UNIT 10
Earth Science

# Chapter 28
# The Changing Earth

Powerful events cause changes on Earth's surface such that it looks different than it did 4.6 billion years ago. In this chapter, you will learn that Earth is a layered ball covered with thin pieces that move, interact, and shape Earth's surface. The theory of plate tectonics, which you will learn about in the second section, explains the dramatic movements of these pieces called tectonic plates. Friction and pressure intensify at the boundaries of the plates. When pressure is released, an earthquake occurs. While the movement of tectonic plates causes slow changes on Earth, amazing and fast changes occur when an earthquake strikes. Earthquakes are the subject of the third section.

**28.1 Understanding Earth** *What story is hidden here?*

Studying the Earth is like detective work—you use clues to uncover the fascinating history waiting to be told. In this Investigation, you will have the opportunity to reconstruct the underlying stories in different situations and rock formations.

**28.2 Plate Tectonics** *What will Earth look like in 50 million years?*

The theory of plate tectonics explains how and in what direction tectonic plates move on Earth's surface. In this Investigation, you will simulate the movement of the plates and predict how Earth will look in 50 million years.

**28.3 Earthquakes** *What mechanical factors affect earthquakes?*

In this Investigation, you will simulate the causes and effects of an earthquake. In the process, you will discover some of the factors that affect the timing and magnitude of an earthquake and use the results to develop a simple explanation of the cause of earthquakes.


Photo courtesy U.S. Geological Survey

## Learning Goals

In this chapter, you will:

- ✔ Use relative dating to sequence events recorded in a rock formation.
- ✔ Learn about Earth's interior and the role it plays in shaping Earth's surface.
- ✔ Apply basic science concepts like density, viscosity, convection, and energy transformation to Earth science.
- ✔ Learn about the theory of plate tectonics and be about to explain evidence that supports this theory.
- ✔ Learn about the three main kinds of plate boundaries: convergent, divergent, and transform.
- ✔ Learn about the causes and effects of earthquakes and where they occur.
- ✔ Learn about the role of seismic waves in understanding Earth's interior.
- ✔ Learn about the scales that are used to rate the magnitude of an earthquake.
- ✔ Calculate the location of an epicenter of an earthquake using seismic data.
- ✔ Learn how to keep safe during an earthquake.

## Vocabulary

| | | | |
|---|---|---|---|
| asthenosphere | focus | original horizontally | sea-floor spreading |
| continental drift | geology | paleontology | seismic wave |
| cross-cutting relationships | inclusions | Pangaea | subduction |
| epicenter | lateral continuity | plate tectonics | superposition |
| fault | lithosphere | P-wave | S-wave |
| faunal succession | mid-ocean ridge | relative dating | tsunami |

# 28.1 Understanding Earth

In the 1600s, all rocks and minerals found in the ground were called fossils. Today, we define a *fossil* as the preserved remains of ancient animals, plants, or preserved evidence of life such as footprints or nests). Our understanding of fossils is based on the work of people who were fascinated by the planet Earth. The purpose of this section is to encourage your curiosity about Earth's land formations. Soon you will be able to explain mountains, earthquakes, volcanoes, and the long history of a rock. In other words, you will be able to explain some of Earth's geology. Geology is the study of rocks and materials that make up Earth and the processes that shape it. Below you will learn about the beginnings of geology and the methods that are used in geology today.


**Figure 28.1:** *This illustration is from Nicholas Steno's 1667 paper titled "The Head of a Shark Dissected."*

## The beginnings of modern geology

**Tonguestones and shark's teeth**

In 1666, Nicholas Steno (1638-87), a Danish physician with a strong interest in science, received the head of a shark from some local fishermen. Curious about the shark's anatomy, Steno dissected the head and published his findings (Figure 28.1). While dissecting, Steno noticed that the shark's teeth resembled mysterious stones called "tonguestones" that were found in local rocks. From ancient times until the 1600s, people believed that tonguestones were mystical and had fallen from the moon. Others believed they grew inside rocks.

**How did shark's teeth get into a rock?**

Although scientists had noticed that tonguestones looked like sharks' teeth, they had not understood how the teeth could have gotten into a rock. In puzzling over this problem, Steno realized over time the remains of an animal will be covered by layers of sediment. After a short time, the animal's soft parts decay quickly, but harder parts like bones and teeth resist decomposing. After a very long time, the sediment surrounding a decayed animal can become a *rock formation*.

**Relative dating and modern geology**

Steno's explanation helped him develop ideas about how rocks and fossils form. These ideas are used in a technique called relative dating. Relative dating is a way to put events in the order in which they happened. This technique contributed to the development of modern geology. It is used today by geologists as they study rock formations and by scientists called paleontologists who study and identify fossils. A simple example of relative dating is presented in Figure 28.2.

