HS Earthquakes

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CHAPTER

HS Earthquakes

CHAPTER OUTLINE

- 1.1 Stress in Earth's Crust
- 1.2 The Nature of Earthquakes
- 1.3 Measuring and Predicting Earthquakes
- 1.4 Staying Safe in Earthquakes
- 1.5 References



A portion of the 800-mile-long San Andreas Fault as it runs through the San Francisco Bay Area is seen from the upper left to the lower right of this image. The development in pink and green is San Mateo and Burlingame. Foster City, which is built on fill, has curved streets extending into the bay. The fault forms a trough that is filled with water at Crystal Springs Reservoir. Scientists will use space-based radar along this same flight path over the next years to look for changes in the ground surface along the fault.

1.1 Stress in Earth's Crust

Lesson Objectives

- List the different types of stresses that cause different types of deformation.
- Compare the different types of folds and the conditions under which they form.
- Compare fractures and faults and define how they are related to earthquakes.
- Compare how mountains form and at what types of plate boundaries they form.

Vocabulary

- anticline
- basin
- compression
- confining stress
- deformation
- dip
- dip-slip fault
- dome
- elastic deformation
- fault
- fold
- fracture
- joint
- monocline
- normal fault
- plastic deformation
- reverse fault
- shear
- slip
- strain
- stress
- strike-slip fault
- syncline
- tension
- thrust fault
- uplift

Introduction

Enormous slabs of lithosphere move unevenly over the planet's spherical surface, resulting in earthquakes. This chapter deals with two types of geological activity that occur because of plate tectonics: mountain building and earthquakes. First, we will consider what can happen to rocks when they are exposed to stress.

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Causes and Types of Stress

Stress is the force applied to an object. In geology, stress is the force per unit area that is placed on a rock. Four types of stresses act on materials.

- A deeply buried rock is pushed down by the weight of all the material above it. Since the rock cannot move, it cannot deform. This is called **confining stress.**
- **Compression** squeezes rocks together, causing rocks to fold or fracture (break) (**Figure 1**.1). Compression is the most common stress at convergent plate boundaries.



FIGURE 1.1 Stress caused these rocks to fracture.

- Rocks that are pulled apart are under **tension**. Rocks under tension lengthen or break apart. Tension is the major type of stress at divergent plate boundaries.
- When forces are parallel but moving in opposite directions, the stress is called **shear** (**Figure 1**.2). Shear stress is the most common stress at transform plate boundaries.



FIGURE 1.2

Shearing in rocks. The white quartz vein has been elongated by shear.

When stress causes a material to change shape, it has undergone **strain** or **deformation**. Deformed rocks are common in geologically active areas.

A rock's response to stress depends on the rock type, the surrounding temperature, and pressure conditions the rock is under, the length of time the rock is under stress, and the type of stress.

Rocks have three possible responses to increasing stress (illustrated in **Figure 1.3**):

- elastic deformation: the rock returns to its original shape when the stress is removed.
- plastic deformation: the rock does not return to its original shape when the stress is removed.



FIGURE 1.3 With increasing stress, the rock undergoes: (1) elastic deformation, (2) plastic deformation, and (3) fracture.

• **fracture**: the rock breaks.

Under what conditions do you think a rock is more likely to fracture? Is it more likely to break deep within Earth's crust or at the surface? What if the stress applied is sharp rather than gradual?

- At the Earth's surface, rocks usually break quite quickly, but deeper in the crust, where temperatures and pressures are higher, rocks are more likely to deform plastically.
- Sudden stress, such as a hit with a hammer, is more likely to make a rock break. Stress applied over time often leads to plastic deformation.

Geologic Structures

Sedimentary rocks are important for deciphering the geologic history of a region because they follow certain rules.

- 1. Sedimentary rocks are formed with the oldest layers on the bottom and the youngest on top.
- 2. Sediments are deposited horizontally, so sedimentary rock layers are originally horizontal, as are some volcanic rocks, such as ash falls.
- 3. Sedimentary rock layers that are not horizontal are deformed.

You can trace the deformation a rock has experienced by seeing how it differs from its original horizontal, oldest-onbottom position (**Figure 1.4**). This deformation produces geologic structures such as folds, joints, and faults that are caused by stresses (**Figure 1.4**). Using the rules listed above, try to figure out the geologic history of the geologic column below.

Folds

Rocks deforming plastically under compressive stresses crumple into **folds** (**Figure 1.5**). They do not return to their original shape. If the rocks experience more stress, they may undergo more folding or even fracture.

Three types of folds are seen.

• Mononcline: A **monocline** is a simple bend in the rock layers so that they are no longer horizontal (see **Figure** 1.6 for an example).



(a) In the Grand Canyon, the rock layers are exposed like a layer cake. Each layer is made of sediments that were deposited in a particular environment - perhaps a lake bed, shallow offshore region, or a sand dune. (b) In this geologic column of the Grand Canyon, the sedimentary rocks of groups 3 through 6 are still horizontal. Group 2 rocks have been tilted. Group 1 rocks are not sedimentary. The oldest layers are on the bottom and youngest are on the top.



FIGURE 1.5

Snow accentuates the fold exposed in these rocks in Provo Canyon, Utah.



FIGURE 1.6

At Colorado National Monument, the rocks in a monocline plunge toward the ground.

1.1. Stress in Earth's Crust

• Anticline: An **anticline** is a fold that arches upward. The rocks dip away from the center of the fold (**Figure** 1.7). The oldest rocks are at the center of an anticline and the youngest are draped over them.



FIGURE 1.7(a) Schematic of an anticline.(b) Ananticline exposed in a road cut in NewJersey.

When rocks arch upward to form a circular structure, that structure is called a **dome.** If the top of the dome is sliced off, where are the oldest rocks located?

