Chapter 19

Earthquakes

Earthquake damage in Taiwan, 1999

What You'll Learn

- What causes earthquakes and how they affect Earth's surface.
- How earthquakes and the destruction they cause are measured.
- What factors determine seismic risk.

Why It's Important

Earthquakes are natural phenomena that can cause vast amounts of damage as well as many deaths. Understanding what causes earthquakes is essential to our being prepared for these natural disasters.

Earth Science Online

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

CONTENTS

Discovery Lab

Model An Earthquake

Earthquakes are natural vibrations of the ground. Most quakes are caused by movement along enormous fractures in Earth's crust. In this activity, you will model how movements along these fractures can cause earthquakes.

1. Slide the largest surfaces of two smooth wooden blocks against each other. Describe the movement.
2. Cut two pieces of coarse-grained sandpaper so that they are about 1 cm larger than the largest surface of each block.
3. Place the sandpaper, coarse side up, against the largest surface of each block. Wrap the paper over the edges of the blocks and secure it with thumbtacks.
4. Slide the sandpaper-covered sides of the blocks against each other. What happens?

Observe and Infer

In your science journal, compare the two movements. Infer which of the two scenarios models what happens during an earthquake.

Section 19.1 Forces Within Earth

OBJECTIVES

- **Define** *stress and strain as they apply to rocks.*
- **Distinguish** *among the three types of faults.*
- **Contrast** *three types of seismic waves.*

VOCABULARY

stress
strain
fault
primary wave
secondary wave
surface wave
focus
epicenter

Earthquakes are natural vibrations of the ground caused by movement along gigantic fractures in Earth's crust, or sometimes, by volcanic eruptions. If you've experienced an earthquake or heard about quakes in the news, you know that they can be extremely destructive. There are some instances in which a single earthquake has killed more than 100 000 people. Earthquakes have even destroyed entire cities. Anyone living in an area prone to earthquakes should be aware of the potential danger posed by these events and how to minimize the damage that they cause.

Stress and Strain

Most earthquakes occur when rocks fracture, or break, deep within Earth. Fractures form when **stress,** the forces per unit area acting on a material, exceeds the strength of the rocks involved. There are three kinds of stress that act on Earth's rocks: compression, tension, and shear. Compression is stress that decreases the volume of a material, tension is stress that pulls a material apart, and shear is stress that causes a material to twist. The deformation of materials in response to stress is called **strain.** ***Figure 19-1*** illustrates the strain caused by compression, tension, and shear.

Laboratory experiments on rock samples show a distinct relationship between stress and strain. When the stress applied to a rock is plotted against strain, a stress-strain curve, like the one shown in ***Figure 19-2,*** is produced. A stress-strain curve usually has two segments: a straight segment and a curved segment. Low stresses produce the straight segment, which represents the elastic strain of a material. Elastic strain causes a material to bend and stretch, and can be demonstrated by gently applying tension to a rubber band. When this tensional stress is released, the rubber band returns to its original size and shape. In ***Figure 19-2,*** note that elastic strain is proportional to stress, and thus, if the stress is reduced to zero, the strain, or deformation, disappears.

Ductile Deformation When stress exceeds a certain value, however, a material undergoes ductile deformation, shown by the curved segment of the graph in ***Figure 19-2.*** Unlike elastic strain, this type of strain produces permanent deformation, which means that the material stays deformed even if the stress is reduced to zero. A rubber band undergoes ductile deformation when it is stretched beyond its elastic limit. This permanent deformation results in an increase in size and produces slight tears or holes in the band. When stress exceeds the strength of a material, the material breaks, or fails, as designated by the *X* on the graph. From experience, you probably know that exerting too much tension on a rubber band will cause it to snap.

Most materials exhibit both elastic and ductile behavior. Brittle materials, such as glass, certain plastics, and dry wood, fail before much ductile deformation occurs. Ductile materials such as rubber,

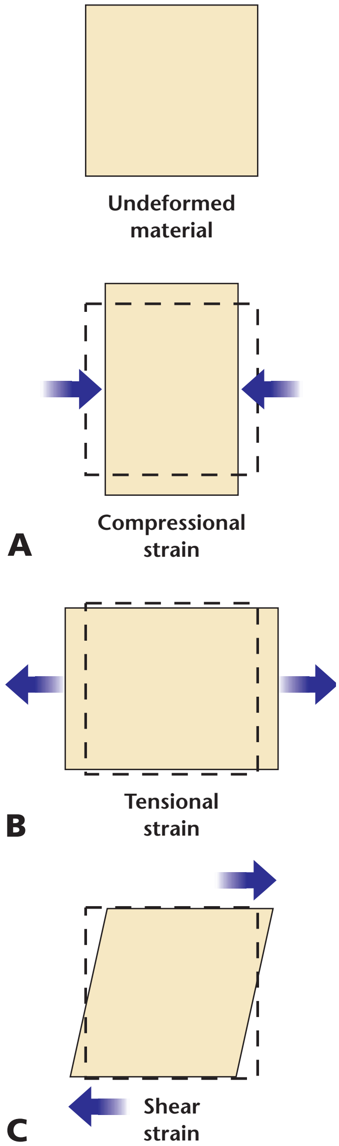


Figure 19-1 Compression causes a material to shorten **(A).** Tension causes a material to lengthen **(B).** Shear causes distortion of a material **(C).**

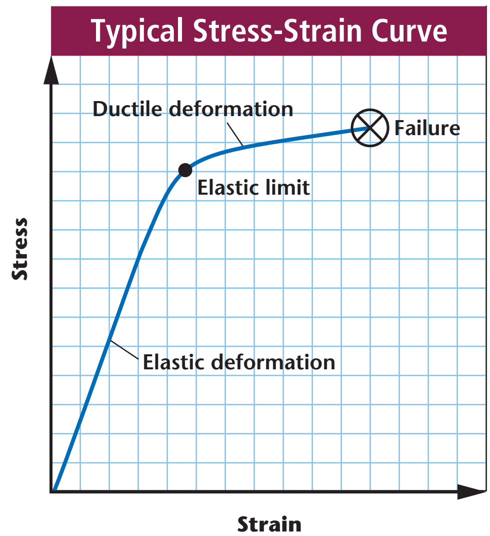


Figure 19-2 A typical stress–strain curve has two parts. Elastic deformation occurs as a result of low stress; ductile deformation occurs when stress is high. ***When does failure occur?***

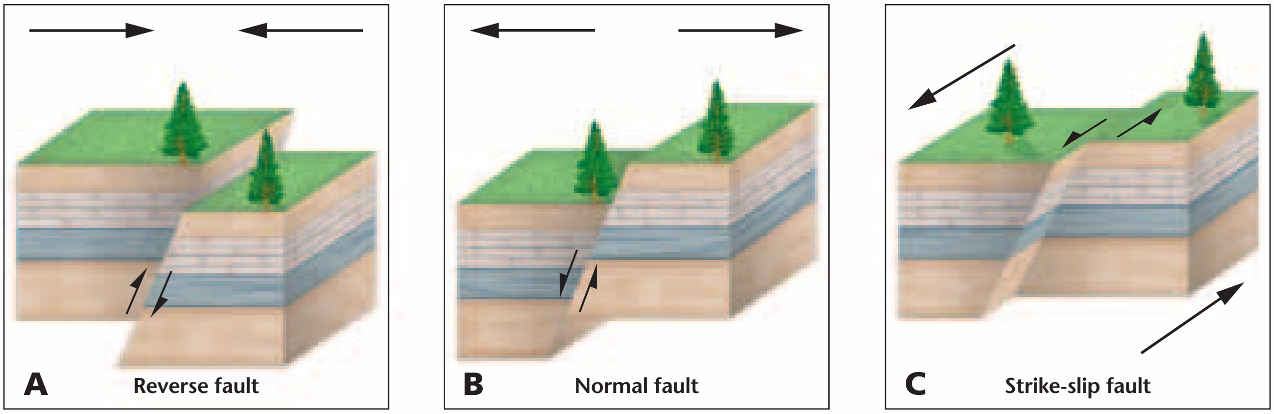


Figure 19-3 Reverse faults form when horizontal stress is exerted on a rock body from opposite sides **(A).** Normal faults form when bodies of rock are pulled from opposite sides **(B).** Strike-slip faults are caused by horizontal shear stress **(C).**

silicon putty, and metals, on the other hand, can undergo a great deal of ductile deformation before failure occurs, or, they may not fail at all. Most rocks are brittle under the relatively low temperatures that exist in Earth's crust but become ductile at the higher temperatures present at greater depths.

FAULTS

Many kinds of rocks that make up Earth's crust fail when stress is applied too quickly, or when stress is great. The resulting fracture or system of fractures, along which movement occurs, is called a **fault.** The surface along which the movement takes places is called the fault plane. The orientation of the fault plane can vary from nearly horizontal to almost vertical. In diagrams, small arrows along the fault plane indicate the direction of movement of the rocks involved.

Types of Faults There are three basic types of faults, as shown in ***Figure 19-3.*** Reverse faults are fractures that form as a result of horizontal compression. Note that the compressional force results in a horizontal shortening of the crust involved. What evidence in ***Figure 19-3A*** indicates this shortening? Normal faults are fractures caused by horizontal tension. Movement along a normal fault is partly horizontal and partly vertical. The horizontal movement along a normal fault occurs in such a way as to extend the crust. Note in ***Figure 19-3B*** that the two trees separated by the normal fault are farther apart than they were before the faulting.

