

Chapter 9

Earthquakes

Earth is not a solid ball. Rather, as you have learned, it has different layers. And Earth's surface is so interesting because the outer shell of Earth—the lithosphere—is broken up into pieces. As you learned in Chapter 8, these pieces—the lithospheric plates—move! Scientists have learned that a great deal of geologic action takes place at the boundaries of these plates. How do scientists know where the plate boundaries are? The quickest and easiest way to find plate boundaries is to plot earthquakes on a map. This chapter is all about earthquakes!



Key Questions

1. *How is an earthquake like a stuck door?*
2. *How are seismic waves like race cars?*
3. *What is the Richter magnitude of the largest earthquake ever recorded?*



9.1 What Is an Earthquake?

Have you ever tried to open a stuck door? You pull and pull and then... Bang! The door flies open with a sound that would wake a statue! This particular experience is similar to how an earthquake happens in Earth's interior. Read on!

Stick-slip motion

Three conditions needed for stick-slip motion The scenario described above illustrates *stick-slip motion* (Figure 9.1), the same motion that causes earthquakes. Three conditions are needed for stick-slip motion:

1. Two objects that are touching each other where at least one of the objects can move.
2. A force, or forces, that will cause the movement.
3. Friction strong enough to temporarily keep the movement from starting. Recall that friction is a resistance to slip that occurs when two objects rub against each other (Figure 9.2).

An everyday example Can you identify these three things in the stuck-door example? The two objects are the door and its frame. The force that will cause movement is you pulling on the door. The friction that made the door stick was probably due to changing moisture in the house. Moisture in a wooden door makes it swell so that it jams in the door frame. You have to pull hard to overcome the friction, so that when the door opens, you hear a loud noise as some of the energy stored is released.

Earthquakes and stick-slip motion An *earthquake* is a form of stick-slip motion. The movement of lithospheric plates over Earth's surface causes earthquakes at plate boundaries and even within plates. However, transform fault boundaries are especially likely to cause earthquakes. Review the different types of plate boundaries in Section 8.3.



Figure 9.1: A stuck door is an example of stick-slip motion.



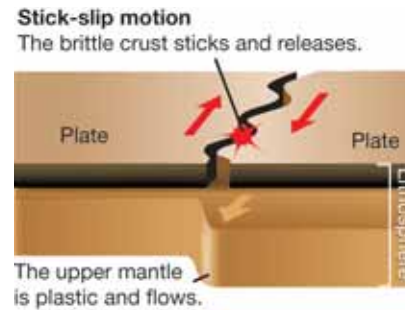
Figure 9.2: There is more friction between a sneaker and a gym floor than between a sock and the gym floor.



What causes earthquakes?

Plates stick together, then break

Lithospheric plates on Earth's surface slide past each other. As this happens, the plates stick together at the brittle crust near the surface of Earth. However, the *plastic* (plastic here means “able to change shape without breaking,” like modeling clay) upper mantle continues to flow underneath. With the crust stuck and the upper mantle moving, the rocks at plate boundaries stretch or compress. As a result, *potential energy* (stored energy) builds in the plate. Just like the stick-slip motion of the stuck door, when the potential energy exceeds the strength of the rock—BANG!—the rock breaks.



Parts of an earthquake

An **earthquake** is the movement of Earth's crust resulting from the release of built-up potential energy between two stuck lithospheric plates. The point below the surface where the rock breaks is called the earthquake **focus**. As soon as the rock breaks, there is movement along the broken surface causing a split in the surface called a **fault**. The energy of the movement is spread by *seismic waves*. The seismic waves from an earthquake are usually strongest at the **epicenter**, the point on the surface right above the focus (Figure 9.3).

Shallow and deep quakes

Earthquakes that result from movement in the crust are called *shallow focus earthquakes* because their focus is less than 50 kilometers below the surface. There are also other kinds of earthquakes. *Deep focus earthquakes* occur at subduction zones when a subducting plate breaks. The focus of a breaking plate may be as deep as 700 kilometers below the surface.

VOCABULARY

earthquake - the movement of Earth's crust resulting from the building up of stored energy between two stuck lithospheric plates.

focus - the point below Earth's surface where a rock breaks and causes an earthquake.

fault - a region on Earth's surface that is split into two pieces.

epicenter - a point on Earth's surface right above the focus of an earthquake.

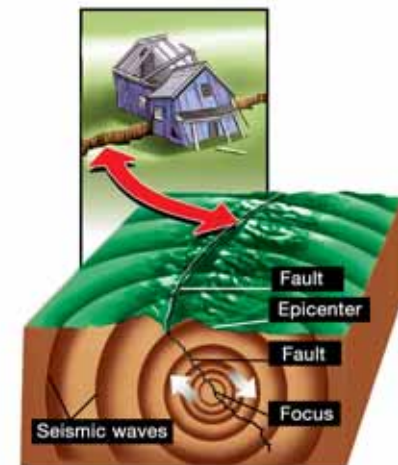


Figure 9.3: The focus, epicenter, and seismic waves of an earthquake occurring at an active fault.

Slickensides, evidence of plate boundaries

What are slickensides?

The photo at the near right shows the effect of rock moving against rock along a fault in the Coronado Heights section of San Francisco. The polished surface is called *slickensides*. At one time, the slickensides were below Earth's surface with another mass of rock pressing against it. The other mass has since weathered away.



Figure 9.4: The edge that is sticking out indicates that the slickensides moved away from you.

Motion of the slickensides

Figure 9.4 is a close-up of the slickensides looking to the right. Look at the edge that is sticking out. This edge indicates that the direction that the slickensides moved in the past was away from you. The rock mass that weathered away would have been to the right of the slickensides. The graphic below at the left gives you a bird's eye view of how these plates moved.

Looking at a transform fault boundary

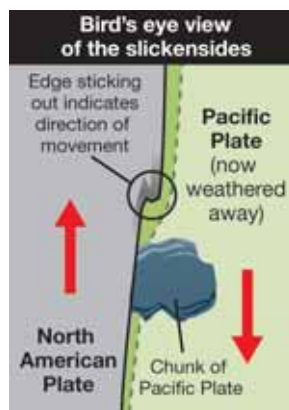


Figure 9.5 is another close-up of the same slickensides, but looking to the left. From this view we can see part of the rock mass that moved against the slickensides rock mass. The blue pen marks the fault that separates the two rock masses. The rock mass to the left of the fault was part of the Pacific Plate. The slickensides rock mass to the right of the fault was part of the North American Plate. This is the location of a transform fault boundary!

