Chapter 8 Earthquakes and Earth’s Interior

Section 1 What Is an Earthquake?

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

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

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

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

Earthquakes
An earthquake is the vibration of Earth produced by the rapid release of energy. Earthquakes are often caused by slippage along a break in the lithosphere, called a fault. Faults are fractures in Earth where movement has occurred.

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

The focus of an earthquake is the place within Earth where the earthquake originates. When you see a news report about an earthquake, the reporter always mentions the place on Earth’s surface where the earthquake has been located. The epicenter is the location on the surface directly above the focus, as shown in Figure 2.
Figure 2 The focus of each earthquake is the place within Earth where the earthquake originated. The foci (plural of focus) are located along faults. The surface location directly above the focus is called the epicenter.

Predicting: Where do you think the damage from an earthquake is usually greatest?

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

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

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

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

Inferring: How do you think the temperature of rock would affect its ability to bend or break?

**Elastic Rebound Hypothesis**
The springing back of the rock into its original place is called elastic rebound. The rock behaves much like a stretched rubber band does when it is released. The explanation says that when rocks are deformed, they first bend and then break, releasing stored energy. This explanation for the release of energy stored in deformed rocks is called the elastic rebound hypothesis. Most earthquakes are produced by the rapid release of elastic energy stored in rock that has been subjected to great forces. When the strength of the rock is exceeded, it suddenly breaks, causing the vibrations of an earthquake. Earthquakes most often happen along existing faults. They occur when the frictional forces on the fault surfaces are overcome.

**Aftershocks and Foreshocks**
The intense shaking of the 1906 San Francisco earthquake lasted about 40 seconds. Most of the movement along the fault occurred in this short time period. However, additional movements along this and nearby faults continued for several days. The movements that follow a major earthquake often produce smaller earthquakes called aftershocks. These aftershocks are usually much weaker than the main earthquake, but they can sometimes destroy structures weakened by the main quake. Small earthquakes called foreshocks often come before a major earthquake. These foreshocks can happen days or even years before the major quake. The San Andreas Fault is the most studied fault system in the world. Studies have shown that displacement has occurred along segments that are 100 to 200 kilometers long. Each fault segment behaves a bit differently than the other segments. Some parts of the San Andreas show a slow, gradual movement known as fault creep. This movement happens fairly smoothly. Other segments regularly slip and produce small earthquakes. However, some segments stay locked and store elastic energy for hundreds of years before they break and cause great earthquakes.

Section 2 Measuring Earthquakes
Key Concepts
- What are the types of seismic waves?
- How is an earthquake epicenter located?
- How is the size of an earthquake measured?

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

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

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

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

Figure 6 Typical Seismogram The first wave to arrive is the P wave, followed later by S waves. The last waves recorded are the surface waves.

Measuring: What is the time interval in minutes between the start of the first P wave and the start of the first S wave?

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

**Surface Waves**

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

![Figure 7](image)

**Figure 7** Each type of seismic wave has characteristic motions.

**Body Waves**

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

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

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

Earthquake Distance

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

Figure 8 Locating an Earthquake

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

Earthquake Direction

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

**Earthquake Zones**

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

![Figure 9 Distribution of the 14,229 earthquakes with magnitudes equal to or greater than 5 from 1980 to 1990.](image)

Observing Where do you find most of the earthquakes—in the interiors of the continents or at the edges?

**Measuring Earthquakes**

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

**Richter Scale**

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

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

**Moment Magnitude**

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

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

### Table 1  Earthquake Magnitudes and Expected World Incidence

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

### Table 2  Some Notable Earthquakes

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

### Section 3  Destruction from Earthquakes

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

**Vocabulary**
- liquefaction
- tsunami
- seismic gap

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

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

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

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

Reading Checkpoint
(a) When does liquefaction occur?

Tsunamis
Most deaths associated with the 1964 Alaskan quake were caused by seismic sea waves, or tsunamis. These destructive waves often are called tidal waves by news reporters. However, this name is incorrect because these waves are not produced by the tidal effect of the moon or sun.
Causes of Tsunamis
A tsunami triggered by an earthquake occurs where a slab of the ocean floor is displaced vertically along a fault. A tsunami also can occur when the vibration of a quake sets an underwater landslide into motion. Once formed, a tsunami resembles the ripples created when a pebble is dropped into a pond. A tsunami travels across the ocean at speeds of 500 to 950 kilometers per hour. Despite this speed, a tsunami in the open ocean can pass without notice because its height is usually less than 1 meter, and the distance between wave crests can range from 100 to 700 kilometers. However, when the wave enters shallower coastal water, the waves are slowed and the water begins to pile up to heights that sometimes are greater than 30 meters, as shown in Figure 11.