Strike-slip faults are fractures caused by horizontal shear. The movement along a strike-slip fault is mainly horizontal, as shown in ***Figure 19-3C.*** The San Andreas Fault, which runs through California, is a strike-slip fault. This fault is one of thousands of faults responsible for many of the state's earthquakes. Motion along this fault has offset features that were originally continuous across the fault, as shown in ***Figure 19-4.***

Figure 19-4 The orange trees in the background have moved to the right relative to those in the foreground as the result of the 1940 Imperial Valley earthquake along the San Andreas Fault.

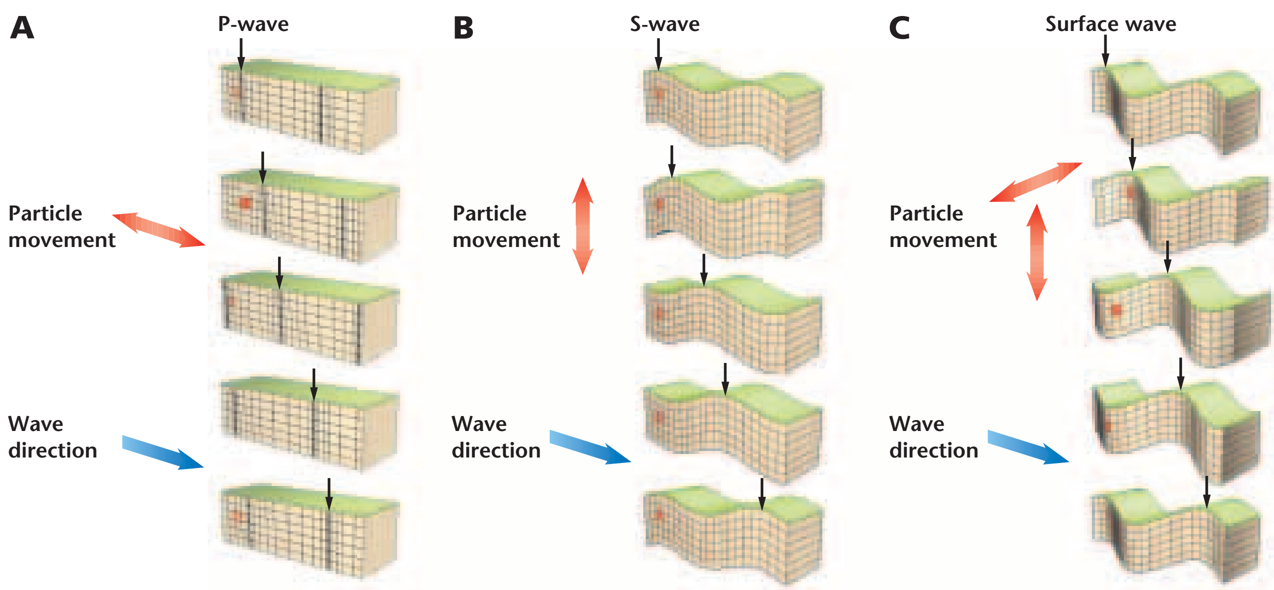
Earthquake Waves

Most earthquakes are caused by movements along faults. Recall from the *Discovery Lab* that some slippage along faults is relatively smooth. Other movements, modeled by the sandpaper-covered blocks, show that irregular surfaces in rocks can snag and lock. As stress continues to build in these rocks, they reach their elastic limit, break, and produce an earthquake.

Types of Seismic Waves The vibrations of the ground during an earthquake are called seismic waves. Every earthquake generates three types of seismic waves. **Primary waves,** or P-waves, squeeze and pull rocks in the same direction along which the waves are traveling, as shown in ***Figure 19-5A.*** Note how a volume of rock, which is represented by the small red square, changes shape as a P-wave passes through it. **Secondary waves,** or S-waves, cause rocks to move at right angles in relation to the direction of the waves, as shown in ***Figure 19-5B.*** **Surface waves** are a third type of seismic wave that move in two directions as they pass through rock. An up-and-down movement similar to that of an ocean wave occurs as a surface wave travels through a rock. A surface wave also causes rocks to move from side to side as it passes, as shown in ***Figure 19-5C.***

As you might guess from the name, surface waves travel along Earth's surface. P-waves and S-waves, on the other hand, pass through Earth's interior. For this reason, P-waves and S-waves are also called body waves. The first body waves generated by a quake

Figure 19-5 A P-wave causes rock particles to move back and forth as it passes **(A).** An S-wave causes rock particles to move at right angles to the direction of the wave **(B).** A surface wave causes rock particles to move both up and down and from side to side **(C).**



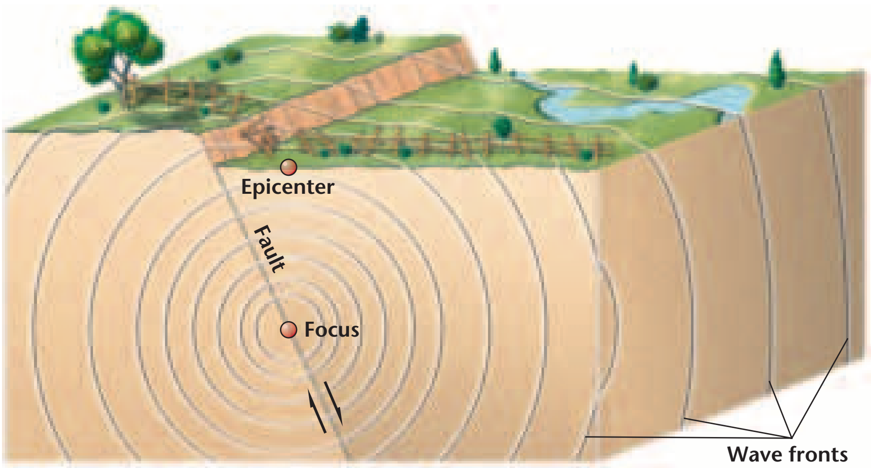


Figure 19-6, The focus of an earthquake is the point of initial fault rupture. The surface point directly above the focus is the epicenter.

spread out from the point of failure of rocks at depth. This point, where an earthquake originates, is the **focus** of the earthquake. The focus is usually at least several kilometers below Earth's surface. The point on Earth's surface directly above the focus is the earthquake's **epicenter.** Locate the focus and the epicenter in the diagram shown in *Figure 19-6.*

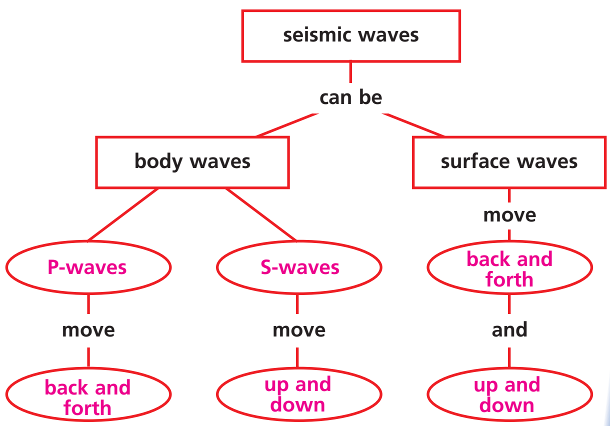
You've just learned that Earth's rocks deform when stress is exerted on them. If stress exceeds a certain limit, the rocks fracture to form faults. Movement along faults causes most earthquakes. How are these earth-shattering events measured and what do they tell us about Earth's interior? You'll find out the answer to this question in the next section.

SECTION ASSESSMENT

1. What are stress and strain?
2. Describe a typical stress-strain curve and the relationship between the segments of the curve and stress and strain.
3. Compare and contrast the three types of faults.
4. What causes most earthquakes?
5. **Thinking Critically** Most earthquakes are shallow. Use the concepts of elastic and ductile deformation to explain this fact.

SKILL REVIEW

6. **Concept Mapping** Use the following terms to complete the concept map to organize some of the major ideas in this section. For more help, refer to the *Skill Handbook.*



SECTION 19.2 Seismic Waves and Earth's Interior

OBJECTIVES

- **Describe** *how a seismometer works.*
- **Explain** *how seismic waves have been used to determine the structure and composition of Earth's interior.*

VOCABULARY

seismometer
seismogram

The study of earthquake waves is called seismology. In view of the potential for major disaster, it should come as no surprise to you that many scientists study earthquakes. Some seismologists, however, study earthquakes for another reason. The seismic waves that shake the ground during a quake also penetrate Earth's interior. This has provided information that has enabled Earth scientists to construct models of Earth's internal structure. Thus, even though seismic waves can wreak havoc on the surface, they are invaluable for their contribution to our understanding of Earth's interior.