• Syncline: A syncline is a fold that bends downward. The youngest rocks are at the center and the oldest are at the outside (Figure 1.8).



FIGURE 1.8(a) Schematic of a syncline. (b) This syncline is in Rainbow Basin, California.

When rocks bend downward in a circular structure, that structure is called a **basin** (**Figure** 1.9). If the rocks are exposed at the surface, where are the oldest rocks located?

Faults

A rock under enough stress will fracture. If there is no movement on either side of a fracture, the fracture is called a **joint**, as shown in (**Figure 1**.10).

If the blocks of rock on one or both sides of a fracture move, the fracture is called a **fault** (**Figure 1.11**). Sudden motions along faults cause rocks to break and move suddenly. The energy released is an earthquake.

Slip is the distance rocks move along a fault. Slip can be up or down the fault plane. Slip is relative, because there is usually no way to know whether both sides moved or only one. Faults lie at an angle to the horizontal surface of



Basins can be enormous. This is a geologic map of the Michigan Basin, which is centered in the state of Michigan but extends into four other states and a Canadian province.



FIGURE 1.10

Granite rocks in Joshua Tree National Park showing horizontal and vertical jointing. These joints formed when the confining stress was removed from the granite.



FIGURE 1.11

Faults are easy to recognize as they cut across bedded rocks.

1.1. Stress in Earth's Crust

the Earth. That angle is called the fault's **dip**. The dip defines which of two basic types a fault is. If the fault's dip is inclined relative to the horizontal, the fault is a **dip-slip fault** (**Figure 1.12**). There are two types of dip-slip faults. In **normal faults**, the hanging wall drops down relative to the footwall. In **reverse faults**, the footwall drops down relative to the hanging wall.



FIGURE 1.12

This diagram illustrates the two types of dip-slip faults: normal faults and reverse faults. Imagine miners extracting a resource along a fault. The hanging wall is where miners would have hung their lanterns. The footwall is where they would have walked.

An animation of a normal fault is seen here: http://earthquake.usgs.gov/learn/animations/animation.php?flash_titl e=Normal+Fault&flash_file=normalfault&flash_width=220&flash_height=320.

A **thrust fault** is a type of reverse fault in which the fault plane angle is nearly horizontal. Rocks can slip many miles along thrust faults (**Figure 1.13**).

An animation of a thrust fault is seen here: http://earthquake.usgs.gov/learn/animations/animation.php?flash_titl e=Thrust+Fault&flash_file=thrustfault&flash_width=220&flash_height=320.



FIGURE 1.13

At Chief Mountain in Montana, the upper rocks at the Lewis Overthrust are more than 1 billion years older than the lower rocks. How could this happen?

Normal faults can be huge. They are responsible for uplifting mountain ranges in regions experiencing tensional stress (**Figure 1.14**).

A **strike-slip fault** is a dip-slip fault in which the dip of the fault plane is vertical. Strike-slip faults result from shear stresses. (**Figure 1.15**).

California's San Andreas Fault is the world's most famous strike-slip fault. It is a right-lateral strike slip fault (**Figure** 1.16).



FIGURE 1.14 The Teton Range in Wyoming rose up along a normal fault.



FIGURE 1.15

Imagine placing one foot on either side of a strike-slip fault. One block moves toward you. If that block moves toward your right foot, the fault is a right-lateral strike-slip fault; if that block moves toward your left foot, the fault is a left-lateral strike-slip fault.

A strike-slip fault animation: http://earthquake.usgs.gov/learn/animations/animation.php?flash_title=Strike-Slip+Fa ult&flash_file=strikeslip&flash_width=240&flash_height=310.

People sometimes say that California will fall into the ocean someday, which is not true. This animation shows movement on the San Andreas into the future: http://visearth.ucsd.edu/VisE_Int/aralsea/bigone.html.

Stress and Mountain Building

Two converging continental plates smash upwards to create mountain ranges (**Figure 1.17**). Stresses from this **uplift** cause folds, reverse faults, and thrust faults, which allow the crust to rise upwards.

Subduction of oceanic lithosphere at convergent plate boundaries also builds mountain ranges (Figure 1.18).

When tensional stresses pull crust apart, it breaks into blocks that slide up and drop down along normal faults. The result is alternating mountains and valleys, known as a basin-and-range (**Figure** 1.19).

This is a very quick animation of movement of blocks in a basin-and-range setting: http://earthquake.usgs.gov/learn/animations/animation.php?flash_title=Horst+%26amp%3B+Graben&flash_file=horstandgraben&flash_width=380&flash_height=210.



The San Andreas is a massive transform fault.

Lesson Summary

- Stress is the force applied to a rock and may cause deformation. The three main types of stress are typical of the three types of plate boundaries: compression at convergent boundaries, tension at divergent boundaries, and shear at transform boundaries.
- Where rocks deform plastically, they tend to fold. Brittle deformation brings about fractures and faults.
- The two main types of faults are dip-slip (the fault plane is inclined to the horizontal) and strike-slip (the fault plane is perpendicular to the horizontal).
- The world's largest mountains grow at convergent plate boundaries, primarily by thrust faulting and folding.

Review Questions

- 1. Why don't rocks deform under confining stress?
- 2. What type of stress is compression and at what type of plate boundary is this found?
- 3. What type of stress is tension and at what type of plate boundary is it found?



FIGURE 1.17	
(a) The world	



The Andes Mountains are a chain of continental arc volcanoes that build up as the Nazca Plate subducts beneath the South American Plate.