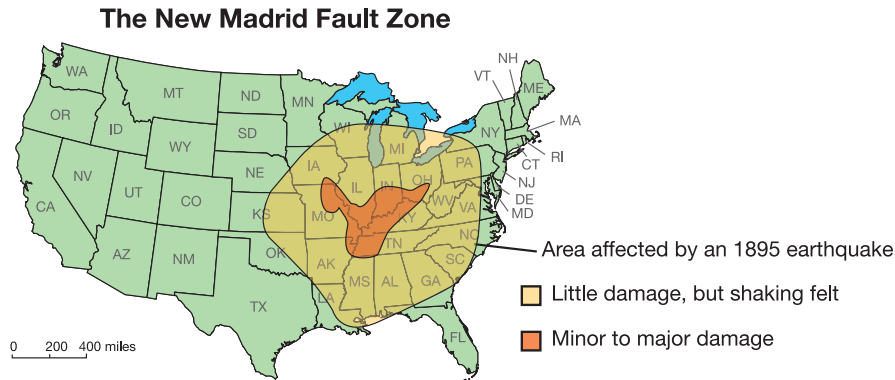


Figure 9.5: A transform fault boundary between the Pacific Plate to the left and the North American Plate to the right (marked by the photographer's blue pen).



The nature of plates

Boundaries within boundaries Throughout Earth’s history, lithospheric plates have been torn apart, added to, and joined with other plates. As a result of this reshaping, there are old plate boundaries inside of the plate boundaries we see today. These old boundaries are now faults inside the plates. The New Madrid Fault, for example, is a fault zone within the North American Plate. This zone is an “old” plate boundary that can break when the North American crust flexes as a result of plate tectonic activity. This can result in a major earthquake, such as the New Madrid event in 1895.



Plates as grocery carts A cracked shell on a hard-boiled egg is similar to lithospheric plates on Earth’s surface (Figure 9.6). However, a line of grocery carts is a better analogy of a lithospheric plate because it demonstrates movement of the plate. (Figure 9.7). You’ve seen people pushing long lines of grocery carts around supermarket parking lots. The line of carts moves along as a single unit, but there are small “wiggles” between each cart. In the same way, a plate moves across Earth’s surface as a single unit. However, a part of the plate may “wobble” at one of its old faults inside the more recent plate boundaries. This kind of movement is what causes earthquakes in the interior sections of plates, far away from plate boundaries.



Figure 9.6: Are lithospheric plates on Earth like pieces of eggshell on a hard-boiled egg?



Figure 9.7: A moving line of grocery carts is like a moving lithospheric plate.

Lithospheric plates have many sections

Plates have sections Transform fault boundaries are much longer than the longest area affected by any earthquake. This tells us that although a plate may be moving as a single unit, its boundaries act as though they were made of many sections like the line of carts.

A plate is like a long line of grocery carts When one end of the shopping cart line is pushed, the carts on the other end of the line remain still for a moment. It takes some time for the first cart to push the second, the second to push the next, and so on, until the last cart starts to move. Since a plate is thousands of kilometers across, it can take a long time for movement on one end of the plate to affect the section furthest away.

The San Andreas Fault For example, parts of the San Andreas Fault can be stuck together and other parts may creep along at any given time (Figure 9.8). Each section of a plate may move a little earlier or later than another. An earthquake happens each time a plate section moves, but only in the section that moved.

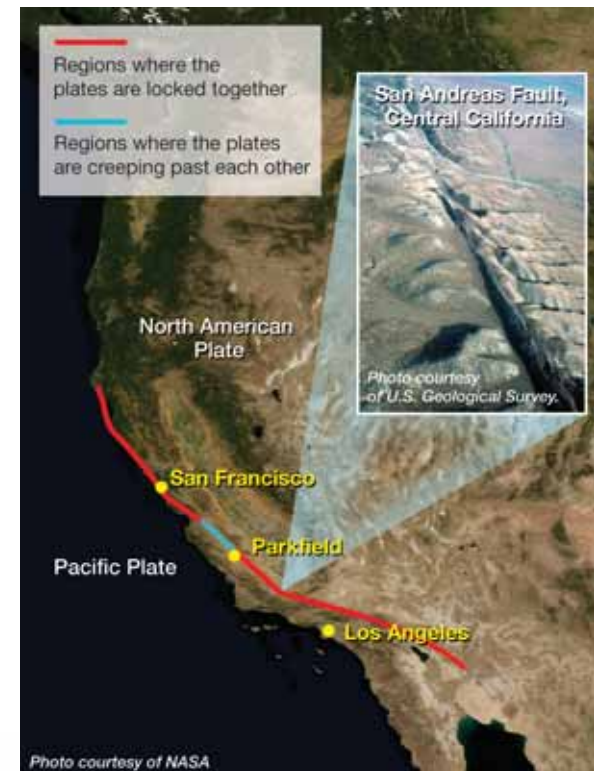
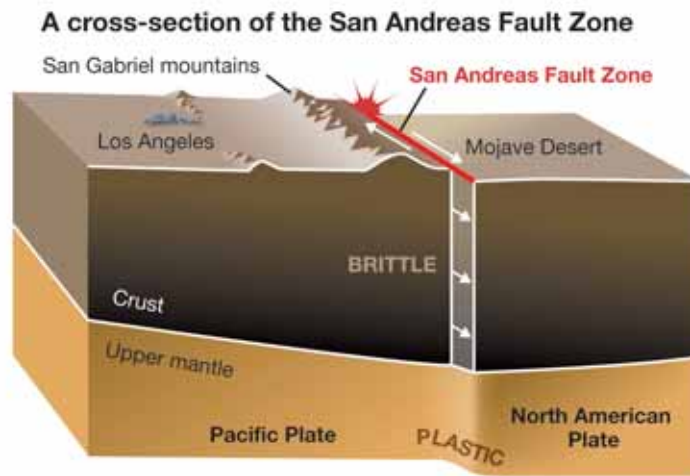


Figure 9.8: The San Andreas Fault in California. The graphic illustrates that some parts of the fault are locked together and some parts creep along at any given time.



When do earthquakes happen?

Earthquakes release energy The release of built-up potential energy causes earthquakes. In this sense, an earthquake is a stress reliever for a lithospheric plate! However, once a quake occurs, potential energy builds up again.

Earthquake frequency and strength Imagine two sections along the same transform fault boundary. Both sections should move at the same rate (like a single line of grocery carts). Let's say the first section has frequent earthquakes (a few times a year). Potential energy cannot build up when earthquakes happen frequently. Therefore, not much energy is released when an earthquake occurs. Earthquakes are mild in the first section. Now, let's say the second section has earthquakes only once every 20 years. In the time between earthquakes, a great deal of potential energy builds. Therefore, earthquakes in this section are more violent when they occur.