SEISMOMETERS AND SEISMOGRAMS

Vibrations sent out by earthquakes shake the entire globe. Although most of the vibrations can't be felt great distances from a quake's epicenter, they can be detected and recorded by sensitive instruments called seismographs, or **seismometers**. Some seismometers consist of a rotating drum covered with a sheet of paper, a pen or other such recording tool, and a mass. Seismometers vary in design, as shown in ***Figure 19-7,*** but all include a frame that is anchored to the ground and a mass that is suspended from a spring or wire. Because of inertia, the mass tends to stay at rest as the ground and, consequently, the frame, vibrate during an earthquake. The relative motion of the mass in relation to the frame is then registered on the paper with the recording tool, or is directly recorded onto a computer disk. The record produced by a seismometer is called a **seismogram,** a portion of which is shown in ***Figure 19-8.***

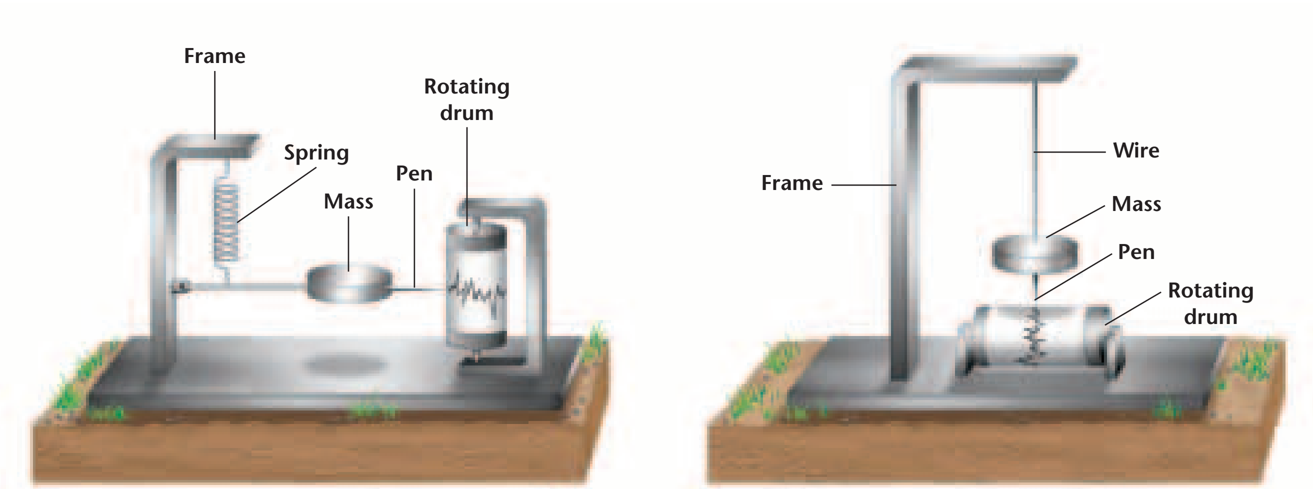


Figure 19-7 ***Which of these seismometers records horizontal motion during an earthquake? Which detects vertical motion?***

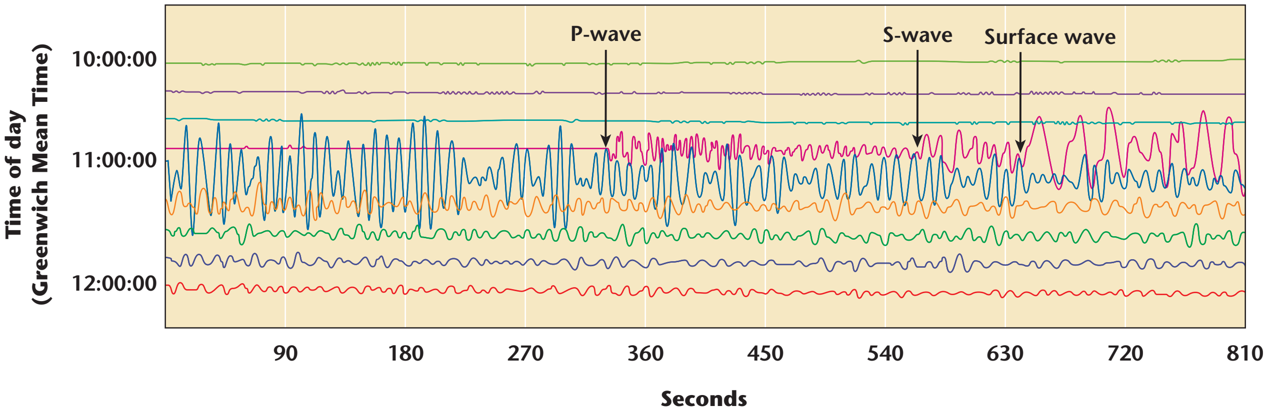


Figure 19-8 *Use this section of a seismogram, which contains colored lines to make it easier to read, to determine which of the three types of seismic waves is the fastest. Which type is the slowest?*

Travel-Time Curves Seismic waves that travel from the epicenter of an earthquake are recorded by seismometers housed in distant facilities. Over many years, the arrival times of seismic waves from countless earthquakes at seismic facilities all over the globe have been collected. Using these data, seismologists have been able to construct global travel-time curves for the initial P-waves and S-waves of an earthquake, as shown in ***Figure 19-9.*** These general curves have provided the average travel times of all seismic waves for different distances, no matter where on Earth an earthquake occurs. You can make and use a travel-time curve by doing the *Problem-Solving Lab* on the next page.

Look at ***Figure 19-9.*** Note that for any distance from the epicenter, the P-waves always arrive first at a seismic facility. Note, too, that with increasing travel distance, the time separation between the curves for the P-waves and S-waves increases. This means that waves recorded on seismograms from more distant facilities are farther apart than waves recorded on seismograms at stations closer to the epicenter. This separation of seismic waves on seismograms can be used to determine the distance from the epicenter of a quake to the seismic facility that recorded the seismogram. Can you guess how? This method of precisely locating an earthquake's epicenter will be discussed later in this chapter.

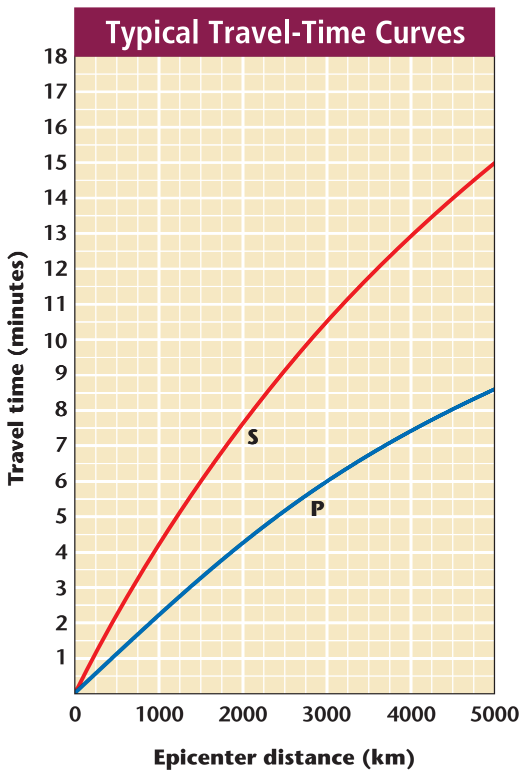


Figure 19-9 Travel-time curves show the time it takes for P-waves and S-waves to travel to seismic stations located at different distances from an earthquake's epicenter.

Clues to Earth's Interior

Most of the knowledge of Earth's interior comes from the study of seismic waves, which change speed and direction when they encounter different materials. Note in ***Figure 19-10*** that P-waves and S-waves traveling through the mantle follow fairly direct paths. P-waves that strike the core, however, are refracted, or bent, so that beyond a distance of about 11 000 km from the quake's epicenter, they disappear. The P-waves refracted into the core reemerge at a distance of about 16 000 km from the epicenter. The region between these two distances doesn't receive direct P-waves and is known as the P-wave shadow zone.

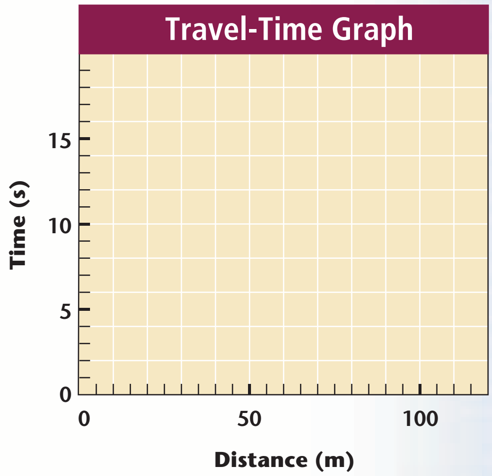
What happens to the S-waves generated by an earthquake? S-waves do not enter Earth's core because they cannot travel through liquids. Thus, like P-waves, they also do not reappear beyond the

Problem-Solving Lab

Making and Using Graphs

Model seismic-wave travel times

Seismic waves can be compared to runners. Suppose that Pam and Sam are running the 100-m dash. Pam runs the 100 m in 12 s, and Sam runs it in 14.5 s.



Procedure

1. Copy the graph shown. Plot two points to show the running times for Pam and Sam. Draw a straight line from each point to the origin. These are Pam's and Sam's travel-time curves.
2. Measure the separation of the two lines at a distance of 50 m. Is it more or less than 1 s?
3. Slide a ruler, parallel to the vertical axis, along the curves until you find the distance at which the separation is 1 s. What is that distance?

Analysis

4. Is there any other distance with the same separation?
5. What is the average speed, in m/s, of each runner?

Thinking Critically

6. Double-check your answer by dividing the distance in step 3 by each runner's speed to get each runner's time to that point. Do these times differ by 1 s?
7. What do Pam and Sam represent in terms of seismic waves? Discuss some ways in which a seismic travel-time curve differs from yours.