- 4. What type of stress is shear and at what type of plate boundary is it found?
- 5. What is the difference between plastic and elastic strain?
- 6. Under what conditions is a rock more likely to deform plastically than to break?
- 7. In the picture of the Grand Canyon geologic column (Figure 1.4), what type of fold do you see?
- 8. While walking around in the field, you spot a monocline. The fossils indicate that the oldest rocks are at the top and the youngest at the bottom. How do you explain this?
- 9. Describe an anticline and name the age order of rocks.
- 10. Describe a syncline and name the age order of rocks.
- 11. What are domes and basins and what is the age order of rocks in each?
- 12. Name one similarity and one difference between a fracture and a fault.
- 13. What are the two types of dip-slip faults and how are they different from each other?
- 14. Why are so many severe earthquakes located along the San Andreas Fault?
- 15. Describe the plate tectonics processes and associated stresses that have led to the formation of the Himalayas, the world's largest mountain range.



(a) In basin-and-range, some blocks are uplifted to form ranges, known as horsts, and some are down-dropped to form basins, known as grabens. (b) Mountains in Nevada are of classic basin-and-range form. The photographer is in the Nopah Range and is looking across a basin to the Kingston Range beyond.

Points to Consider

- Where in an ocean basin would you find features that indicate tensional stresses? Where would you find the features that indicate compressional stresses?
- Earthquakes are primarily the result of plate tectonic motions. List the three types of plate boundaries and what you think the stresses are that would cause earthquakes there.
- Which type of plate boundary do you think has the most dangerous earthquakes? How do earthquakes cause the greatest damage?

1.2 The Nature of Earthquakes

Lesson Objectives

- Be able to identify an earthquake focus and its epicenter.
- Identify earthquake zones and what makes some regions prone to earthquakes.
- Compare the characteristics of the different types of seismic waves.
- Describe how tsunamis are caused by earthquakes, particularly using the 2004 Boxing Day Tsunami as an example.

Vocabulary

- amplitude
- body waves
- crest
- earthquake
- elastic rebound theory
- focus
- seismology
- surface waves
- trough
- tsunami
- wavelength

Introduction

An **earthquake** is sudden ground movement caused by the sudden release of energy stored in rocks. Earthquakes happen when so much stress builds up in the rocks that the rocks rupture. The energy is transmitted by seismic waves. Each year there are more than 150,000 earthquakes strong enough to be felt by people and 900,000 recorded by seismometers!

Causes of Earthquakes

The description of how earthquakes occur is called elastic rebound theory (Figure 1.20).

Elastic rebound theory in an animation: http://earthquake.usgs.gov/learn/animations/animation.php?flash_title=El astic+Rebound&flash_file=elasticrebound&flash_width=300&flash_height=350.

In an earthquake, the initial point where the rocks rupture in the crust is called the **focus**. The epicenter is the point on the land surface that is directly above the focus. In about 75% of earthquakes, the focus is in the top 10 to 15 kilometers (6 to 9 miles) of the crust. Shallow earthquakes cause the most damage because the focus is near where people live. However, it is the epicenter of an earthquake that is reported by scientists and the media (**Figure 1**.21).

This animation shows the relationship between focus and epicenter of an earthquake: http://highered.mcgraw-hill. com/olcweb/cgi/pluginpop.cgi?it=swf::640::480::/sites/dl/free/0072402466/30425/16_04.swf::Fig.%20%2016.4%20-%20Focus%20of%20an%20Earthquake.



Elastic rebound theory. Stresses build on both sides of a fault, causing the rocks to deform plastically (Time 2). When the stresses become too great, the rocks break and end up in a different location (Time 3). This releases the built up energy and creates an earthquake.



FIGURE 1.21

In the vertical cross section of crust, there are two features labeled - the focus and the epicenter, which is directly above the focus.

Earthquake Zones

Nearly 95% of all earthquakes take place along one of the three types of plate boundaries, but earthquakes do occur along all three types of plate boundaries.

- About 80% of all earthquakes strike around the Pacific Ocean basin because it is lined with convergent and transform boundaries (**Figure** 1.22).
- About 15% take place in the Mediterranean-Asiatic Belt, where convergence is causing the Indian Plate to run into the Eurasian Plate.
- The remaining 5% are scattered around other plate boundaries or are intraplate earthquakes.

Transform plate boundaries

Deadly earthquakes occur at transform plate boundaries. Transform faults have shallow focus earthquakes. Why do you think this is so? The faults along the San Andreas Fault zone produce around 10,000 earthquakes a year.



Earthquake epicenters for magnitude 8.0 and greater events since 1900. The earthquake depth shows that most large quakes are shallow focus, but some subducted plates cause deep focus quakes.

Most are tiny, but occasionally one is massive. In the San Francisco Bay Area, the Hayward Fault was the site of a magnitude 7.0 earthquake in 1868. The 1906 quake on the San Andreas Fault had a magnitude estimated at about 7.9 (**Figure 1.23**).



FIGURE 1.23

(a) The San Andreas Fault zone in the San Francisco Bay Area. (b) The 1906 San Francisco earthquake is still the most costly natural disaster in California history. About 3,000 people died and 28,000 buildings were lost, mostly in the fire.

Recent California earthquakes:

- 1989: Loma Prieta earthquake near Santa Cruz, California. Magnitude 7.1 quake, 63 deaths, 3,756 injuries, 12,000+ people homeless, property damage about \$6 billion.
- 1994: Northridge earthquake on a blind thrust fault near Los Angeles. Magnitude 6.7, 72 deaths, 12,000

1.2. The Nature of Earthquakes

injuries, damage estimated at \$12.5 billion.

Although California is prone to many natural hazards, including volcanic eruptions at Mt. Shasta or Mt. Lassen, and landslides on coastal cliffs, the natural hazard the state is linked with is earthquakes. In this video, the boundaries between three different tectonic plates and the earthquakes that result from their interactions are explored (9b): http://www.youtube.com/watch?v=upEh-1DpLMg (1:59).





New Zealand also has strike-slip earthquakes, about 20,000 a year! Only a small percentage of those are large enough to be felt. A 6.3 quake in Christchurch in February 2011 killed about 180 people.