One earthquake may trigger others Imagine that it has been a long time since an earthquake has released the potential energy in both sections. Then, an earthquake occurs in the first section, reducing its potential energy. The movement of the first section may increase the stress and built-up potential energy in the second section. This added stress may be enough to trigger a new earthquake in the second section.

What happens during an earthquake? A strong burst of shaking occurs during an earthquake. The second longest ever recorded earthquake occurred in 1964 in Alaska and lasted for four minutes (Figure 9.9). *Foreshocks* are small bursts of shaking that may precede a large earthquake. Foreshocks can occur days before the earthquake hits, or just minutes before. *Aftershocks* are small tremors that follow an earthquake, lasting for hours or even days after the earthquake. The time between foreshocks gets shorter just before an earthquake. Similarly, aftershocks occur further apart as time passes after an earthquake.



Figure 9.9: *Top image: The 1964 Alaska earthquake was the longest ever recorded and the largest ever recorded in the United States. The red dot shows the epicenter of the earthquake. The pink region indicates the area affected by the quake. Bottom image: Part of a street and sidewalk dropped 11 feet below the original level due to the 1964 Alaska earthquake!*

9.1 Section Review

1. What is the name of the kind of motion that causes an earthquake?
 - a. Give an everyday example of this kind of motion.
 - b. What three conditions are needed for this motion?
2. Lithospheric plates have two parts. Name the parts and describe how they are different from each other.
3. What causes lithospheric plates to build up pressure and finally “give” along transform faults?
4. What is the difference between the focus and the epicenter of an earthquake?
5. How is a lithospheric plate like a long line of moving grocery carts?
6. The polished surfaces of rock which are a result of rock moving against rock along a fault are known as _____.
7. Most earthquakes occur at plate boundaries. However, some occur inside plate boundaries in the interior of a lithospheric plate. Give the explanation for this from the reading.
8. Is the movement of a plate uniform or uneven along its boundary? Explain your answer.
9. Where are earthquakes generally more violent: (a) along a boundary where tension is released frequently, or (b) along a boundary where tension builds up over a greater period of time?
10. From the reading, state how can one earthquake cause another earthquake?
11. Put these events in order and then describe each: aftershock, foreshock, and earthquake.



In this section you learned about the Coronado Heights slickensides in San Francisco, California. Research slickensides to learn of other locations where you could find these geologic formations.



Who named the San Andreas Fault?

Trivia is information that doesn't matter very much but it can be interesting. For example, it may be more important to know that the San Andreas Fault is a transform plate boundary rather than to know who named this fault.

Make a list of 10 trivia facts about earthquakes and/or plate tectonics. You will need to do some research to find trivia about these topics.



9.2 Seismic Waves

An earthquake rapidly converts a large amount of built-up potential energy into the energy of motion. This energy of motion is spread by seismic waves. These waves start underground at the earthquake focus and radiate in all directions. In this section, you will learn more about these special waves.

Body and surface waves

Body waves Seismic waves that travel through Earth's interior are called **body waves**. The two main kinds of body waves are P-waves and S-waves (Figure 9.10). You read about these waves in Chapter 7.

Review of P-waves and S-waves P-waves (primary waves) are faster. These waves push and pull on rock as they travel. The rock moves in the same direction that the wave moves. After an earthquake, P-waves arrive first at any location. S-waves (secondary waves) travel more slowly and arrive after the P-waves. S-waves cause the rock to move in a side-to-side motion. The side-to-side motion is across (perpendicular to) the direction of the traveling wave. Although an S-wave is slower than a P-wave, both are many times faster than the speed of sound.

How materials affect seismic waves The speed of P- and S-waves is affected by the properties of the rock they pass through. They travel faster in cool material and slower in hot material. Seismic waves may bend or be reflected when they contact different materials. Liquid—like the liquid outer core of Earth—acts as a barrier to S-waves. P-waves pass through liquid.

Surface waves Waves on the surface, or body waves that reach the surface, are called **surface waves**. Surface waves are slower than the slowest body wave, but they are the waves that cause the most damage. Surface waves can move up and down, almost like waves on the ocean. They can also move from side to side, often causing buildings to collapse.

VOCABULARY

body waves - seismic waves that travel through the interior of Earth.

surface waves - body waves that reach and travel along Earth's surface.

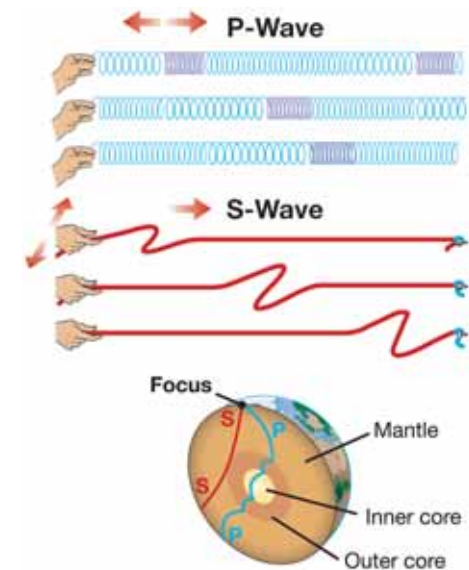
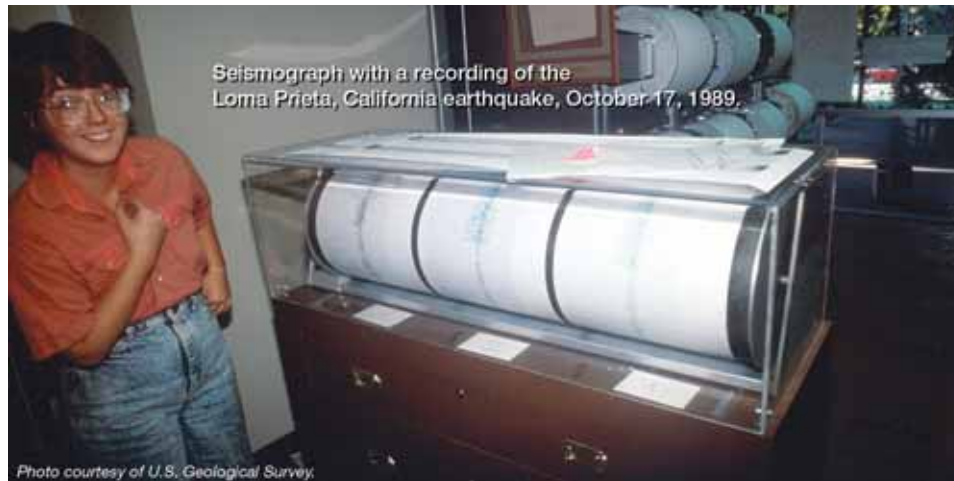


Figure 9.10: P-waves and S-waves are types of body waves.