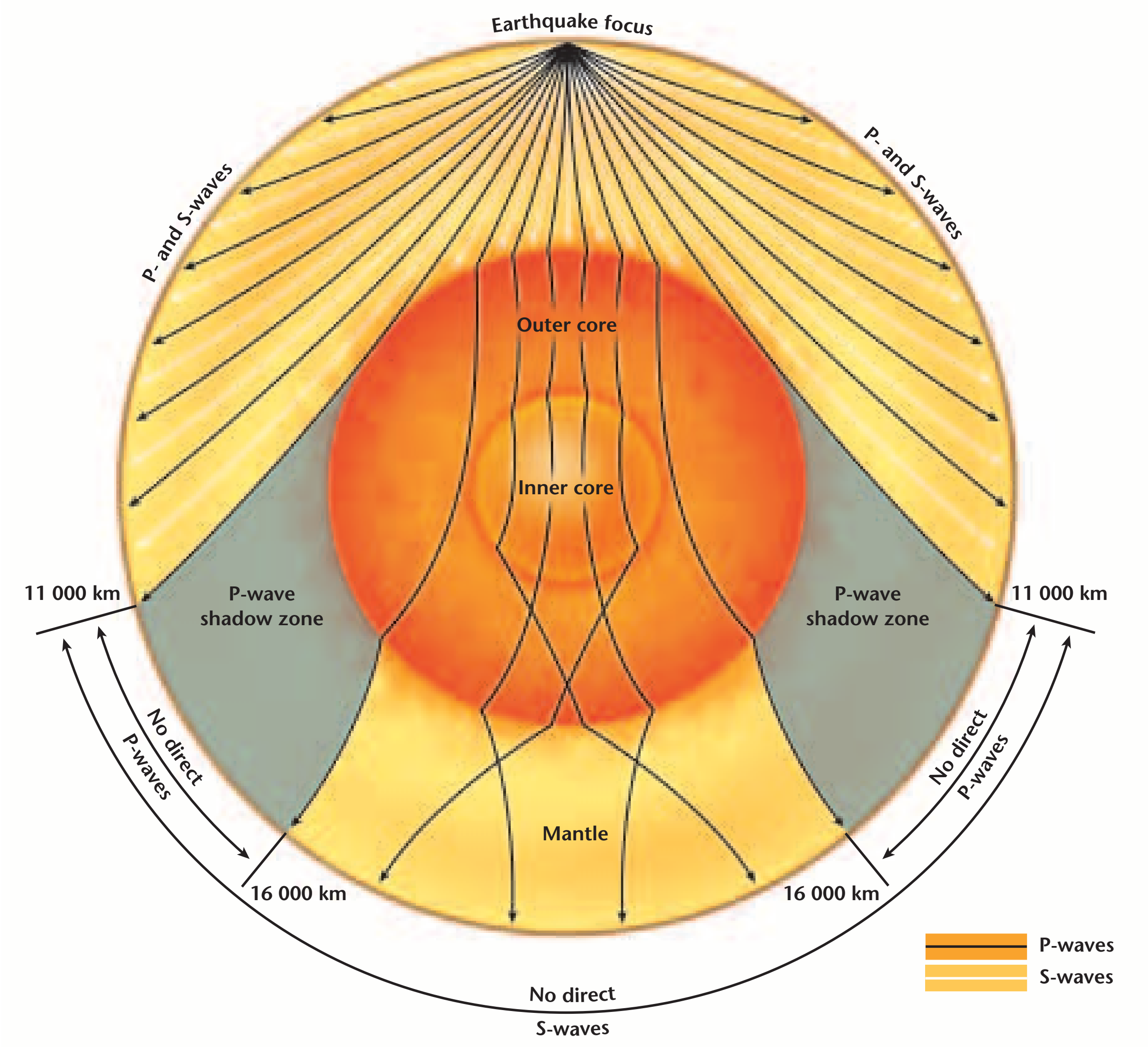


Figure 19–10 Refraction of P-waves into the outer core generates a P-wave shadow zone on Earth's surface where no direct P-waves appear on seismograms. Other P-waves are reflected and refracted by the inner core. S-waves cannot travel through liquids, and thus, don't reappear beyond the P-wave shadow zone.

11 000-km distance. This disappearance of S-waves has allowed seismologists to reason that Earth's outer core must be liquid. Detailed studies of how other seismic waves reflect deep within Earth show that Earth's inner core is solid.

Earth's Internal Structure The travel times and behavior of seismic waves provide a detailed picture of Earth's internal structure. These waves also provide clues about the composition of the various parts of Earth. By studying seismic-wave travel times, scientists have

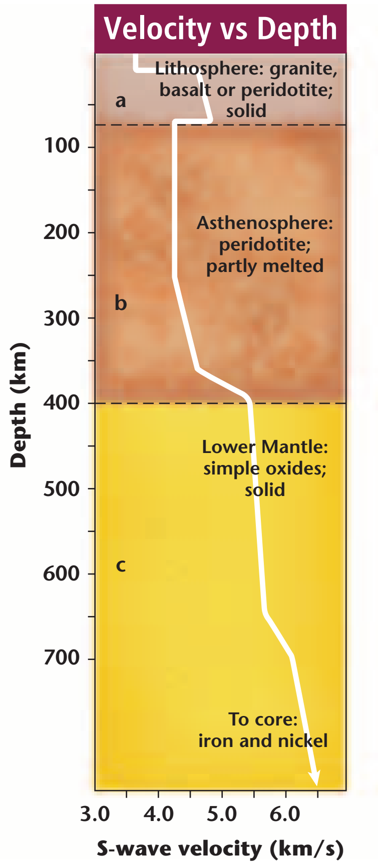


Figure 19-11 Observations of seismic wave velocities have enabled scientists to subdivide Earth's interior into various layers.

determined that the lithosphere, which includes the crust and the top of the upper mantle, is made up primarily of the igneous rocks granite, basalt, and peridotite as shown in ***Figure 19-11.*** The crustal part of the lithosphere is composed of either granite or basalt. The mantle section of the lithosphere is made of a dense, coarse-grained, intrusive rock called peridotite, which is made mostly of the mineral olivine. Much of the partially melted mantle, or asthenosphere, is also thought to be peridotite. Earth's lower mantle is solid and is probably composed of simple oxides containing iron, silicon, and magnesium. Seismic waves traveling through the core, together with gravity studies, indicate that this inner part of the planet is very dense and is probably made of a mixture of iron and nickel.

Earth's Composition The composition data obtained from seismic waves is supported by studies of meteorites, which are solid, interplanetary bodies that enter Earth's atmosphere. You might be thinking, but how can objects from space help to determine the composition of Earth's interior? Meteorites are pieces of asteroids, which are rocky bodies that orbit the Sun. Asteroids are thought to have formed in much the same way and at the same time as the planets in our solar system. Meteorites consist mostly of iron, nickel, and chunks of rock similar to peridotite in roughly the same proportions as the rocks thought to make up Earth's core and mantle.

Meteorites, together with the data provided by the travel times of seismic waves, have enabled scientists to indirectly probe Earth's interior. What other kinds of information can these waves provide? As you'll find out in the next section, seismic waves are used to determine the strength of an earthquake as well as the precise location of its epicenter.

SECTION ASSESSMENT

1. Explain how a seismometer works.
2. What is a seismogram?
3. What is a seismic travel-time curve, and how is it used to study earthquakes?
4. What is the P-wave shadow zone, and what causes it?
5. How have scientists determined the composition of Earth's mantle and core?
6. **Thinking Critically** As shown in ***Figure 19-8,*** on page 501, surface waves are the last to arrive at a seismic station. Why then do they cause so much damage?

SKILL REVIEW

7. **Recognizing Cause and Effect** Is there any way for P-waves to appear in the shadow zone? Explain. For more help, refer to the *Skill Handbook.*

earthgeu.com/self_check_quiz

SECTION 19.3 *Measuring and Locating Earthquakes*

How many earthquakes do you suppose occur each year? If you were to rely only on news accounts of these events, you might guess a dozen or so, at most. It may surprise you to learn that more than one million earthquakes occur each year! However, more than 90 percent of these are not felt and cause little, if any, damage. The earthquakes that make the news are major seismic events that cause much damage, such as the one that occurred in Bam, Iran in December 2003.

OBJECTIVES

- **Compare** *and* **contrast** *earthquake magnitude and intensity and the scales used to measure each.*
- **Explain** *why data from at least three seismic stations are needed to locate an earthquake's epicenter.*
- **Describe** *Earth's seismic belts.*

VOCABULARY

magnitude
Richter scale
moment magnitude scale
modified Mercalli scale

EARTHQUAKE MAGNITUDE AND INTENSITY

The amount of energy released during an earthquake is measured by its **magnitude.** Many news accounts describe the magnitude of an earthquake on a numerical scale called the Richter scale, which was devised by an American seismologist named Charles Richter. An earthquake's rating on the **Richter scale** is based on the size of the largest seismic waves generated by the quake. Each successive number in the scale represents an increase in seismic-wave size, or amplitude, of a factor of 10. For example, the seismic waves of a magnitude-8 earthquake on the Richter scale are ten times larger than those of a magnitude-7 earthquake, and 100 times larger than those of a magnitude-6 earthquake. The differences in the amounts of energy released by earthquakes are even greater than the differences between the amplitudes of their waves. Each increase in magnitude corresponds to about a 32-fold increase in seismic energy. Thus, an earthquake of magnitude-8 releases about 32 times the energy of a magnitude-7 earthquake, and over 1000 times the energy of a magnitude-6 earthquake. Some of the damage caused by a quake measuring 8.6 on the Richter scale is shown in ***Figure 19-12.***

Figure 19-12 The damage shown here was caused by an 8.6-magnitude earthquake that struck Anchorage, Alaska in 1964.

Moment Magnitude Scale While the Richter scale can still be used to describe the magnitude of an earthquake, most seismologists today use a scale called the moment magnitude scale to measure earthquake magnitude. The **moment magnitude scale** takes into account the size of the fault rupture, the amount of movement along the fault, and the rocks' stiffness. Unlike Richter-scale values, which are based on the largest seismic waves generated by a quake, moment magnitude values are estimated from the size of several types of seismic waves produced by an earthquake.