Convergent plate boundaries

Earthquakes at convergent plate boundaries mark the motions of subducting lithosphere as it plunges through the mantle (**Figure 1.24**). Eventually the plate heats up enough deform plastically and earthquakes stop.



FIGURE 1.24

This cross section of earthquake epicenters with depth outlines the subducting plate with shallow, intermediate, and deep earthquakes.

Convergent plate boundaries produce earthquakes all around the Pacific Ocean basin. The Philippine Plate and the Pacific Plate subduct beneath Japan, creating a chain of volcanoes and as many as 1,500 earthquakes annually.

In March 2011 an enormous 9.0 earthquake struck off of Sendai in northeastern Japan. This quake, called the 2011 Tōhoku earthquake, was the most powerful ever to strike Japan and one of the top five known in the world. Damage from the earthquake was nearly overshadowed by the tsunami it generated, which wiped out coastal cities and towns (**Figure 1.25**). Two months after the earthquake, about 25,000 people were dead or missing, and 125,000 buildings had been damaged or destroyed. Aftershocks, some as large as major earthquakes, have continued to rock the region.

A map of aftershocks is seen here: http://earthquake.usgs.gov/earthquakes/seqs/events/usc0001xgp/.

Here is an interactive feature article about the earthquake: http://www.nytimes.com/interactive/2011/03/11/world/ asia/maps-of-earthquake-and-tsunami-damage-in-japan.html.



FIGURE 1.25 Destruction in Ofunato, Japan, from the 2011 T

The Pacific Northwest of the United States is at risk from a potentially massive earthquake that could strike any time. Subduction of the Juan de Fuca plate beneath North America produces active volcanoes, but large earthquakes only hit every 300 to 600 years. The last was in 1700, with an estimated magnitude of around 9.

An image of earthquakes beneath the Pacific Northwest and the depth to the epicenter is shown here: http://pubs.usgs.gov/ds/91/.

Elastic rebound at a subduction zone generates an earthquake in this animation: http://www.iris.edu/hq/files/pro grams/education_and_outreach/aotm/5/AOTF5_Subduction_ElasticRebound480.mov.

Massive earthquakes are the hallmark of the thrust faulting and folding when two continental plates converge (**Figure** 1.26). The 2001 Gujarat earthquake in India was responsible for about 20,000 deaths, and many more people became injured or homeless.

In Understanding Earthquakes: From Research to Resilience, scientists try to understand the mechanisms that cause earthquakes and tsunamis and the ways that society can deal with them (**3d**): http://www.youtube.com/watch?v=W 5Qz-aZ2nUM (8:06).



MEDIA Click image to the left for more content.

Divergent Plate Boundaries

Earthquakes at mid-ocean ridges are small and shallow because the plates are young, thin, and hot. On land where continents split apart, earthquakes are larger and stronger.



FIGURE 1.26			
Damage from the	2005	Kashmir	earth-
quake.			

Intraplate Earthquakes

Intraplate earthquakes are the result of stresses caused by plate motions acting in solid slabs of lithosphere. In 1812, a magnitude 7.5 earthquake struck near New Madrid, Missouri. The earthquake was strongly felt over approximately 50,000 square miles and altered the course of the Mississippi River. Because very few people lived there at the time, only 20 people died. Many more people live there today (**Figure 1**.27). A similar earthquake today would undoubtedly kill many people and cause a great deal of property damage.

Seismic Waves

Energy is transmitted in waves. Every wave has a high point called a **crest** and a low point called a **trough**. The height of a wave from the center line to its crest is its **amplitude**. The distance between waves from crest to crest (or trough to trough) is its **wavelength**. The parts of a wave are illustrated in **Figure** 1.28.

The energy from earthquakes travels in seismic waves, which were discussed in the chapter "Plate Tectonics." The study of seismic waves is known as **seismology.** Seismologists use seismic waves to learn about earthquakes and also to learn about the Earth's interior. The two types of seismic waves described in "Plate Tectonics," P-waves and S-waves, are known as **body waves** because they move through the solid body of the Earth. P-waves travel through solids, liquids, and gases. S-waves only move through solids. **Surface waves** travel along the ground, outward from an earthquake's epicenter. Surface waves are the slowest of all seismic waves, traveling at 2.5 km (1.5 miles) per second. There are two types of surface waves (**Figure 1**.29).

In an earthquake, body waves produce sharp jolts. The rolling motions of surface waves do most of the damage in an earthquake.

Interesting earthquake videos are seen at National Geographic Videos, Environment Video, Natural Disasters, Earthquakes: http://video.nationalgeographic.com/video/player/environment/. Titles include:

- Earthquake 101
- "Inside Earthquakes" looks at this sudden natural disaster.





The New Madrid Seismic Zone is within the North American plate. Around 4,000 earthquakes have occurred in the region since 1974.



FIGURE 1.28

The crest, trough, and amplitude are illustrated in this diagram.

Tsunami

Tsunami are deadly ocean waves from an earthquake. The sharp jolt of an undersea quake forms a set of waves that travel through the sea entirely unnoticed. When they come onto shore, they can grow to enormous heights. Fortunately, few undersea earthquakes generate tsunami.

How a tsunami forms is shown in this animation: http://highered.mcgraw-hill.com/olcweb/cgi/pluginpop.cgi?it=swf: :640::480::/sites/dl/free/0072402466/30425/16_19.swf::Fig.%2016.19%20-%20Formation%20of%20a%20Tsunam i.