Measuring seismic waves

Recording seismic waves People who record and interpret seismic waves are called *seismologists*. Seismic waves are recorded and measured by an instrument called a **seismograph**. Seismographs show the kinds of waves that occur, their strength, and the time that they arrive at the instrument. Seismographs are located all around the world at seismic stations on land, and in special locations in the oceans.

The order of seismic waves In the image below, seismic waves of the Loma Prieta earthquake are recorded on paper wrapped around a large drum. Figure 9.11 shows that seismic waves can also be recorded by computers.



Looking inside Earth Seismologists study the interior of our planet by observing the way seismic waves travel through Earth. This process is similar to using X rays to create a CAT scan of the interior of a human body.

Zeroing in on Earth's features Seismographs can be set up to provide detail about a small area. For example, multiple seismographs have been used to study a particular fault (like the San Andreas Fault), the deep lower mantle convection currents, and other features of Earth's interior.

VOCABULARY

seismograph - an instrument that measures and records seismic waves.

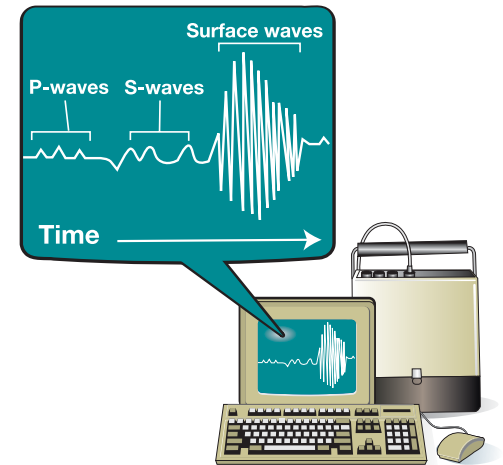


Figure 9.11: After an earthquake occurs, the first seismic waves recorded will be P-waves. S-waves are recorded next, followed by the surface waves. P-waves travel faster than S-waves, and both travel faster than surface waves. This means that P-waves arrive at a seismic station before S-waves, and both arrive before surface waves. The data recorded about an earthquake is used to help locate the epicenter of the quake.



Locating an earthquake epicenter

An analogy All cars start at the starting line on a race track. After a while, the fastest car gets ahead of the slowest car. In a quarter-mile race, the track is so short that fast and slow cars are often just fractions of a second apart. In a long race, like the Indianapolis 500, the cars might be minutes apart. The time difference between slow and fast cars is related to the length of the race track (Figure 9.12).

Seismic waves are like cars in a race Like fast and slow race cars, P- and S-waves have different speeds. Seismologists use the difference in the arrival time of these waves to calculate the distance to the epicenter from the seismic station.

Review Whenever an earthquake occurs, seismologists want to determine the location of the epicenter. Recall that an earthquake starts underground at a focus. The epicenter is the location on Earth's surface above the focus (review Figure 9.3). Seismic waves radiate from the focus after the earthquake.

Three seismic stations are needed Seismic stations can accurately determine the times of body wave arrival. However, a single station cannot determine the exact direction from which the waves arrived. At least three stations are needed to complete the locating process. First, one station draws a circle around its location on a map. The epicenter distance sets the size of the circle. The edge of this circle represents all of the possible locations of the earthquake from that station. Next, the other two stations add their circles to the same map. The second circle will cross the first circle at two points. When the third circle is added, all three circles will cross at only one point, the location of the epicenter (Figure 9.13).

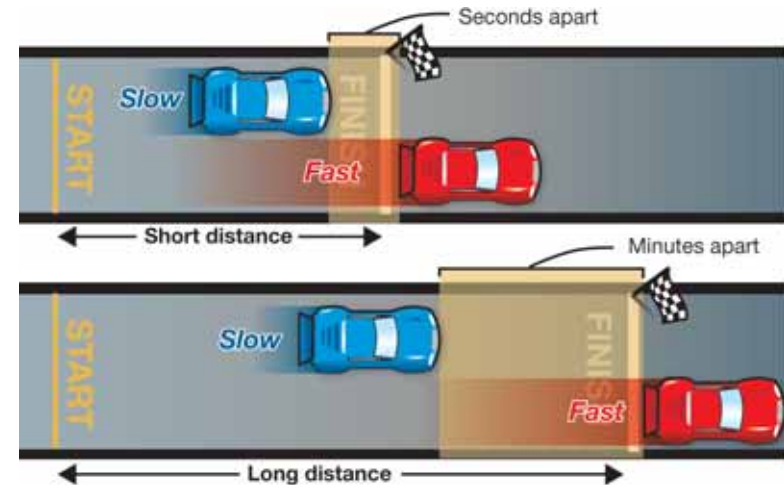


Figure 9.12: The time difference between slow and fast cars is related to the length of the race track.

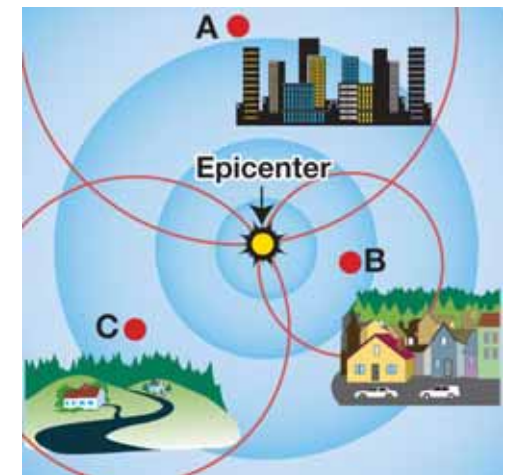
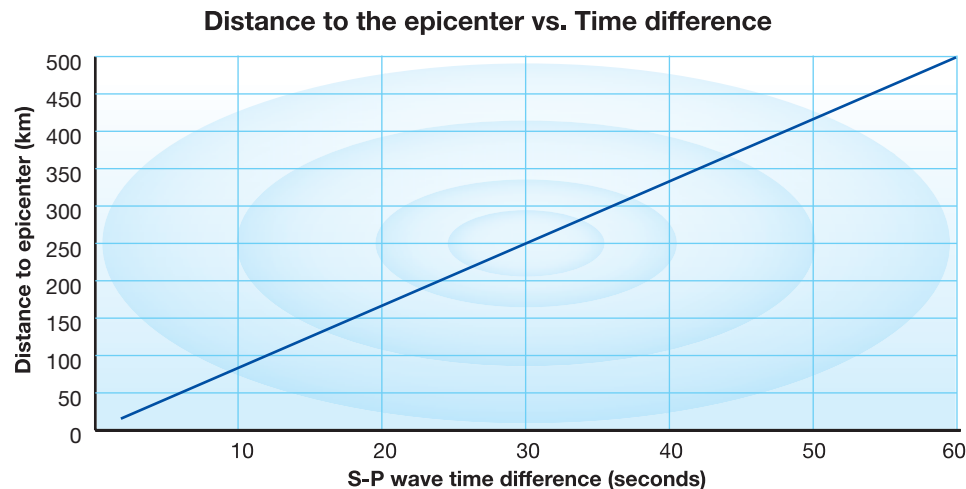


Figure 9.13: An epicenter is identified using data collected from seismographic stations in three different locations.