Modified Mercalli Scale Another way to assess earthquakes is to measure the amount of damage done to the structures involved. This measure, called the intensity of an earthquake, is determined using the **modified Mercalli scale,** which rates the types of damage and other effects of an earthquake as noted by observers during and after its occurrence. This scale uses the Roman numerals I to XII to designate the degree of intensity. Specific effects or damage correspond to specific numerals; the higher the numeral, the worse the damage. A simplified version of the modified Mercalli intensity scale is shown in ***Table 19-1.*** Use the information given in this scale to try to rate the intensity of the earthquake that caused the damage shown in ***Figure 19-13.***

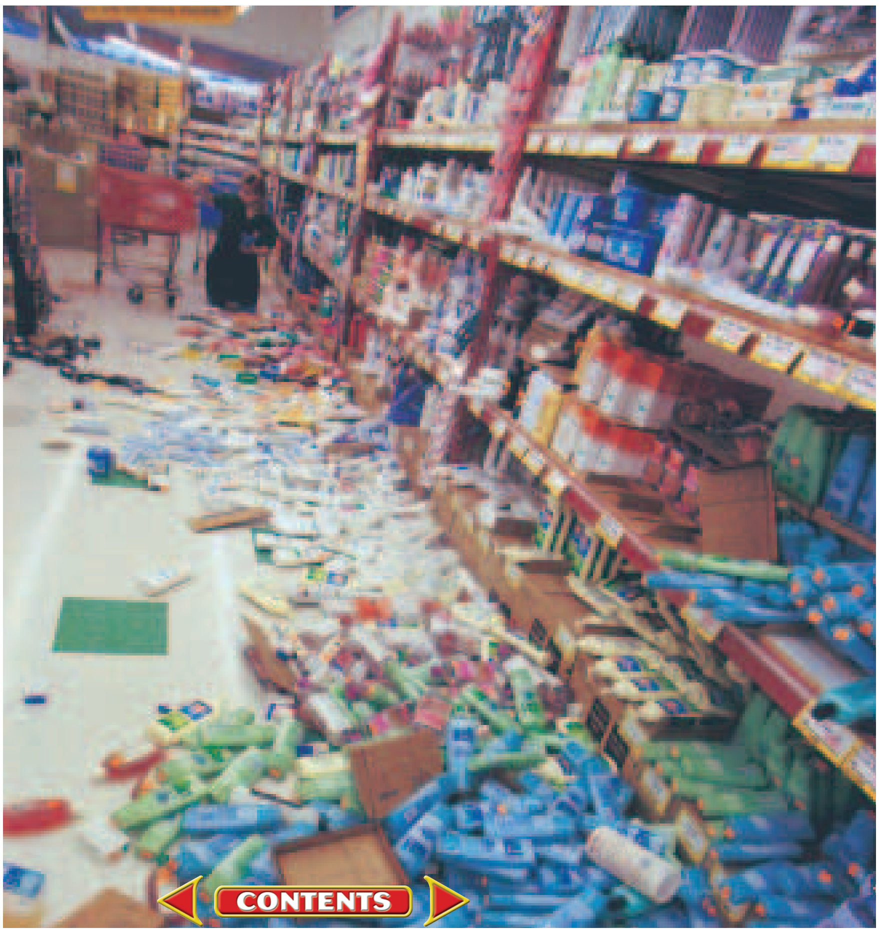


Figure 19-13 *Use the modified Mercalli scale to determine the intensity of the earthquake that caused the damage to this grocery store in Washington State.*

Table 19-1 Modified Mercalli Intensity Scale

I.	Not felt except under unusual conditions.
II.	Felt only by a few persons. Suspended objects may swing.
III.	Quite noticeable indoors. Vibrations are like the passing of a truck.
IV.	Felt indoors by many, outdoors by few. Dishes and windows rattle. Standing cars rock noticeably.
V.	Felt by nearly everyone. Some dishes and windows break, and some plaster cracks.
VI.	Felt by all. Furniture moves. Some plaster falls and some chimneys are damaged.
VII.	Everybody runs outdoors. Some chimneys break. Damage is slight in well-built structures but considerable in weak structures.
VIII.	Chimneys, smokestacks, and walls fall. Heavy furniture is overturned. Partial collapse of ordinary buildings occurs.
IX.	Great general damage occurs. Buildings shift off foundations. Ground cracks. Underground pipes break.
X.	Most ordinary structures are destroyed. Rails are bent. Landslides are common.
XI.	Few structures remain standing. Bridges are destroyed. Railroad ties are greatly bent. Broad fissures form in the ground.
XII.	Damage is total. Objects are thrown upward into the air.

Earthquake intensity depends primarily on the amplitude of the surface waves generated. Because surface waves, like body waves, gradually decrease in size with increasing distance from the focus of an earthquake, the intensity also decreases as the distance from a quake's epicenter increases. Maximum intensity values are observed in the region near the epicenter; Mercalli values decrease to I at distances very far from the epicenter.

Modified Mercalli scale intensity values of places affected by an earthquake can be compiled to make a seismic-intensity map. Contour lines join points that experienced the same intensity. The maximum intensity is usually, but not always, found at the quake's epicenter. You will generate a seismic-intensity map when you do the *MiniLab* on the next page.

Depth of Focus Earthquake intensity is related to earthquake magnitude. Both measurements reflect the size of the seismic waves generated by the quake. Another factor that determines the intensity of an earthquake is the depth of the quake's focus. An earthquake can be classified as shallow, intermediate, or deep depending on the location of the quake's focus. Because a deep-focus earthquake produces smaller vibrations at the epicenter than a shallow-focus quake, a shallow-focus, moderate quake of magnitude-6, for example, may generate a greater maximum intensity than a deep-focus quake of

Earth Science Online

Topic: Bam, Iran
To learn more about damage caused by earthquakes, visit the Earth Science Web Site at earthgeu.com

Activity: Research the December 2003 earthquake in Bam, Iran. Describe what an eyewitness may have seen.

MiniLab

How is a seismic–intensity map made?

Make a Map using seismic–intensity data.

Procedure

1. Trace the map onto paper. Mark the locations indicated by the letters on the map.
2. Plot these Mercalli intensity values on the map next to the correct letter: A, I; B, III; C, II; D, III; E, IV; F, IV; G, IV; H, V; I, V; J, V; K, VI; L, VIII; M, VII; N, VIII; O, III.
3. Draw contours on the map to separate the intensity values.

Analyze and Conclude

1. What is the maximum intensity value?
2. Where is the maximum intensity value located?
3. Where is the earthquake's epicenter?

Intensity Values of a Quake

magnitude-8. Catastrophic quakes with high intensity values are almost always shallow-focus events.

Locating an Earthquake

The exact location of an earthquake's epicenter and the time of the quake's occurrence are initially unknown. All epicenter locations, as well as times of occurrence, however, can be easily determined using seismograms and travel-time curves.

Distance to an Earthquake Look again at ***Figure 19-9*** on page 501. Suppose the separation time for the P-waves and S-waves is six minutes. Based on known travel times of seismic waves, the distance between the earthquake's epicenter and the seismic station that recorded the waves can only be 4500 km—no more, no less. This is because the known travel time over that distance is eight minutes for P-waves and 14 minutes for S-waves. At greater distances from the epicenter, the travel times for both types of waves increase. This results in a larger P-S separation because S-waves lag behind the faster P-waves. The distance to a quake's epicenter, then, is determined by the P-S separation. By measuring this separation on any seismogram as well as the distance on a travel-time graph at which the P-curve and S-curve have the same separation, the distance to a quake's epicenter can be determined. This distance is called the epicentral distance.

The distance between an earthquake's epicenter and a single seismic station does not provide sufficient information to determine the location of that epicenter—it could be located in any direction from the seismic station. The only thing that is certain is that the epicenter is located somewhere on a circle centered on the seismic station. The radius of this circle is equal to

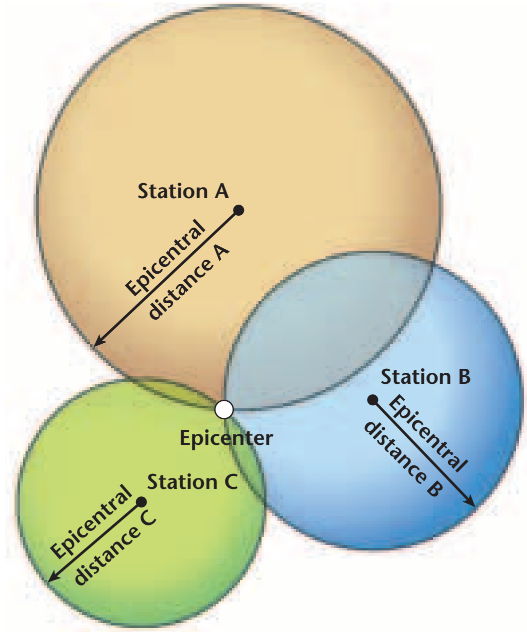


Figure 19-14 To determine the location of an earthquake's epicenter, the locations of three seismic stations are plotted on a map. A circle whose radius is equal to the corresponding epicentral distance is plotted around each station. The point of intersection of these circles is the earthquake's epicenter.

the epicentral distance. If the distances between three or more seismic stations and an earthquake's epicenter are known, the exact location of the epicenter can be determined, as shown in ***Figure 19-14.*** You will locate an actual epicenter in the *GeoLab* at the end of this chapter.

Time of an Earthquake The time of occurrence of an earthquake can be easily calculated, again by using the travel-time graph shown in ***Figure 19-9.*** The exact arrival times of the P-waves and S-waves at a seismic station can be read from the seismogram. The travel time of either wave at the epicentral distance of that station can be read from the travel-time graph. The time of occurrence of the earthquake is then determined by subtracting the appropriate travel time from the known arrival time of the wave.

