings are more susceptible to damage than similar structures built on bedrock. It has been estimated that if earthquakes the size of New Madrid events were to strike in the next decade, they would result in casualties in the thousands and damages in tens of billions of dollars.

Damaging earthquakes that occurred in Aurora, Illinois (1909), and Valentine, Texas (1931), remind us that other areas in the central United States are vulnerable.

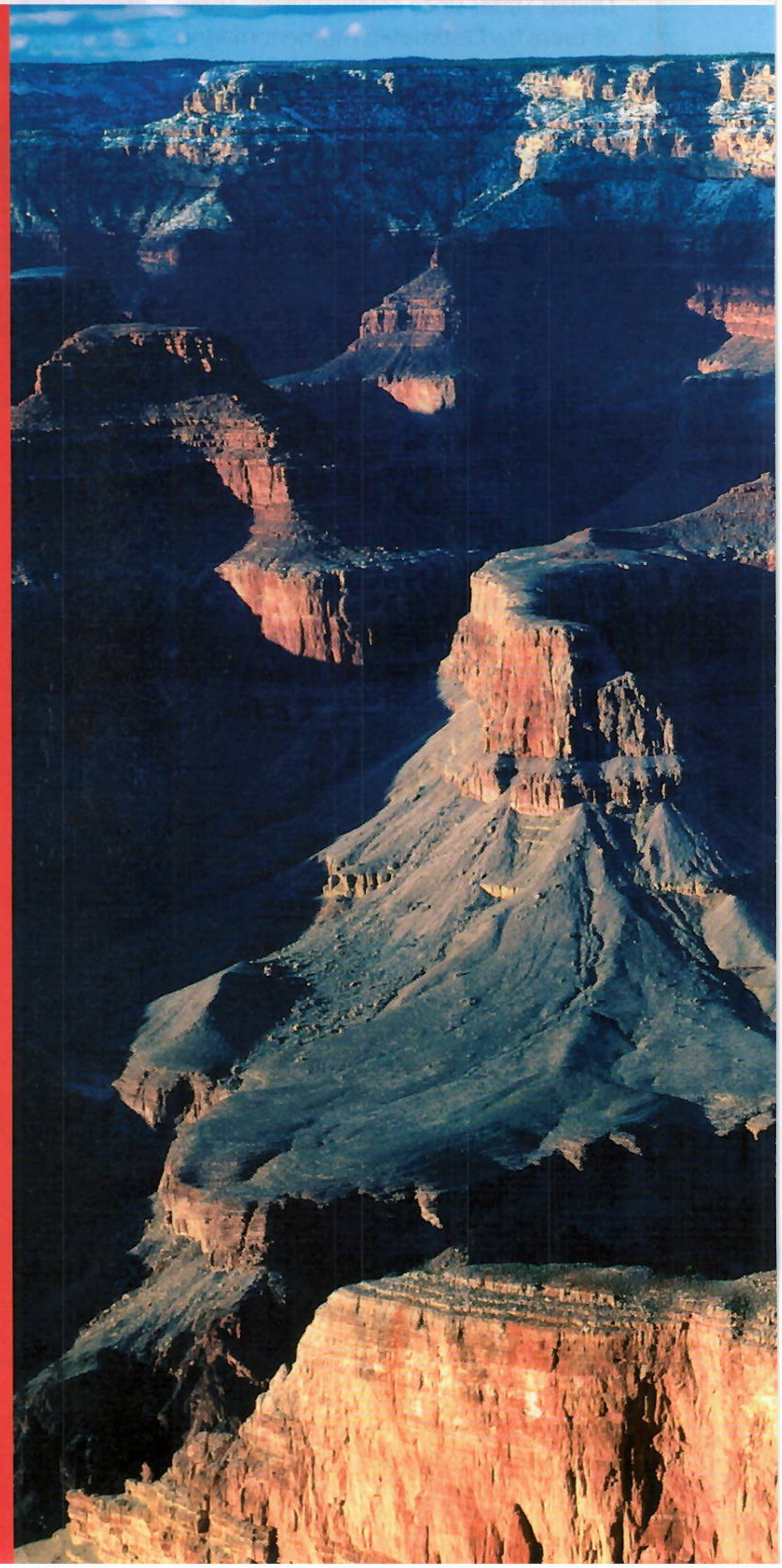
The greatest historical earthquake in the eastern states occurred August 31, 1886, in Charleston, South Carolina. The event, which spanned 1 minute, caused 60 deaths, numerous injuries, and great economic loss within 200 kilometers of Charleston. Within 8 minutes, effects were felt as far away as Chicago and St. Louis, where strong vibrations shook the upper floors of buildings, causing people to rush outdoors. In Charleston alone, over 100 buildings were destroyed, and 90 percent of the remaining structures were damaged. It was difficult to find a chimney still standing as the photograph shows.

Numerous other strong earthquakes have been recorded in the eastern United States. New England and adjacent areas have experienced sizable shocks since colonial times. The first reported earthquake in the Northeast took place in Plymouth, Massachusetts, in 1683, and was followed in 1755 by the destructive Cambridge, Massachusetts, earthquake. Moreover, ever since records have been kept, New York State alone has experienced over 300 earthquakes large enough to be felt.

Earthquakes in the central and eastern United States occur far less frequently than in California. Yet history indicates that the East is vulnerable. Further, these shocks east of the Rockies have generally produced structural damage over a larger area than counterparts of similar magnitude in California. The reason is that the underlying bedrock in the central and eastern United States is older and more rigid. As a result, seismic waves are able to travel greater distances with less weakening than in the western United States. It is estimated that for earthquakes of similar magnitude, the region of maximum ground motion in the East may be up to 10 times larger than in the West. Therefore, the higher rate of earthquake occurrence in the western United States is balanced somewhat by the fact that central and eastern U.S. quakes can damage larger areas.

CHAPTER

12 Geologic Time



CONCEPTS in Action

Exploration Lab
Fossil Occurrence and the Age of Rocks

Understanding Earth
Using Tree Rings to Date and Study the Recent Past

GEODe EARTH SCIENCE
Geologic Time
↳ Relative Dating
Radiometric Dating
Geologic Time Scale

Discovery Channel School **Video Field Trip**
Grand Canyon

Take a field trip to the Grand Canyon with Discovery Channel and get a scenic glimpse of Earth's history. Answer the following questions after watching the video.

1. How was the Grand Canyon formed?
2. What kinds of historic records are contained within the Canyon's walls?

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The rock layers exposed in Arizona's Grand Canyon contain clues to hundreds of millions of years of Earth history. ▶