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

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

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

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

Landslides
With many earthquakes, the greatest damage to structures is from landslides and ground subsidence, or the sinking of the ground triggered by the vibrations. The violent shaking of an earthquake can cause the soil and rock on slopes to fail, resulting in landslides. Figure 12 shows some of the damage landslides can cause. Earthquake vibration can also cause large sections of the ground to collapse, liquefy, or subside. Ground subsidence can cause foundations to collapse, as shown in Figure 12. It can also rupture gas and water pipelines.
Figure 12: This landslide caused by the 1964 Alaskan earthquake destroyed many homes. More than 200 acres of land slid toward the ocean. Interpreting Photos: Assuming the land was originally horizontal, to what angle have the trees on the left side of the photo been tilted?

**Fire**

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

**Predicting Earthquakes**

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

**Short-Range Predictions**

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

**Long-Range Forecasts**

Long-range forecasts give the probability of a certain magnitude earthquake occurring within 30 to 100-plus years. These data are important for updating building codes, which have standards for designing earthquake-resistant structures. Long-range forecasts are based on the idea that earthquakes are repetitive or cyclical. In other words, as soon as one earthquake is over, the forces in Earth will begin to build strain in the rocks again. Eventually the rocks will slip again, causing another earthquake. Scientists study historical records of earthquakes to see if there are any patterns of recurrence. They also study seismic gaps. A seismic gap is an area along a fault where there has not been any earthquake activity for a long period of time. There has been only limited success in long-term forecasting. Scientists don’t yet understand enough about how and where earthquakes will occur to make accurate long-term predictions.
Earth’s interior lies not very far beneath our feet, but we can’t reach it. The deepest well has drilled only 12 kilometers into Earth’s crust. With such limited access, how do we know what Earth’s interior is like? Most knowledge of the interior comes from the study of earthquake waves that travel through Earth.

Layers Defined by Composition

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

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

Crust

The crust, the thin, rocky outer layer of Earth, is divided into oceanic and continental crust. The oceanic crust is roughly 7 kilometers thick and composed of the igneous rocks basalt and gabbro. The continental crust is 8–75 kilometers thick, but averages a thickness of 40 kilometers. It consists of many rock types. The average composition of the continental crust is granitic rock called granodiorite. Continental rocks have an average density of about 2.7 g/cm³ and some are over 4 billion years old. The rocks of the oceanic crust are younger (180 million years or less) and have an average density of about 3.0 g/cm³.

Mantle
Over 82 percent of Earth’s volume is contained in the mantle—a solid, rocky shell that extends to a depth of 2890 kilometers. The boundary between the crust and mantle represents a change in chemical composition. The dominant rock type in the uppermost mantle is peridotite, which has a density of 3.4 g/cm³.

Core
The core is a sphere composed of an iron-nickel alloy. At the extreme pressures found in the center of the core, the iron-rich material has an average density of almost 13 g/cm³ (13 times heavier than water).

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

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

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

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

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

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

Figure 15 Earth’s Layered Structure The left side of the globe shows that Earth’s interior is divided into three different layers based on compositional differences—the crust, mantle, and core. The right side of the globe shows the five main layers of Earth’s interior based on physical properties and mechanical strength—the lithosphere, asthenosphere, mesosphere, outer core, and inner core. The block diagram shows an enlarged view of the upper portion of Earth’s interior.
Discovering Earth’s Layers
In 1909, a Croatian seismologist, Andrija Mohorovičić, presented evidence for layering within Earth. By studying seismic records, he found that the velocity of seismic waves increases abruptly below about 50 kilometers of depth. This boundary separates the crust from the underlying mantle and is known as the Mohorovičić discontinuity. The name is usually shortened to Moho.

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

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

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

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

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

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

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

Tsunami

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

Landslide

In January 2001, an earthquake struck El Salvador. It caused the landslide that left these Salvadoran women homeless. A landslide is a sudden drop of a mass of land down a mountainside or hillside. Emergency relief workers from around the world often rush to the site of an earthquake disaster like the one that occurred in El Salvador.
INFRASTRUCTURE DAMAGE
When an earthquake occurred in Los Angeles in 1994, underground gas and water lines burst, causing fires and floods. Earthquakes often cause tremendous damage to the infrastructure—the network of services that supports a community. Infrastructure includes power utilities, water supplies, and transportation and communication facilities.

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

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

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

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