How to determine the distance to an epicenter

Today, seismologists use computers to determine the distance to an epicenter. However, locating an epicenter can also be done with paper and a pencil. Follow these steps and you will be able to determine the location of an epicenter.

1. Identify three seismic stations and locate them on a map.
2. Determine the time difference between the arrival of the S-waves and the P-waves at each station. See Figure 9.14 for sample data.
3. Use the seismic time-distance graph below to convert the time differences into distances to the epicenter.



4. Use the distance scale on your map to set a geometric compass so that the space between the point and pencil on the compass is proportional to the distances that you found in Step 3.
5. Draw a circle around each seismic station location.

Find the point where all three circles cross (Figure 9.15).

Sometimes the crossed circles make a small triangle, not a single point. The center of the triangle is the epicenter.

Station name	Arrival time difference between P- and S-waves	Distance to epicenter
1	10 seconds	80 km
2	50 seconds	420 km
3	30 seconds	250 km

Figure 9.14: Sample data for finding an epicenter.

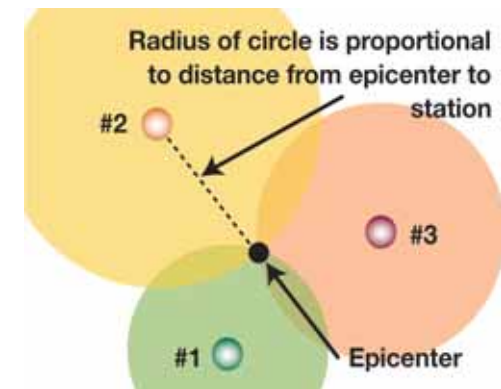


Figure 9.15: The epicenter is located at the point where the circles around three seismic stations cross. The radius of each circle is the distance to the epicenter.



9.2 Section Review

1. What is the difference between these two kinds of seismic waves: body waves and surface waves?
2. This seismic wave is the fastest type of body wave. This wave pushes and pulls rock in the direction the wave travels. This is called a _____ wave.
3. This seismic wave is slower than a P-wave, but still faster than the speed of sound. It moves rock in a side-to-side motion that is perpendicular to the direction of the moving wave. This is called a _____ wave.
4. Which type of seismic waves—body or surface—tend to cause the most damage during an earthquake?
5. As a seismic wave travels through Earth, it encounters different materials. List what can happen to a seismic wave as it moves from one material to another.
6. What information is gained about an earthquake from using a seismograph?
7. How would a seismologist use seismographs to study a small part of a fault zone?
8. What is measured to determine the location of an epicenter?
9. At least how many data stations are needed to find the epicenter of an earthquake?
10. S-waves from a quake arrive at a seismic station 40 seconds after the arrival of P-waves. How far away is the epicenter?
11. The distance scale on a map is 1 centimeter = 10 kilometers. The distance from a seismic station to the epicenter of an earthquake is 50 kilometers. To locate the epicenter, what would be the radius of the circle that is drawn around this station on a map?



STUDY SKILLS

Get to know your waves

You have learned about different seismic waves: surface waves, and body waves (P- and S-waves). How are you going to remember the differences? Here's an idea.

1. **List:** For each type of wave, make a list of words and phrases that describe the wave.
2. **Make a study tool:** Combine the three lists into a table, poster, diagram, concept map, or in another creative way.
3. **Show and tell:** Show your waves study tool to classmates, family, and friends and tell them about it!



MY JOURNAL

How are seismic waves like race cars?

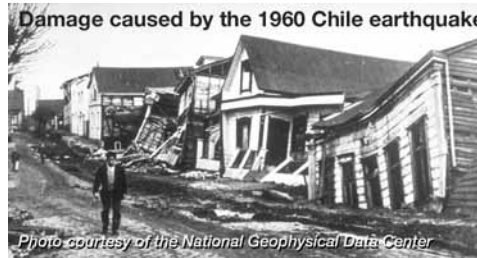
In your own words, write a paragraph that answers this question. Use illustrations to explain your answer.

9.3 Measuring Earthquakes

There are two related measurements taken during and after an earthquake—the energy released and the damage caused. Low magnitude earthquakes are less likely to cause as much damage as high magnitude earthquakes. But, if a high magnitude earthquake occurred in a desert, there would be less damage than if a low magnitude earthquake occurred in a heavily populated city. In this section, you will learn how earthquakes are measured and compared.

Measuring the magnitude of an earthquake

The Richter scale The **Richter scale** rates earthquakes according to the size of the seismic waves recorded on a seismograph. The seismic wave energy increases ten times for each Richter number change. The Richter scale assumes that the measurements were taken near the earthquake epicenter. The largest earthquake recorded occurred in Chile in 1960. It was off the Richter scale; seismologists estimated this quake to be 9.5.



The Moment Magnitude scale Both the Richter scale and the **Moment Magnitude scale** rate the energy of an earthquake. The Moment Magnitude scale rates the total energy released by an earthquake. This scale can be used at locations that are close to and far away from an epicenter. The numbers on this scale combine energy ratings and descriptions of rock movements. The Richter and Moment Magnitude scales are about the same up to a rating of 5. However, when earthquakes are larger, seismologists tend to use the more descriptive Moment Magnitude scale.

VOCABULARY

Richter scale - a scale that rates earthquakes according to the size of the seismic waves.

Moment Magnitude scale - a scale that rates the total energy released by earthquakes.

The Richter scale		
Level	Magnitude	Effects
Micro	Less than 2.0	Barely felt
Very minor	2.0 - 2.9	Recorded but not felt by most people
Minor	3.0 - 3.9	Little damage but felt by people
Light	4.0 - 4.9	No serious damage, objects shake
Moderate	5.0 - 5.9	Major damage to poorly-designed buildings
Strong	6.0 - 6.9	Serious damage over a 100-mile area or less
Major	7.0 - 7.9	Serious damage over a larger area
Great	8.0 - 8.9	Serious damage over several hundred miles
Rare great	9.0 or greater	Serious damage over several thousand miles

Figure 9.16: The Richter scale with a description of the effects at each magnitude.