Earth Science Online

Update For an online update of recent earthquakes, visit earthgeu.com and select the appropriate chapter.

Seismic Belts

Over the years, seismologists have collected and plotted the locations of numerous earthquake epicenters. The global distribution of these epicenters, shown in ***Figure 19-15*** on the next page, reveals an interesting pattern. Earthquake locations are not randomly distributed. The majority of the world's earthquakes occur in relatively narrow seismic belts that separate large regions with little or no seismic activity. What causes this pattern of seismic activity?

Look back at ***Figure 17-13*** on page 455, which shows Earth's tectonic plates and the boundaries between them. How does this map compare with the map shown in ***Figure 19-15?*** By comparing the two maps, you can see that most earthquakes are associated with tectonic plate boundaries. Almost 80 percent of all earthquakes occur in the Circum-Pacific Belt. Another zone of significant seismic activity stretches across southern Europe and Asia. About 15 percent of the

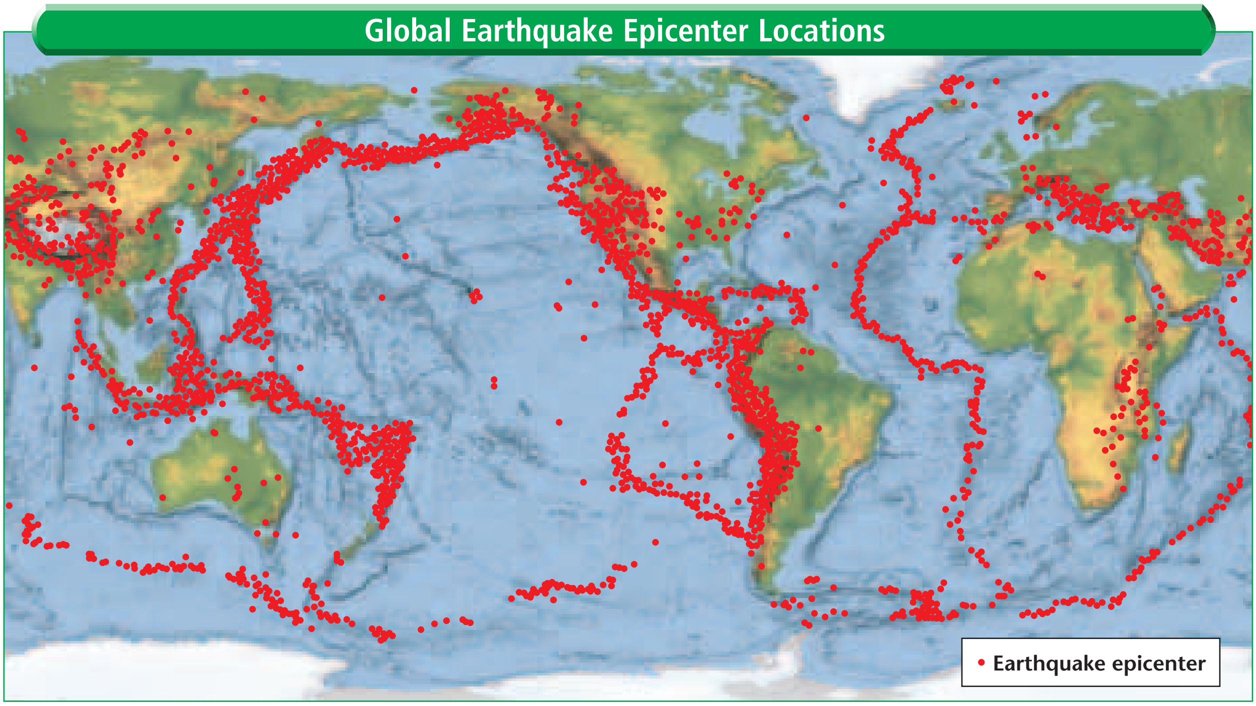


Figure 19-15 This map shows the locations of earthquake epicenters.

world's earthquakes take place in this region, which is sometimes called the Mediterranean-Asian Belt. Most of the remaining earthquakes occur in narrow bands that run along the crests of ocean ridges. A very small percentage of earthquakes happen far from tectonic plate boundaries and are distributed more or less at random.

Look again at ***Figure 19-15.*** Do you live in an area prone to earthquakes? If so, how can you minimize the damage done by these seismic events?

Section Assessment

1. What is earthquake magnitude and how is it measured?
2. What is earthquake intensity and how is it measured?
3. Explain why earthquake data from at least three seismic stations are needed to locate an earthquake's epicenter.
4. **Thinking Critically** The separation of P-waves and S-waves on a seismogram recorded 4500 km from the epicenter of an earthquake is six minutes. On another seismogram that separation is seven minutes. Is the second station closer to or more distant from the epicenter? Explain.

Skill Review

5. **Interpreting Scientific Diagrams** Use ***Figure 19-15*** above to determine which of the following countries has the most earthquakes: Ireland, Pakistan, South Africa, or Australia. Why does this country have more earthquakes than the other three countries? For more help, refer to the *Skill Handbook.*

SECTION 19.4 Earthquakes and Society

Most earthquake damage results from the prolonged shaking of the ground by surface waves. During major quakes, this shaking can last longer than a minute. Many structures cannot withstand such violent motion. Collapsing buildings are responsible for many earthquake-related deaths. What other types of damage are caused by earthquakes? What kinds of factors affect the damage done during a quake? Is it possible to predict earthquakes?

OBJECTIVES

- **Discuss** *factors that affect the amount of damage done by an earthquake.*
- **Explain** *some of the factors considered in earthquake probability studies.*
- **Define** *seismic gaps.*

VOCABULARY

tsunami
seismic gap

SOME EARTHQUAKE HAZARDS

The damage produced by an earthquake is directly related to the strength or quality of the structures involved. The most severe damage occurs to unreinforced buildings made of stone, concrete, or other brittle building materials. Wooden structures, on the other hand, are remarkably resilient and generally sustain significantly less damage. Many high-rise, steel-frame buildings also sustain little damage during an earthquake because they are reinforced to make them earthquake resistant. Some buildings in earthquake-prone areas, such as California, even rest on large rubber structures that absorb most of the vibrations generated during a quake.

Structural Failure In many earthquake-prone areas, buildings are destroyed as the ground beneath them shakes. In some cases, the supporting walls of the ground floor fail and cause the upper floors, which initially remain intact, to fall and collapse as they hit the ground or lower floors. The resulting debris resembles a stack of pancakes, and thus, the process has been called "pancaking". This type of structural failure is shown in the photograph on page 494, and was a common result of the quake that rocked Turkey in 1999. You'll learn more about this quake and the damage it caused in the *Science in the News* feature at the end of this chapter.

Another type of structural failure is related to the height of a building. During the 1985 Mexico City earthquake, for example, most buildings between 5 and 15 stories tall collapsed or were otherwise completely destroyed as shown in ***Figure 19-16.*** Similar structures that were either shorter or taller, however, sustained only minor

Figure 19-16 The buildings damaged or destroyed during the 1985 Mexico City quake vibrated with the same period as the seismic waves.

damage. Can you guess why? The shaking caused by the quake had the same period of vibration as the natural sway of the intermediate buildings, which caused them to sway violently during the quake. The ground vibrations, however, were too rapid to affect taller buildings, whose periods of vibration were longer than the earthquake waves, and too slow to affect shorter buildings, whose periods of vibration were shorter.

Land and Soil Failure In addition to their effects on structures made by humans, earthquakes can wreak havoc on Earth itself. In sloping areas, earthquakes may trigger massive landslides. Most of the estimated 30 000 deaths caused by the 7.8-magnitude earthquake that struck in Peru in 1970 resulted from a landslide that buried several towns. In areas with fluid-saturated sand, seismic vibrations may cause subsurface materials to liquefy and behave like quicksand, generating landslides even in areas of low relief. Soil liquefaction can also cause trees and houses to fall over or to sink into the ground and can cause underground pipes and tanks to rise to the surface.

In addition to causing soil liquefaction, earthquake waves can be amplified as they travel through a soil. Because soft materials have little resistance to deformation, seismic waves are amplified in such materials but are muted in more-resistant materials. Consequently, wave size and earthquake intensity are greatest in soft, unconsolidated sediments and relatively small in hard, resistant rocks such as granite. The severe damage to structures in Mexico City during the 1985 earthquake is attributed to the fact that Mexico City is built on soft sediments. The thickness of the sediments caused them to resonate with the same frequency as that of the surface waves generated by the quake. This produced reverberations that greatly enhanced the ground motion and the resulting damage.

Figure 19-17 This fault scarp was produced by faulting associated with an earthquake that struck Mount Borah, Idaho, in 1983.

Fault Scarps Fault movements associated with earthquakes can produce areas of great vertical offset where the fault intersects the ground surface. These offsets are called fault scarps. As shown in ***Figure 19-17,*** a distinct fault scarp formed as the result of an earthquake that struck central Idaho in 1983. The magnitude-7.6 quake that rocked Taiwan in

Figure 19-18 Vertical offset along a fault caused this waterfall to form during the 1999 Taiwan earthquake.