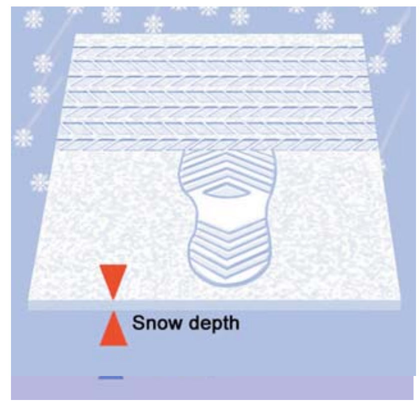



**Figure 28.2:** *This graphic illustrates three events: a footstep, a tire track, and snowfall. Which event happened first? Sequencing these events in the correct order is a form of relative dating.*

## Steno's ideas and relative dating

**What is relative dating?**

In Earth science, relative dating is a method used to determine the general age of a rock, rock formation, or fossil. When you use relative dating, you are not trying to determine the exact age of something. Instead, you use clues to sequence events that occurred first, then second, and so on. Steno's ideas—*superposition*, *original horizontality*, and *lateral continuity*—help identify the clues.

**Superposition**

The approximate age of each layer of a rock formation can be determined by applying Steno's idea called **superposition**. Superposition states that the bottom layer of a rock formation is older than the layer on top because the bottom layer formed first. Stacking old newspapers in the order in which you received them illustrates superposition (Figure 28.3). The oldest newspaper tends to be on the bottom, and the newest on the top.

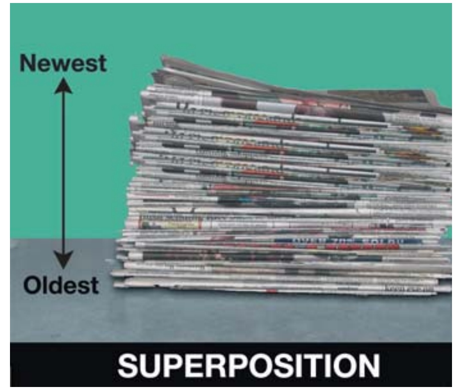
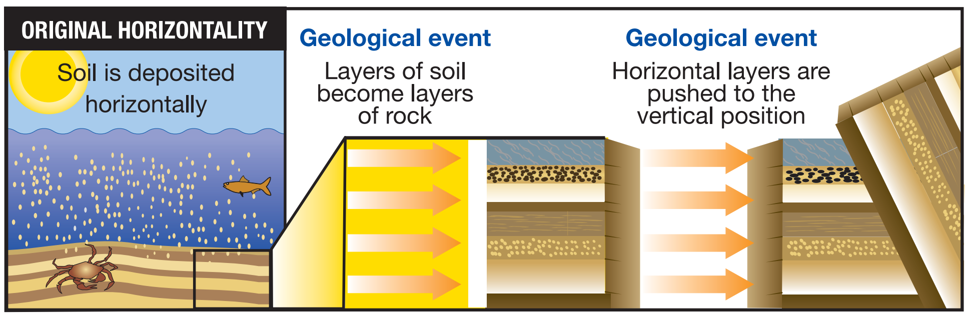



**Figure 28.3:** *A stack of newspapers illustrates superposition. Superposition means that the bottom layers of rock are older than the layers on the top.*

**Original horizontality**

**Original horizontality** states that sediment particles fall to the bottom of a basin, such as a riverbed, in response to gravity and result in *horizontal* layers. Over time, these layers can become layers of rock. Sometimes rock layers are found in a *vertical* position. Steno realized that slow movements of Earth could move horizontal rock layers to the vertical position.




**Lateral continuity**

**Lateral continuity** is the idea that layers of sediment extend in all directions when they form and before they become rock layers. For example, if you were to compare rock layers in the Grand Canyon, you would find that the layers on one side more or less match up with the layers on the other. A flowing river can interrupt these layers and an earthquake can offset them (Figure 28.4). The Colorado River formed the gap that is now the canyon of the Grand Canyon.

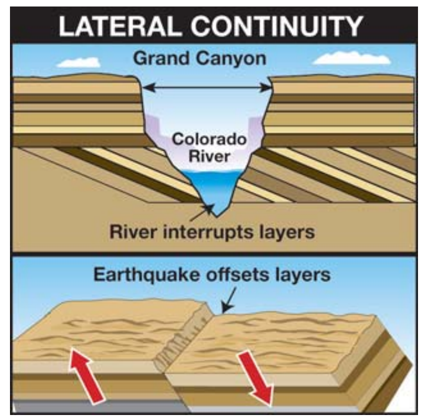



**Figure 28.4:** *The idea of lateral continuity states that layers of rock are continuous unless a geologic event like a river interrupts the layers or an earthquake them.*

## Interpreting rocks formations

**The present explains the past**

Using Steno's ideas, you can begin to describe the history of a rock formation. Another important idea, developed by Scottish geologist James Hutton (1726-97), is that the *present explains the past*. In other words, if you understand the geologic processes that are happening now, you can explain what happened a long time ago. Both Hutton and Steno were important in the development of relative dating and modern geology. The following ideas are also useful in relative dating.