Measuring the damage caused by an earthquake

The Mercalli Intensity scale The **Mercalli Intensity scale** has 12 descriptive categories. Each category is a rating of the damage suffered by buildings, the ground, and people. Because earthquake damage can be different from place to place, a single earthquake may have different Mercalli numbers in different locations (Figure 9.17).

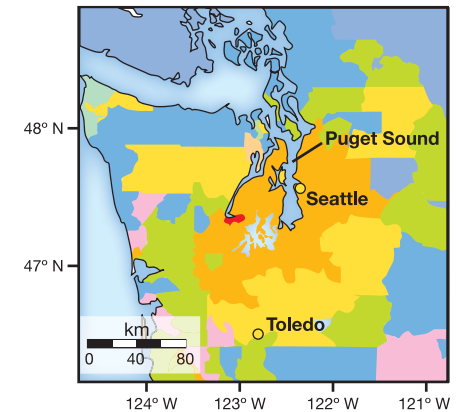
VOCABULARY

Mercalli Intensity scale - a scale that rates the damage suffered by buildings, the ground, and people during an earthquake.

Table 9.1: Mercalli Intensity Scale.

Mercalli Intensity	Characteristic Effects	Approximate Richter Magnitude
I. Instrumental	Not felt	1
II. Just perceptible	Felt by only a few people, especially on upper floors of tall buildings	1.5
III. Slight	Felt by people lying down, seated on a hard surface, or in the upper stories of tall buildings	2
IV. Perceptible	Felt indoors by many, by few outside	3
V. Rather strong	Generally felt by everyone; sleeping people may be awakened	4
VI. Strong	Trees sway, chandeliers swing, bells ring, some damage from falling objects	5
VII. Very strong	General alarm; walls and plaster crack	5.5
VIII. Destructive	Felt in moving vehicles; chimneys collapse; poorly constructed buildings seriously damaged	6
IX. Ruinous	Some houses collapse; pipes break	6.5
X. Disastrous	Obvious ground cracks; railroad tracks bent; some landslides on steep hillsides	7
XI. Very disastrous	Few buildings survive; bridges damaged or destroyed; all services interrupted (electrical, water, sewage, railroad); severe landslides	7.5
XII. Catastrophic	Total destruction; objects thrown into the air; river courses and topography altered	8

Sample intensity map for an earthquake in Washington state



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
Shaking	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
Damage	None	None	None	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy

Figure 9.17: A sample intensity map for a single earthquake in Washington state. From the map, you can see that the earthquake was a category IX on the Mercalli Intensity scale in a very small area. Most of the surrounding areas experienced less shaking and damage.

Where do earthquakes occur?

Boundaries of plates When earthquake locations are plotted for many years, a map like the one below (at the lower left) can be created. Earthquakes commonly occur at the boundaries of lithospheric plates. Earthquakes occur less commonly at faults that are inside plate boundaries. Note that in Figure 9.18, the earthquakes along the converging plates do not form a neat line. This is because plate boundaries tend to be *zones* of seismic activity. In particular, faults at transform fault boundaries, like the San Andreas Fault in Figure 9.19, have many branches. These fault branches form an *earthquake zone*.

Earthquakes along a transform fault boundary The California coast lies along the San Andreas Fault (Figure 9.19). This famous fault passes right through San Francisco and part of Los Angeles. These metropolitan areas have a combined population of over ten million people. San Francisco

has experienced several severe earthquakes and many smaller ones. The earthquake of 1906, together with the fires that it caused, destroyed much of the city. The damage caused by the earthquake was probably 8 or 9 on the Mercalli scale. Future earthquakes must be expected here because the fault that lies under the city is still active.

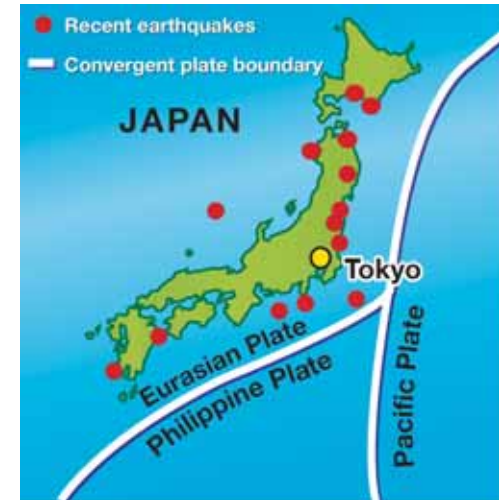


Figure 9.18: These moderate earthquakes in Japan are associated with subduction occurring at plate boundaries.



Figure 9.19: The California coast lies along the San Andreas Fault.



9.3 Section Review

1. What two measurements are taken during and after an earthquake?
2. Compare and contrast the three earthquake measuring scales discussed in this section.
3. How many times stronger is a 3.0 magnitude earthquake compared to a 2.0 magnitude earthquake on the Richter scale?
4. A friend tells you that he once experienced an earthquake. He said that he witnessed books and other objects falling off his bookcase.
 - a. What was the magnitude of this earthquake on the Mercalli Intensity scale?
 - b. What was the most likely magnitude of this earthquake on the Richter scale?
5. The largest earthquake ever recorded occurred in Chile which is on the west coast of South America. Why are earthquakes to be expected in Chile? Explain your answer.
6. Why is it possible for a single earthquake to have different Mercalli Intensity scale ratings in different locations?
7. Why don't earthquakes follow plate boundary lines exactly?
8. In the text, you read that future earthquakes will probably occur near the San Andreas Fault because the fault is still "active." What do you think it means to say a fault is "active?"



CHALLENGE

Earthquakes inside plate boundaries

Here are two descriptions of earthquakes that occurred inside plate boundaries. Pick one and find out more information about the quake. Imagine you are an investigative reporter. Write a paragraph about each quake. Read your paragraph to the class as if you were reporting on the quake after it has happened.

(1) The New Madrid Fault is a 250-mile long fault located in the Midwest. Very strong earthquakes in 1811 and 1812 destroyed most of the town of New Madrid, Missouri.

(2) You probably don't think of New England as an earthquake area. But in 1755, a strong earthquake struck colonial Boston and destroyed many homes. The damage was greatest north of Boston and the earthquake was felt as far north as Montreal, Canada.



2004 Indian Ocean Earthquake and Tsunami



December 26, 2004



January 1, 2004

The top satellite picture of Kalutara, Sri Lanka was taken about an hour after the first tsunami wave hit on December 26, 2004. Water is rushing back out to sea after inundating the land. The lower picture shows what the same area looked like under normal conditions in January 2004.