1999 produced vertical offsets of up to 10 m, the greatest fault movement observed in recent history. An 8-m-high waterfall that formed where the fault crosses a river is shown in ***Figure 19-18.***

Tsunami Another type of earthquake hazard is a **tsunami,** a large ocean wave generated by vertical motions of the seafloor during an earthquake. These motions displace the entire column of water overlying the fault, creating bulges and depressions in the water. The disturbance then spreads out from the epicenter in the form of extremely long waves. While these waves are in the open ocean, their height is generally less than 1 m. When the waves enter shallow water, however, they may form huge breakers with heights occasionally exceeding 30 m! These enormous wave heights, together with open-ocean speeds between 500 and 800 km/h, make tsunamis dangerous threats to coastal areas both near and far from the quake's epicenter. The magnitude-9.5 earthquake that struck Chile in 1960 generated a tsunami that destroyed many villages along an 800-km section of the South American coast. The wave then spread across the entire Pacific Ocean and struck Japan 23 hours later, killing 200 people. Even several days after the quake had struck, significant changes in water levels were observed in many coastal cities.

Seismic Risk

Recall that most earthquakes occur in areas called seismic belts. The probability of future quakes is much greater in these belts than elsewhere around the globe. The past seismic activity in any region is also a reliable indicator of future earthquakes and can be used to generate seismic-risk maps. A seismic-risk map of the United States is shown in ***Figure 19-19*** on the next page. Can you locate the areas of highest seismic risk on the map? In addition to Alaska, Hawaii, and some western states, there are several regions of relatively high

Using Math

Using Numbers The speed of tsunamis in the open ocean can reach 800 km/h. At this speed, how long, will it take a tsunami to travel from Japan to California, a distance of about 9000 km? If the waves are 160 km long, how far apart in time are the wave crests?

Seismic Risk Map of the United States

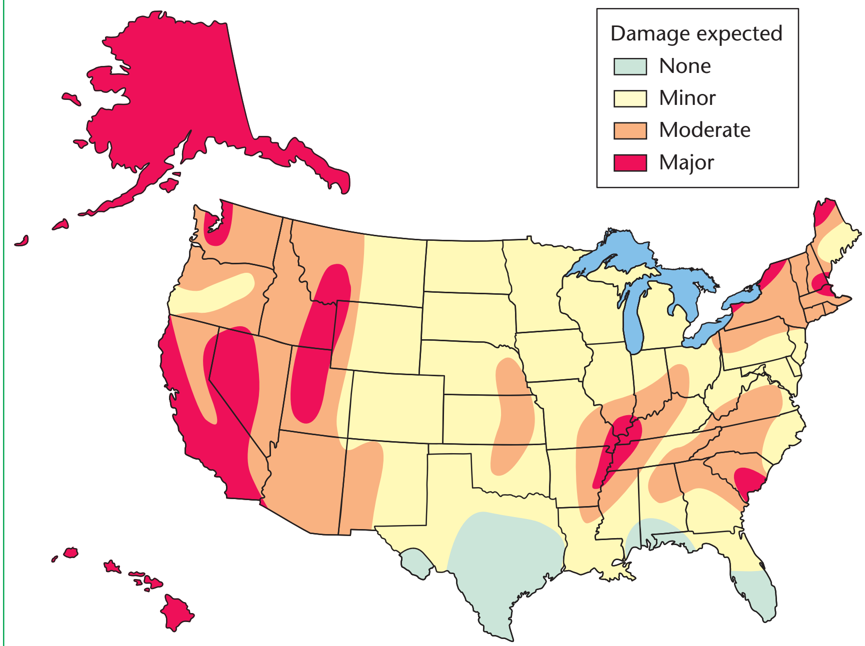


Figure 19-19 Areas of high seismic risk in the United States include Alaska, Hawaii, and some of the western states.

seismic risk in the central and eastern United States. These regions have suffered disastrous earthquakes in the past and probably will experience significant seismic activity in the future. Locate your state in ***Figure 19-19.*** What is the seismic risk of your area?

Earthquake Prediction

To minimize the damage and deaths caused by quakes, seismologists are searching for ways to predict these events. Earthquake prediction research is largely based on probability studies. The probability of an earthquake's occurring is based on two factors: the history of earthquakes in an area and the rate at which strain builds up in the rocks.

Earthquake History Earthquake recurrence rates can indicate that the fault involved ruptures repeatedly at regular intervals to generate similar quakes. The earthquake-recurrence rate at Parkfield, California, for example, shows that a sequence of quakes of approximately magnitude-6 shook the area about every 22 years from 1857 until 1966. This record indicates a 90-percent probability that a major quake will rock the area within the next few decades. Several kinds of instruments, including the lasers shown in ***Figure 19-20,*** are in place around Parkfield in an attempt to predict future quakes.

Probability forecasts are also based on the location of seismic gaps. **Seismic gaps** are sections of active faults that haven't experienced significant earthquakes for a long period of time. One seismic gap in the San Andreas Fault cuts through San Francisco. This section of the fault hasn't ruptured since the devastating earthquake that struck the city in 1906. Because of this inactivity, seismologists currently predict that there is a 67-percent probability that the San Francisco area will experience a magnitude-7 or higher quake within the next 30 years.

Figure 19-20 Lasers are just one technique being used to study earthquake probability in the area around Parkfield, California. Lasers can record very small movements along a fault.

Strain Accumulation The rate at which strain builds up in rocks is another factor used to determine the earthquake probability along a section of a fault. To predict when a quake might occur, scientists make several measurements. The strain accumulated in a particular part of the fault, together with how much strain was released during the last quake along that section of the fault, are two important factors in earthquake probability studies. Another factor is how much time has passed since an earthquake has struck that section of the fault.

Earthquake prediction is still a relatively new branch of geology. Being able to predict these destructive events can prevent damage to property, possibly reduce the number of injuries as a result of the quake, and, most importantly, save many lives.

Section Assessment

1. Describe structural damage caused by earthquakes.
2. What are some of the effects caused by soil liquefaction?
3. How are tsunamis generated?
4. What are some of the factors considered in earthquake probability studies?
5. **Thinking Critically** Which structure is less likely to suffer severe damage during an earthquake: a high-rise, steel-frame hotel built on sediments, or a wood-frame house built on bedrock? Explain.

Skill Review

6. **Comparing and Contrasting** Compare and contrast the seismic risk of your state to at least three neighboring states. For more help, refer to the *Skill Handbook*.

earthgeu.com/self_check_quiz

GeoLab

Locating an Epicenter

The separation of P- and S-waves on a seismogram allows you to estimate the distance between the seismic station that recorded the data and the epicenter of that earthquake. If the epicentral distance from three or more seismic stations is known, then the exact location of the quake's epicenter can be determined.

Preparation

Problem

Determine the epicenter location and the time of occurrence of an actual earthquake, using the travel times of P- and S-waves recorded at three seismic stations.

Materials

Figures 17-13, 19-8, and *19-9*

map on facing page
drafting compass
tracing paper
calculator
metric ruler

Objectives

In this GeoLab, you will:

- **Determine** the arrival times of P- and S-waves from a seismogram.
- **Interpret** travel-time curves.
- **Plot** an epicenter location on a map.
- **Relate** seismic data to plate tectonics.

Safety Precaution

Procedure

1. The seismogram in ***Figure 19-8*** shows the arrival time of the first P-wave at 10 h, 50 min, 32 s GMT, Greenwich mean time. Estimate the arrival time of the first S-wave to the nearest tenth of a minute.

2. Subtract this S-wave time from the initial P-wave time. What is the P-S separation on the seismogram, in minutes and tenth of minutes? Enter this value in the data table for the Berkeley seismic station.

GeoLab Data Table

Seismic Station	P-S Separation *(min)*	Epicenter Distance *(km)*	Map Distance *(cm)*
Berkeley, CA	3.9	2300	4.6
Boulder, CO	3.6	1900	3.8
Knoxville, TN	4.9	2600	5.2

3. The P-S separation observed on two other seismograms, which are not shown, are also listed in the table. Use the travel-time curves in ***Figure 19-9*** to determine the distances at which the P- and S-curves are separated by the time intervals listed in the table. Enter these distances in the table under the Epicenter Distance.
4. Carefully trace the map on this page. Accurately mark the three seismic station locations.
5. Determine the epicentral distances on your tracing, using a scale of about 0.9 cm = 500 km. Enter your values in the table under the Map Distance.
6. Use the compass to draw circles around each station on the map with the radius of each circle equal to the map distance, in cm, for that station.
7. Mark the point of intersection. This is the epicenter of the earthquake.
8. Determine the time of occurrence of this earthquake by reading the P-wave travel time from ***Figure 19-9*** for the epicentral distance for Berkeley. Subtract this from the initial P-wave arrival time at Berkeley, which was 10 h, 50.5 min. Express this time in terms of hours, minutes, and seconds.

Analyze

1. Where is this epicenter located?
2. In which major seismic belt did this earthquake occur?
3. Use ***Figure 17-13*** to determine which plates form the boundary associated with this earthquake.

Conclude & Apply

1. What type of plate boundary is this?
2. Briefly describe the relative motion of the plates involved.
3. Describe the tectonic motions that caused the earthquake.

Science in the News

Earthquake in Iran

At 5:26 am local time on December 26, 2003, an earthquake rocked the city of Bam, located in southeastern Iran. Some residents were already sleeping outside due to a foreshock that occurred the previous evening. The earthquake had a magnitude of 6.6 and caused extensive damage in terms of human life and property, including leveling an ancient fortress that had been a World Heritage Site.

It is estimated that as many as 40,000 people were killed in the quake, up to 30,000 more were injured, and more than 75,000 people were left without homes. Eighty-five percent of the buildings in the city were damaged or destroyed, and the water supply system was damaged. A 2,000-year-old citadel, Arg-e Bam, thought to be the world's greatest mud fortress, was reduced to rubble as a result of the quake. The historic fortress was the city's most popular tourist attraction.