The Boxing Day Tsunami of December 26, 2004 was by far the deadliest of all time (**Figure 1.30**). The tsunami was caused by the 2004 Indian Ocean Earthquake. With a magnitude of 9.2, it was the second largest earthquake ever recorded. The extreme movement of the crust displaced trillions of tons of water along the entire length of the rupture. Several tsunami waves were created with about 30 minutes between the peaks of each one. The waves that



P-waves move material forward and backward in the direction they are traveling. The material returns to its original size and shape after the P-wave goes by. S-waves move up and down, perpendicular to the direction the wave is traveling. This motion produces shear stresses.

struck nearby Sumatra 15 minutes after the quake reached more than 10 meters (33 feet) in height. The size of the waves decreased with distance from the earthquake and were about 4 meters (13 feet) high in Somalia.





About 230,000 people died in eight countries (**Figure 1.31**) with fatalities even as far away as South Africa, nearly 8,000 kilometers (5,000 miles) from the earthquake epicenter. More than 1.2 million people lost their homes and many more lost their ways of making a living.



FIGURE 1.	31			
The Boxing Day tsunami strikes a beach				
in Thailand.				

The 2011 Tōhoku earthquake in Japan created massive tsunami waves that hit the island nation. As seen in **Figure** 1.32, waves in some regions topped 9 meters (27 feet). The tsunami did much more damage than the massive earthquake (**Figure** 1.33). Worst was the damage done to nuclear power plants along the northeastern coast.



FIGURE 1.32

This map shows the peak tsunami wave heights.

As a result of the 2004 tsunami, an Indian Ocean warning system was put into operation in June 2006. Prior to 2004, no one had thought a large tsunami was possible in the Indian Ocean. In comparison, a warning system has been in effect around the Pacific Ocean for more than 50 years (**Figure** 1.34). Why do you think a Pacific warning system has been in place for so long? The system was used to warn of possible tsunami waves after the Tōhoku earthquake. People were evacuated along many pacific coastlines although the waves were not nearly as large as those that struck



An aerial view shows the damage to Sendai, Japan caused by the earthquake and tsunami. The black smoke is coming from an oil refinery, which was set on fire by the earthquake. The tsunami prevented efforts to extinguish the fire until several days after the earthquake.

Japan shortly after the quake.

FIGURE 1.34

This sign indicates a tsunami hazard zone in California.

Lesson Summary

- During an earthquake, the ground shakes as stored up energy is released from rocks.
- Elastic rebound theory states that rock will deform plastically as stresses build up until the stresses become too great and the rock breaks.
- Earthquakes occur at all types of plate boundaries.
- The Pacific Ocean basin and the Mediterranean-Asiatic Belt are the two geographic regions most likely to experience quakes.
- Surface waves do the most damage in an earthquake.
- Body waves travel through the planet and travel faster than surface waves.
- Tsunami are deadly ocean waves that are caused by undersea earthquakes.

Review Questions

- 1. What is an earthquake's focus? What is its epicenter?
- 2. Why do most earthquakes take place along plate boundaries?
- 3. Using elastic rebound theory, describe what triggers an earthquake.
- 4. Why are there far more earthquakes around the Pacific Ocean than anywhere else?
- 5. What causes intraplate earthquakes?
- 6. Besides the San Andreas Fault zone, what other type of plate boundary in or near California can produce earthquakes?
- 7. Using plate tectonics and elastic rebound theory, describe why Juan de Fuca plate subduction produces so few earthquakes. What will happen in the future?
- 8. What type of faulting is found where two slabs of continental lithosphere are converging?
- 9. What are the characteristics of body waves? What are the two types?
- 10. What types of materials can P-waves travel through and how fast are they? Describe a P-wave's motion.
- 11. What material can S-waves travel through and how fast are they? Describe an S-wave's motion.
- 12. How are surface waves different from body waves? Which are more damaging?

Further Reading / Supplemental Links

- The U.S. Geological survey earthquake site is found here: http://earthquake.usgs.gov/.
- Fault line discusses seismic science: http://www.exploratorium.edu/faultline/index.html.
- How the geography of the Pacific Northwest reflects the plate tectonic features is found here: http://www.iris. edu/hq/files/programs/education_and_outreach/aotm/interactive/2.NWplateRollover.swf.

Points to Consider

- Do the largest earthquakes cause the most deaths and the most damage to property?
- The last time there was a large earthquake on the Hayward Fault in the San Francisco Bay area of California was in 1868. Use elastic rebound theory to describe what may be happening along the Hayward Fault today and what will likely happen in the future.
- Why is California so prone to earthquakes?
- How could coastal California be damaged by a tsunami? Where would the earthquake occur? How could such a tsunami be predicted?

1.3 Measuring and Predicting Earthquakes

Lesson Objectives

- Describe how to find an earthquake epicenter.
- Describe the different earthquake magnitude scales and what the numbers for moment magnitude mean.
- Describe how earthquakes are predicted and why the field of earthquake prediction has had little success.

Vocabulary

- seismogram
- seismograph
- seismometer

Introduction

Seismograms record seismic waves. Over the past century, scientists have developed several ways of measuring earthquake intensity. The currently accepted method is the moment magnitude scale, which measures the total amount of energy released by the earthquake. At this time, seismologists have not found a reliable method for predicting earthquakes.

Measuring Magnitude

A seismograph produces a graph-like representation of the seismic waves it receives and records them onto a seismogram (Figure 1.35). Seismograms contain information that can be used to determine how strong an earthquake was, how long it lasted, and how far away it was. Modern seismometers record ground motions using electronic motion detectors. The data are then kept digitally on a computer.

If a seismogram records P-waves and surface waves but not S-waves, the seismograph was on the other side of the Earth from the earthquake. The amplitude of the waves can be used to determine the magnitude of the earthquake, which will be discussed in a later section.

- A seismograph records an earthquake 50 miles away: http://www.iris.edu/hq/files/programs/education_and_ outreach/aotm/17/Seismogram_RegionalEarthquake.mov.
- This animation shows three different stations picking up seismic waves: http://www.iris.edu/hq/files/program s/education_and_outreach/aotm/10/4StationSeismoNetwork480.mov.