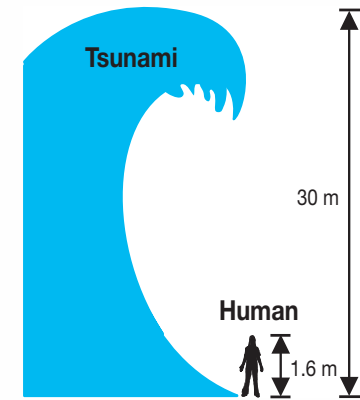
Tilly Smith probably never imagined what she learned in geography class would help save lives. When the Indian Ocean tsunami hit on December 26, 2004, Tilly and her family were vacationing at Miakho Beach in Phuket, Thailand. Tilly, 10 years old, noticed something strange happening on the beach. The water at the beach suddenly went away. In the distance, she could see boats bouncing wildly and the water bubbling. The ocean water returned quickly and kept coming onto

shore. Tilly screamed for her family to leave the beach right away. Her parents warned others. Due to her knowledge of tsunami early warning signs, the girl from England saved other tourists on the beach that day.

What is a tsunami?

Tilly had just learned that underwater earthquakes could cause tsunamis. *Tsunami* is a Japanese word meaning “harbor wave.” Underwater earthquakes, landslides, and volcanoes may cause tsunamis. Not every earthquake leads to a tsunami. Yet, large ocean earthquakes that move the sea floor up and down cause many tsunamis.

The size of a tsunami depends on many factors. How large is the earthquake? Where does the earthquake occur? How much of the sea floor moves up and down? How deep is the ocean water where the earthquake occurs? In the deep ocean, tsunamis may be only several feet high. Often ships at sea never feel a tsunami. This is not the case as the tsunami travels toward shore and shallower water. The amount of water begins to build. Wave height increases as they approach land. Some waves may travel 800-1,000 kilometers per hour (500-600 miles per hour) and be as high as 15 to 30 meters (50 to 100 feet).



The Indian Ocean tsunami

The Indian Ocean tsunami may be one of the deadliest natural disasters in modern history. Officials believe over 275,000 people died. The final number of deaths may never be known. The US Geological Survey originally reported the earthquake at a 9.0 magnitude. This is the strongest in the world since 1964 and the fourth largest since 1900. Scientists used data from around the world to revise the earthquake to a 9.3 magnitude. This would make it the second largest earthquake since the 9.5 magnitude in Chile in 1960.

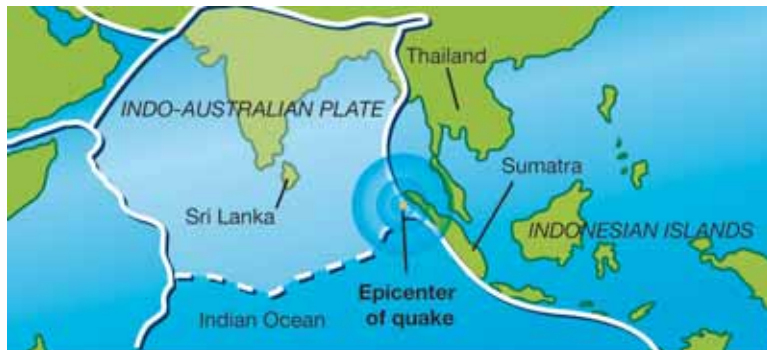
Earth's surface is made up of plates that are constantly in motion. Plates meet one another along plate boundaries. Pressure along these boundaries causes rock to break creating earthquakes.

During the Indian Ocean earthquake, 1,200 kilometers (750 miles) of the plate boundary slipped when the India Plate (part of the Indo-Australian Plate) slid under the

Burma Plate (part of the Eurasian Plate). That is about 400 kilometers (250 miles) more than the distance between San Diego and San Francisco! The seabed rose over six feet causing huge tsunami waves.

Imagine a plastic squeeze bottle filled to the top with water. As you squeeze the container the water spills out over the top. The upward motion of the earthquake displaced an enormous amount of water similar to the squeeze bottle. This displacement of water created the tsunami that flooded the coastlines.

The Indian Ocean earthquake occurred off the west coast of Sumatra, an Indonesian island. Waves reached 20 to 30 meters (65 to 100 feet) high. The tsunami destroyed the shores of Indonesia, Sri Lanka, and Thailand. The tsunami even traveled as far as Africa, nearly 8,000 kilometers (5000 miles) from the center of the earthquake.



The tsunami waves did not start from one central location, but occurred along the entire 750 miles of fault line. That is why the waves affected so many areas of the world.

Indian Ocean tsunami warning system

Why did so many people die from the tsunami? Tsunamis are rare in the Indian Ocean and a warning system was not in place. The last major tsunami in the region was caused by the 1883 volcanic eruption of Krakatoa in Indonesia.

People were not aware of the signs of a tsunami—a strong earthquake in the area and a quick rise or fall in water levels by the coast.

Historically, tsunamis usually happen in the Pacific Ocean where many earthquakes occur. In the Pacific, there are two warning centers monitoring the area: the Alaska and the Pacific Tsunami Warning Centers. The Alaska Tsunami Warning Center includes the west coast of the United States and Canada. The Pacific Tsunami Warning Center covers Hawaii and all other Pacific areas. The centers monitor the size and location of earthquakes in the ocean. If a tsunami is possible, the center sends out a warning estimating when the tsunami will reach land. This allows coastal areas to have time to evacuate.



One month after the Indian Ocean tsunami, the United Nations recommended a warning system for the Indian Ocean. Plans are in place to have as many as 27 centers created, one for each Indian Ocean country. In May of 2005, Thailand opened a center linked to the Pacific Tsunami Warning Center. The goal is to have all systems in place by July 2006. There has been discussion about creating a global warning system that would include the Atlantic Ocean and the Caribbean.

Questions:

1. What causes a tsunami?
2. What are signs that a tsunami might be coming?
3. Why was there no tsunami warning system in the Indian Ocean?


**CHAPTER
ACTIVITY**

The Dragon and Toad Mystery

In this chapter, you learned about earthquakes and how scientists collect data using seismographs. In this activity, you will learn something about the history of using seismographs.

In about 132 A.D., a long time ago, a Chinese philosopher, Chang Heng, invented the earliest known seismoscope. The paragraph below describes Heng's seismograph.

Imagine a large, ceramic vessel or jar about six feet in diameter. On the outside of this vessel were eight dragon heads. These faced the eight main directions that you would find on a compass. Not attached to the vessel, but seated below each of the dragon heads were eight toads, with their mouths open in the direction of the dragon head it was below. In the mouth of the dragon was a ball. The idea was that when an earthquake happened, a dragon would release its ball and it would fall into the appropriate toad's mouth. The direction of the shaking would determine which ball was released. Heng would know if an earthquake happened and from what direction it came.