Tectonic Factors

The southeastern portion of Iran is a seismically active area. Although no earthquakes have previously been reported in Bam, major earthquakes have occurred in the region northwest of Bam. Between 1981 and 1998, four earthquakes with magnitudes greater than 5.6 occurred in this area. The origin of the December 26 quake is thought to be the Bam fault, a fault line that runs north-south through the region. According to the U.S. Geological Survey, the quake occurred as a result of stresses created by the motion of the Arabian plate northward against the Eurasian plate at a rate of approximately 3 cm/yr. The horizontal and vertical movement along a strike-slip fault resulted in the destruction of homes and buildings throughout Bam.

The Aftermath

Immediately following the quake, rescue efforts and humanitarian aid were launched by international organizations such as the United Nations and the Red Cross. Food, water, shelter, and medical services were provided to victims through relief efforts and donations. Search teams found one man alive beneath rubble 13 days after the quake struck. Initial estimates for recovery and rebuilding of the city of Bam were between $70 million and $1 billion dollars. The World Health Organization estimated that 30 million dollars would be needed to reestablish Bam's health services. Two hospitals were destroyed and half of Bam's health workers were killed in the earthquake. A minimum estimate of two years was given by the United Nations Office of Coordination of Human Affairs for rebuilding the fallen city.

Activity

Dealing with disasters of the magnitude of the Bam earthquake can seem overwhelming. Contact emergency preparedness agencies in your area to find out what steps have been taken to locally prepare for natural disasters. What kinds of disasters do these agencies primarily prepare for? Make a pamphlet to summarize your findings.

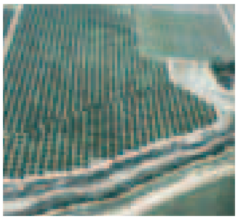
CHAPTER 19

Study Guide

Summary

Section 19.1

Forces Within Earth



Main Ideas

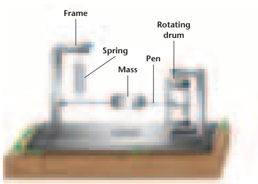
- Stress is a force per unit area that acts on a material. The deformation of materials in response to stress is called strain.
- Reverse faults form as a result of horizontal compression; normal faults, horizontal tension; strike-slip faults, horizontal shear.
- P-waves squeeze and pull rocks in the same direction along which the waves travel. S-waves cause rocks to move at right angles to the direction of the waves. Surface waves cause both an up-and-down and a side-to-side motion as they pass through rocks.

Vocabulary

epicenter (p. 499)
fault (p. 497)
focus (p. 499)
primary wave (p. 498)
secondary wave (p. 498)
strain (p. 496)
stress (p. 495)
surface wave (p. 498)

Section 19.2

Seismic Waves and Earth's Interior



Main Ideas

- A seismometer has a frame that is anchored to the ground and a suspended mass. Because of inertia, the mass tends to stay at rest as the ground and, thus, the frame vibrate during a quake. The motion of the mass in relation to the frame is registered and recorded.
- Seismic waves are reflected and refracted as they strike different materials. Analysis of these waves has enabled scientists to determine the structure and composition of Earth's interior.

Vocabulary

seismogram (p. 500)
seismometer (p. 500)

Section 19.3

Measuring and Locating Earthquakes

Main Ideas

- Earthquake magnitude is a measure of the energy released during a quake and can be measured on the Richter scale. Intensity is a measure of the damage caused by a quake and is measured with the modified Mercalli scale.
- Data from at least three seismic stations are needed to locate an earthquake's epicenter.
- Most earthquakes occur in areas associated with plate boundaries called seismic belts.

Vocabulary

magnitude (p. 505)
modified Mercalli scale (p. 506)
moment magnitude scale (p. 506)
Richter scale (p. 505)

Section 19.4

Earthquakes and Society

Main Ideas

- Earthquakes cause structural collapse, landslides, soil liquefaction, fissures, fault scarps, uplift or subsidence, and tsunamis. Factors that affect the extent of damage done by a quake include the type of subsurface as well as the quality, height, and structure of buildings and other structures involved.
- The probability of an earthquake is based on the history of quakes in an area and the rate at which strain builds in the rocks.
- Seismic gaps are places along an active fault that haven't experienced significant earthquakes for a long period of time.

Vocabulary

seismic gap (p. 515)
tsunami (p. 513)

earthgeu.com/vocabulary_puzzlemaker

CHAPTER 19
Assessment

Understanding Main Ideas

1. What is stress?
- **a.** movement of waves parallel to rock particles
- **b.** deformation of a material caused by applied forces
- **c.** forces per unit area acting on a material
- **d.** unit of measure on the Richter scale

2. What is strain?
- **a.** forces per unit area acting on a material
- **b.** deformation of a material caused by applied forces
- **c.** unit of measure on the Mercalli scale
- **d.** travel time of seismic waves

3. Which type of seismic wave causes rock particles to move in the same direction as the wave movement?
- **a.** P-wave
- **b.** S-wave
- **c.** tension wave
- **d.** shear wave

4. What part of Earth doesn't receive direct P-waves from a quake?
- **a.** epicenter
- **b.** focus
- **c.** shadow zone
- **d.** mantle

5. Which is used to measure magnitude?
- **a.** Richter scale
- **b.** Mercalli scale
- **c.** shadow zone
- **d.** seismic gap

6. What is earthquake intensity?
- **a.** a measure of the energy released
- **b.** a measure of seismic risk
- **c.** a measure of damage done
- **d.** a measure of the quake's focus

7. What is a seismic gap?
- **a.** a large fault scarp
- **b.** a part of an active fault that hasn't recently experienced seismic activity
- **c.** the time separation between P- and S-waves
- **d.** the liquefaction of soil during a quake

8. Compare and contrast the three types of faults.

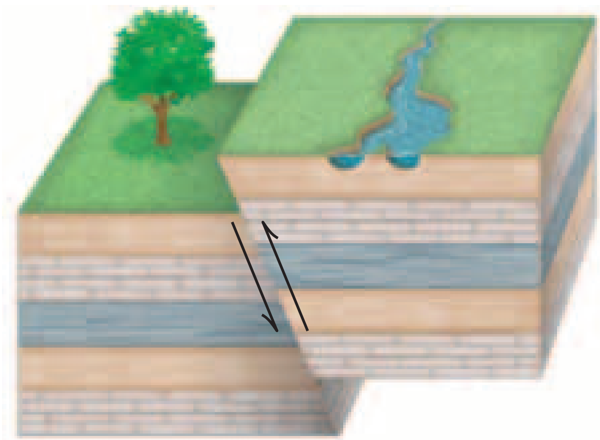
9. Draw three diagrams to show how each type of seismic wave moves through rocks.

10. Explain how a seismometer works.

11. How have seismic waves been used to determine Earth's structure and composition?

12. Why are data from at least three seismic stations needed to locate an epicenter?

Use this figure to answer questions 13–15.



13. What type of fault is shown?

14. What type of force caused this fault to form?

15. Where is the fault plane?

16. Explain the relationship between worldwide earthquake distribution and tectonic boundaries.

17. What factors affect the damage done by an earthquake?

Test-Taking Tip

MORE THAN ONE GRAPHIC If a test question refers to more than one table, graph, diagram, or drawing, use them all. If you answer based on just one graphic, you'll probably miss an important piece of information.

18. What factors are studied in the field of earthquake probability?

Applying Main Ideas

19. Explain why a stress-strain curve usually has two segments.
20. Why do surface waves cause so much destruction?
21. Why are two types of seismometers generally used to record the same earthquake?
22. How were P-waves and S-waves used to determine the physical state of Earth's core?
23. Compare and contrast the Richter scale and the moment magnitude scale.
24. Explain how shear stress is different from tension and compression.
25. Compare and contrast the composition of Earth's mantle and core with the composition of meteorites.

Thinking Critically

26. How do you think a thin, plastic, ruler would react to a small amount of stress? What would happen if the stress applied exceeded the elastic limit of the ruler?
27. Describe several reasons why an earthquake of magnitude-3 can cause more damage than a quake of magnitude-6.
28. Why are tsunamis so destructive?
29. If rocks below the lithosphere are too hot to undergo brittle fracture, how is it possible to have deep-focus earthquakes beneath island arcs?
30. Refer to ***Figure 19-19*** on page 514. Explain why some areas in the eastern part of the United States are prone to major earthquake damage even though these places are far from present tectonic plate boundaries.

Standardized Test Practice

1. What happens to a material when it undergoes stress that exceeds its strength?
   a. The material undergoes ductile formation.
   b. The material is deformed permanently.
   c. The material returns to its original state.
   d. The material breaks or fails.

2. What is the order in which seismic waves are recorded by a seismometer?
   a. S-wave, P-wave, surface wave
   b. surface wave, P-wave, S-wave
   c. P-wave, S-wave, surface wave
   d. S-wave, surface wave, P-wave

INTERPRETING DATA Use the table below to answer questions 3 and 4.

Some Earthquakes In Recent History

Location	Year	Richter Magnitude
Chile	1960	8.5
California	1906	7.9
Alaska	1964	8.6
Columbia	1994	6.8
Taiwan	1999	7.6

3. Approximately how much more energy was released by the Chilean quake than the Taiwan earthquake?
   a. twice as much
   b. ten times as much
   c. thirty two times as much
   d. one thousand times as much

4. Approximately how much larger was the amplitude of the waves generated by the Alaskan quake than the Taiwan quake?
   a. about twice as large
   b. about ten times as large
   c. about one hundred times as large
   d. about one thousand times as large

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