Finding the Epicenter

To locate an earthquake epicenter:

^{1.} Scientists first determine the epicenter distance from three different seismographs. The longer the time between the arrival of the P-wave and S-wave, the farther away is the epicenter. So the difference in the P and S wave arrival times determines the distance between the epicenter and a seismometer. This animation shows how distance is determined using P, S, and surface waves: http://www.iris.edu/hq/files/programs/education_and_outreach/aotm/12 /IRIStravelTime_Bounce_480.mov.

These seismograms show the arrival of P-waves and S-waves. The surface waves arrive just after the S-waves and are difficult to distinguish. Time is indicated on the horizontal portion (or x-axis) of the graph.

2. The scientist then draws a circle with a radius equal to the distance from the epicenter for that seismograph. The epicenter is somewhere along that circle. This is done for three locations. Using data from two seismographs, the two circles will intercept at two points. A third circle will intercept the other two circles at a single point. This point is the earthquake epicenter (**Figure 1.36**). Although useful for decades, this technique has been replaced by digital calculations.

Seismic stations record ten earthquakes in this animation: http://www.iris.edu/hq/files/programs/education_and_outr each/aotm/12/TravelTime_Sphere_10Stn_480.mov.

Earthquake Intensity

Measuring Earthquakes

People have always tried to quantify the size of and damage done by earthquakes. Since early in the 20^{th} century, there have been three methods. What are the strengths and weaknesses of each?

• Mercalli Intensity Scale. Earthquakes are described in terms of what nearby residents felt and the damage that was done to nearby structures.

Circles are drawn with radii representing the distance from each seismic station to the earthquake's epicenter. The intersection of these three circles is the earthquake's epicenter.

- Richter magnitude scale. Developed in 1935 by Charles Richter, this scale uses a seismometer to measure the magnitude of the largest jolt of energy released by an earthquake.
- Moment magnitude scale. Measures the total energy released by an earthquake. Moment magnitude is calculated from the area of the fault that is ruptured and the distance the ground moved along the fault.

The Richter scale and the moment magnitude scale are logarithmic.

- The amplitude of the largest wave increases ten times from one integer to the next.
- An increase in one integer means that thirty times more energy was released.
- These two scales often give very similar measurements.

How does the amplitude of the largest seismic wave of a magnitude 5 earthquake compare with the largest wave of a magnitude 4 earthquake? How does it compare with a magnitude 3 quake? The amplitude of the largest seismic wave of a magnitude 5 quake is 10 times that of a magnitude 4 quake and 100 times that of a magnitude 3 quake.

How does an increase in two integers on the moment magnitude scale compare in terms of the amount of energy released? Two integers equals a 900-fold increase in released energy.

Which scale do you think is best? With the Richter scale, a single sharp jolt measures higher than a very long intense earthquake that releases more energy. The moment magnitude scale more accurately reflects the energy released and the damage caused. Most seismologists now use the moment magnitude scale.

The way scientists measure earthquake intensity and the two most common scales, Richter and moment magnitude, are described along with a discussion of the 1906 San Francisco earthquake in *Measuring Earthquakes* video (**3d**): http://www.youtube.com/watch?v=wtlu_aDteCA (2:54).

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Annual Earthquakes

In a single year, on average, more than 900,000 earthquakes are recorded and 150,000 of them are strong enough to be felt. Each year about 18 earthquakes are major with a Richter magnitude of 7.0 to 7.9, and on average one earthquake has a magnitude of 8 to 8.9.

Magnitude 9 earthquakes are rare. The United States Geological Survey lists five since 1900 (see **Figure 1.37**) and (**Table 1.1**). All but the Great Indian Ocean Earthquake of 2004 occurred somewhere around the Pacific Ocean basin.

FIGURE 1.37

The 1964 Good Friday Earthquake centered in Prince William Sound, Alaska released the second most amount of energy of any earthquake in recorded history.

TABLE 1.1: Earthquakes of magnitude 9 or greater

Location	Year	Magnitude
Valdivia, Chile	1960	9.5
Prince William Sound, Alaska	1964	9.2
Great Indian Ocean Earthquake	2004	9.1
Kamchatka, Alaska	1952	9.0
Tōhoku, Japan	2011	9.0

Earthquake Prediction

Scientists are a long way from being able to predict earthquakes. A good prediction must be accurate as to where an earthquake will occur, when it will occur, and at what magnitude it will be so that people can evacuate. An unnecessary evacuation is expensive and causes people not to believe authorities the next time an evacuation is ordered.

Where an earthquake will occur is the easiest feature to predict. Scientists know that earthquakes take place at plate boundaries and tend to happen where they've occurred before (**Figure 1.38**). Earthquake-prone communities should always be prepared for an earthquake. These communities can implement building codes to make structures earthquake safe.

When an earthquake will occur is much more difficult to predict. Since stress on a fault builds up at the same rate

The probabilities of earthquakes striking along various faults in the San Francisco area between 2003 (when the work was done) and 2032.

over time, earthquakes should occur at regular intervals (Figure 1.39). But so far scientists cannot predict when quakes will occur even to within a few years.

FIGURE 1.39

Around Parkfield, California, an earthquake of magnitude 6.0 or higher occurs about every 22 years. So seismologists predicted that one would strike in 1993, but that quake came in 2004 - 11 years late. Signs sometimes come before a large earthquake. Small quakes, called foreshocks, sometimes occur a few seconds to a few weeks before a major quake. However, many earthquakes do not have foreshocks and small earthquakes are not necessarily followed by a large earthquake. Often, the rocks around a fault will dilate as microfractures form. Ground tilting, caused by the buildup of stress in the rocks, may precede a large earthquake, but not always. Water levels in wells fluctuate as water moves into or out of fractures before an earthquake. This is also an uncertain predictor of large earthquakes. The relative arrival times of P-waves and S-waves also decreases just before an earthquake occurs.