The mystery is this—the inside of this early seismoscope is unknown.

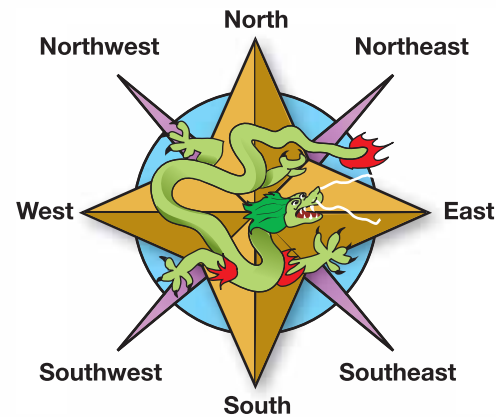
What you will do

1. Draw your interpretation of the outside of this vessel.
2. Spend some time thinking about mechanisms that might be found inside to make this instrument work. Once you have given it some thought and come up with an idea, draw/sketch your idea.
3. Below your sketch, write a step-by-step procedure of how this instrument works. Be sure to write clearly.

4. Exchange your instrument description and procedure with the instrument and procedure completed by someone else in your class.
5. You will present the description and procedure of one your classmates. This classmate will present your description and procedure to the class.
6. Your procedure on how to use it needs to be clear because that person is going to explain your instrument to the class and you will be explaining theirs based on the sketch and description. Remember, there are no right answers for this activity!

Applying your knowledge

- a. Which instrument in the class would work best and why? Write a paragraph to answer this question.
- b. How did your description and drawing compare to Chang Heng's seismograph? Learn more about Chang Heng's seismograph on the Internet—<http://neic.usgs.gov/neis/seismology/part03.html>. Write a paragraph comparing your seismograph to Heng's.
- c. How do modern seismographs work? Research modern seismographs and write a paragraph about them.



Chapter 9 Assessment

Vocabulary

Select the correct term to complete the sentences.

earthquake	fault	Richter scale
surface waves	seismograph	Moment Magnitude scale
body waves	epicenter	Mercalli Intensity scale
focus		

Section 9.1

1. The place on Earth's surface above where the rock breaks during an earthquake is the _____.
2. Stick-slip motion between lithospheric plates is what causes an _____.
3. The point below the epicenter is called the _____.
4. A _____ is a place where rocks break and there is movement.

Section 9.2

5. The type of seismic waves that travel at Earth's surface are called _____.
6. _____ are seismic waves that travel through the planet.
7. The instrument used to record seismic waves is a _____.

Section 9.3

8. Each number change on the _____ means a 10-fold increase in seismic wave energy.
9. Eyewitness accounts of earthquake damage are incorporated into this earthquake measurement scale: _____
10. The _____ rates the total energy of an earthquake.

Concepts

Section 9.1

1. What is friction?

2. Stick-slip motion can occur between any two objects. Give an example of stick-slip motion that you have experienced.
3. When two plates slide past each other, what happens to the crusts of these plates? What happens to the upper mantle parts of these plates?
4. The upper mantle is described as being *plastic*. Why is this a good term to describe the upper mantle?
5. What's the difference between shallow focus earthquakes and deep focus earthquakes?
6. What is a slickensides?

Section 9.2

7. Describe surface waves and how they affect an area that is experiencing an earthquake.
8. How are S- and P-waves used to find the distance from a seismic station to the epicenter of an earthquake?
9. What is the smallest number of seismic stations needed to determine the location of the epicenter of an earthquake?

Section 9.3

10. Why is a seismograph useful for measuring the magnitude of an earthquake on the Richter scale?
11. Is it possible that an earthquake could happen and you would not know it? Explain your answer.
12. What is the difference between the Moment Magnitude scale and the Richter scale?
13. After an earthquake, one person says that the intensity of the quake was VI on the Mercalli Intensity scale. Another person says that the intensity was III. Why might these individuals have had different experiences?
14. Where do most earthquakes occur? Explain your answer.

Math and Writing Skills

Section 9.1

1. In this chapter, you learned about the depth at which shallow and deep focus earthquakes originate in Earth. In what layers of Earth (from the detailed view of Earth in Chapter 7) do these types of earthquakes originate?
2. How wide was the area affected by the 1895 New Madrid earthquake? Refer to the New Madrid Fault Zone graphic in Section 9.1. Give your answer in miles. Then, convert this value to kilometers (1.6 km = 1 mile).
3. Since 1964, the longest earthquake ever recorded was the 1964 Alaskan earthquake. It lasted 4 minutes. The 2004 Indonesian earthquake broke the 1964 record. Find out the new record for the longest earthquake ever recorded. Write a short paragraph that describes three interesting facts you learned from your research.

Section 9.2

4. P-waves travel faster than S-waves and both of these seismic body waves travel faster than the speed of sound. Given the approximated values in this table, how much faster do P-waves travel than S-waves? How much faster do S-waves travel than sound (in air)? (Hint: Divide the smaller value into the larger value.)

	Approximate Speed (km/s)
P-wave	7
S-wave	3.6
Sound in air	0.34

5. The time difference between the arrival of a P-wave and an S-wave at a seismic station is 25 seconds. How far away is the epicenter?

6. The distance from the epicenter of a quake to a seismic station is 180 kilometers. If the distance scale on your map is 1 centimeters = 20 kilometers, what would be the radius of the circle that is drawn around this station on the map?

Section 9.3

7. If each Richter value represents seismic waves 10 times greater than the one before, than how much larger are the waves of an earthquake with a magnitude 6 versus a magnitude 3?
8. What is the Richter magnitude and Mercalli Intensity for an earthquake that causes enough shaking to wake you up, but not enough to cause damage?

Chapter Project—Demonstrating Liquefaction

First, gather the following items: brick, rubber mallet, water, sand, a plastic bin. Place the bin on a table. Fill the plastic bin $\frac{2}{3}$ full with sand. Pour water into the bin to just below the surface of the sand. Hold the brick upright so that it represents a tall building. Wiggle it into the sand so that it stands up on its own. Using your mallet, tap the side of the bin repeatedly and gently. Watch what happens to the sand and brick.

This model demonstrates what can happen when an earthquake shakes an area that has been filled by humans, such as Boston's Back Bay or the China Basin in the southeast portion of San Francisco. There are several regions in the Bay Area of California that have been filled to create land. They are all susceptible to liquefaction.

Liquefaction occurs when the seismic waves travel through the ground, the sandy soil is suspended in the water as the water fills in all the spaces in between the soil particles. Now the soil acts like a liquid and losing the ability to support buildings. The soil and water engulf the buildings as they sink into the ground.