Folklore tells of animals behaving erratically just before an earthquake. Mostly these anecdotes are told after the earthquake. If indeed animals sense danger from earthquakes or tsunami, scientists do not know what it is they could be sensing, but they would like to find out.

The geology of California underlies the state's wealth of natural resources as well as its natural hazards. This video explores the enormous diversity of California's geology (9a): http://www.youtube.com/watch?v=QzdBx9zL0ZY (57:50).

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KQED: Earthquakes: Breaking New Ground

Earthquake prediction is very difficult and not very successful, but scientists are looking for a variety of clues in a variety of locations and to try to advance the field. Learn more at: http://science.kqed.org/quest/video/earthquakes-breaking-new-ground/

KQED: Predicting the Next Big One

It's been twenty years since the Loma Prieta Earthquake ravaged downtown Santa Cruz and damaged San Francisco's Marina District and the Bay Bridge. QUEST looks at the dramatic improvements in earthquake prediction technology since 1989. But what can be done with ten seconds of warning? Learn more at: http://science.kqed.org/ quest/audio/predicting-the-next-big-one/

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Lesson Summary

• Seismograms indicate an earthquake's strength, how far away it is, and how long it lasts.

- Epicenters can be calculated using the difference in the arrival times of P- and S-waves from three seismograms.
- Three different methods can be used to determine an earthquake's strength. The Mercalli Scale identifies the damage done and what people felt after an earthquake has occurred, the Richter scale measures the greatest single shock, and the moment magnitude scale measures the total energy released.
- Seismologists have not come too far in their ability to predict earthquakes.

Review Questions

- 1. How can a seismograph measure ground shaking if all parts of it must be attached to the ground?
- 2. On a seismogram, which waves arrive first, second, third, and last?
- 3. What information is needed to calculate the distance from a seismic station to an earthquake's epicenter?
- 4. If a seismogram records P-waves and surface waves but not S-waves, where was the earthquake epicenter located relative to the seismograph and why?
- 5. On the Richter or magnitude moment scale, what is the difference in energy released by an earthquake that is a 7.2 versus an 8.2 in magnitude? A 7.2 versus a 9.2?
- 6. Why do you need at least three seismographs to locate an earthquake epicenter?
- 7. What were the problems with the Mercalli scale of measuring earthquake magnitudes? Why did Richter and moment magnitude scales need to be developed?
- 8. Why is the moment magnitude scale thought to be more accurate than the Richter scale for measuring earthquake magnitudes?
- 9. What is the difference in energy released between a 6 and a 7 on the Richter scale? How about a 6 and a 7 on the moment magnitude scale?
- 10. How do seismologists use earthquake foreshocks to predict earthquakes? Why are foreshocks not always an effective prediction tool?
- 11. For earthquake prediction to be really useful, what would need to be predicted?

Further Reading / Supplemental Links

• How to triangulate for an earthquake epicenter: http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/swf_eart hquake_triangulation/p_activity_eqtriangulation.html.

Points to Consider

- If you live in an earthquake prone area, how do you feel about your home now? What can you do to minimize the risk to you and your family? If you do not live in an earthquake prone area, what would it take to get you to move to one? What risks from natural disasters do you face where you live?
- What do you think are the most promising clues that scientists might someday be able to use to predict earthquakes?
- What good does information about possible earthquake locations do for communities in those earthquakeprone regions?

1.4 Staying Safe in Earthquakes

Lesson Objectives

- Describe different types of earthquake damage.
- Describe the features that make a structure earthquake safe.
- Describe how to protect a person or household in earthquake country.

Vocabulary

• liquefaction

Introduction

Earthquakes are natural disasters that cause enormous amounts of damage, second only to hurricanes. Earthquakesafe construction techniques, securing heavy objects, and preparing an emergency kit are among the precautions people can take to minimize damage.

Damage from Earthquakes

Earthquakes kill people and cause property damage. However, the ground shaking almost never kills people, and the ground does not swallow someone up. The damage depends somewhat on the earthquake size but mostly on the quality of structures. Structures falling on people injure and kill them. More damage is done and more people are killed by the fires that follow an earthquake than the earthquake itself.

What makes an earthquake deadly?

- Population density. The magnitude 9.2 Great Alaska Earthquake, near Anchorage, of 1964 resulted in only 131 deaths. At the time few people lived in the area (**Figure** 1.40).
- Not size. Only about 2,000 people died in the 1960 Great Chilean earthquake, the largest earthquake ever recorded. The Indian Ocean earthquake of 2004 was one of the largest ever, but most of the 230,000 fatalities were caused by the tsunami, not the earthquake itself.
- Ground type. Solid bedrock vibrates less than soft sediments so there is less damage on bedrock. Sediments that are saturated with water undergo **liquefaction** and become like quicksand (**Figure 1.41**). Soil on a hillside may become a landslide.

Earthquake effects on buildings are seen in this animation: http://www.iris.edu/hq/files/programs/education_and_outreach/aotm/6/SeismicBuilding-Narrated480.mov.

In earthquake-prone areas, city planners try to reduce hazards. For example, in the San Francisco Bay Area, maps show how much shaking is expected for different ground types (**Figure 1.42**). This allows planners to locate new hospitals and schools more safely.

A landslide in a neighborhood in Anchorage, Alaska, after the 1964 Great Alaska earthquake.

FIGURE 1.41

Liquefaction of sediments in Mexico City caused the collapse of many buildings in the 1985 earthquake.

Earthquake-Safe Structures

Construction is a large factor in what happens during an earthquake. For example, many more people died in the 1988 Armenia earthquake where people live in mud houses than in the 1989 earthquake in Loma Prieta. Most buildings in California's earthquake country are designed to be earthquake safe.

- Skyscrapers and other large structures built on soft ground must be anchored to bedrock, even if it lies hundreds of meters below the ground surface.
- The correct building materials must be used. Houses should bend and sway. Wood and steel are better than brick, stone, and adobe, which are brittle and will break.
- Larger buildings must sway, but not so much that they touch nearby buildings. Counterweights and diagonal steel beams are used to hold down sway.
- Large buildings can be placed on rollers so that they move with the ground.
- Buildings may be placed on layers of steel and rubber to absorb the shock of the waves.
- Connections, such as where the walls meet the foundation, must be made strong.

The expected Modified Mercalli Intensity Scale for an earthquake of magnitude 7.1 on the northern portion of the Hayward Fault.

• In a multi-story building, the first story must be well supported (Figure 1.43).

To make older buildings more earthquake safe, retrofitting with steel or wood can reinforce a building's structure and its connections (**Figure 1.44**). Elevated freeways and bridges can also be retrofitted so that they do not collapse.

Fires often cause more damage than the earthquake. Fires start because seismic waves rupture gas and electrical lines, and breaks in water mains make it difficult to fight the fires (**Figure 1.45**). Builders zigzag pipes so that they bend and flex when the ground shakes. In San Francisco, water and gas pipelines are separated by valves so that areas can be isolated if one segment breaks.

Why aren't all structures in earthquakes zones constructed for maximum safety? Cost, of course. More sturdy structures are much more expensive to build. So communities must weigh how great the hazard is, what different building strategies cost, and make an informed decision.

The first floor of this San Francisco building is collapsing after the 1989 Loma Prieta earthquake.

FIGURE 1.44

Steel trusses were built in an x-pattern to retrofit a dormitory at the University of California, Berkeley. The building is very near the Hayward Fault.

KQED: The Hayward Fault: Predictable Peril

In 1868, the Hayward Fault erupted in what would be a disastrous earthquake today. Since the fault erupts every 140 years on average, East Bay residents and geologists are working to prepare for the inevitable event. Learn more at: http://www.kqed.org/quest/television/the-hayward-fault-predictable-peril

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In the 1906 San Francisco earthquake, fire was much more destructive than the ground shaking.

Protecting Yourself in an Earthquake

There are many things you can do to protect yourself before, during, and after an earthquake.

Before the Earthquake

- Have an engineer evaluate the house for structural integrity. Make sure the separate pieces—floor, walls, roof, and foundation—are all well attached to each other.
- Bracket or brace brick chimneys to the roof.
- Be sure that heavy objects are not stored in high places.
- Secure water heaters all around and at the top and bottom.
- Bolt heavy furniture onto walls with bolts, screws, or strap hinges.
- Replace halogen and incandescent light bulbs with fluorescent bulbs to lessen fire risk.
- Check to see that gas lines are made of flexible material so that they do not rupture. Any equipment that uses gas should be well secured.
- Everyone in the household should know how to shut off the gas line.
- Prepare an earthquake kit with three days supply of water and food, a radio, and batteries.
- Place flashlights all over the house and in the glove box of your car.
- Keep several fire extinguishers around the house to fight small fires.
- Be sure to have a first aid kit. Everyone should know basic first aid and CPR.
- Plan in advance how you will evacuate and where you will go. Do not plan on driving as roadways will likely be damaged.

During the Earthquake

- If you are in a building, get beneath a sturdy table, cover your head, and hold on.
- Stay away from windows, mirrors, and large furniture.
- If the building is structurally unsound, get outside as fast as possible.
- If you are outside, run to an open area away from buildings and power lines that may fall.
- If you are in a car, stay in the car and stay away from structures that might collapse, such as overpasses, bridges, or buildings.

After the Earthquake

- Be aware that aftershocks are likely.
- Avoid dangerous areas like hillsides that may experience a landslide.
- Turn off water and power to your home.
- Use your phone only if there is an emergency. Many people will be trying to get through to emergency services.
- Be prepared to wait for help or instructions. Assist others as necessary.

Lesson Summary

- A person standing in an open field in an earthquake will almost certainly be safe. Nearly all earthquake danger is from buildings falling, roadways collapsing, or from the fires and tsunami that come after the shaking stops.
- Communities can prepare for earthquakes by requiring that buildings be earthquake safe and by educating citizens on how to prepare.
- Individuals and households can prepare in two ways: by making sure that their house and its contents are not a hazard and by being ready to live independently for a few days.

Review Questions

- 1. What usually kills or injures people in an earthquake?
- 2. In two earthquakes of the same magnitude, what could produce more damage in a location further from the epicenter than in one nearer the epicenter?
- 3. Describe why Mexico City was so devastated in 1985 by an 8.1 earthquake with an epicenter far from the city.
- 4. What is liquefaction and how does it cause damage in an earthquake?
- 5. If you live in an old home in an earthquake-prone region, what should you do to minimize the harm that will come to yourself and your home?
- 6. What can an architect do to make a skyscraper earthquake safe?
- 7. Which types of buildings deserve the greatest protection from earthquake hazards?
- 8. Using what you know about elastic strength, will a building better withstand an earthquake if it is built absolutely solid or if it is able to sway? Why?
- 9. Why do wealthy communities tend to have greater earthquake protection than poorer communities, e.g. communities in developed versus developing nations?
- 10. What are the two goals of earthquake preparation?
- 11. What should you include in an earthquake kit?
- 12. Under what circumstances should you run outside in an earthquake?

Points to Consider

- Many people think that in a large earthquake, California will fall into the ocean and that Arizona and Nevada will be beachfront property. Why is this not true?
- If you were the mayor of a small city in an earthquake-prone area, what would you like to know before choosing the building site of a new hospital?
- How are decisions made for determining how much money to spend preparing people and structures for earthquakes?
- Why do wealthy communities (such as those in California) tend to have greater earthquake protection than poorer communities (such as those in developing nations)?
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