**Cross-cutting relationships**

The idea of **cross-cutting relationships** states that a vein of rock is younger than the rock that surrounds a vein. Figure 28.5 shows a rock formation with three layers and a cross-cutting vein. The layers formed first. The vein formed when melted rock oozed into the original rock, cutting across the layers. Then the melted rock solidified. The bottom layer is the oldest part of the rock formation and the vein is the youngest. The middle and top layers formed after the bottom layer and before the vein.

**Inclusions**

Sometimes rock pieces called **inclusions** are contained in another rock. During the formation of a rock with inclusions, sediments or melted rock surrounded the inclusion and then solidified. Therefore, the inclusions are older than the surrounding rock (Figure 28.5). A rock with inclusions is like a chocolate chip cookie. The chocolate chips are made first by a manufacturer. Then they are added to the batter before baking.

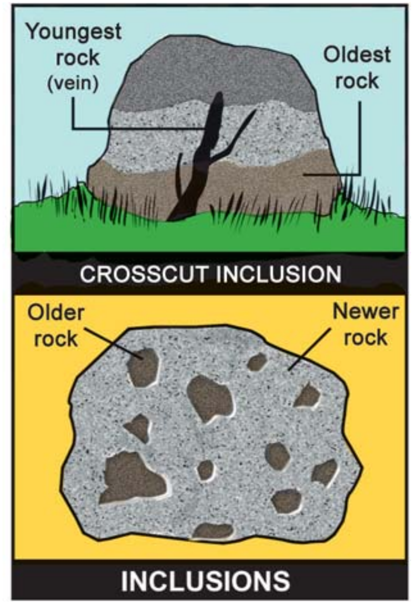



**Figure 28.5:** *Cross-cutting relationships versus inclusions.*

**Faunal succession**

Over geologic history, many animals and plants have lived and become extinct. Their remains have become fossils. The idea of **faunal succession** states that fossils can be used to identify the relative age of layers of a rock formation (Figure 28.6). For example, dinosaur fossils are found in rock that is about 65 to 200 million years old because these animals lived on Earth about 65 to 200 million years ago. We can learn what else lived with the dinosaurs by studying other kinds of fossils found in layers of rock that are this old. The fossils of modern human beings (*Homo sapiens*) are found in rock that is about 40,000 years old, but not in rock that is 65 to 200 million years old. And dinosaur fossils are *not* found in rock that is 40,000 years old. Faunal succession also assumes that evolution occurs in one direction. For example, present-day animals will not evolve into dinosaurs.

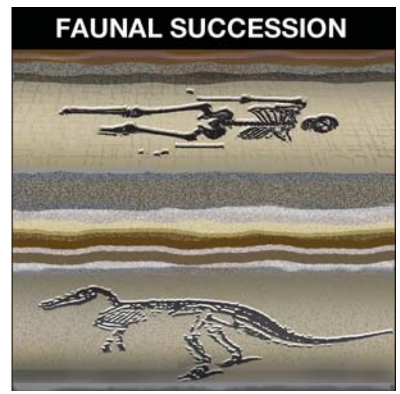


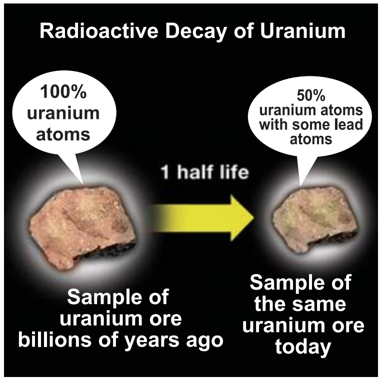

**Figure 28.6:** *Faunal succession. (MYA = millions of years ago.)*

## Calculating Earth's age

**Calculating Earth's age**

William Thompson Kelvin (1824-1907), known for proposing the absolute temperature scale that came to be named after him, meticulously calculated Earth's age to be between 10 million and 100 million years. His calculations were based on his prediction of how long it would take for a hot Earth to cool.

**Radioactive decay and Earth's age**




Lord Kelvin's calculation was not accurate because he did not realize that Earth has internal heat from the core and radioactive decay. Radioactivity was not understood until the early 1900s. In 1907, Earth's age was estimated by measuring the radioactive decay of uranium to lead. This estimation was performed by comparing the amount of lead to uranium in a piece of uranium ore. With improved techniques and evidence from tree rings and glaciers, the age of Earth is estimated to be about 4.6 billion years.

**Comparing ages**

Moon rocks, meteorites, and the solar system are estimated to be about the same age as Earth, about 4.6 billion years. This information indicates that the solar system, the moon, and Earth were formed around the same time.

**The geologic time scale**

The geologic time scale is a model of Earth's history. In this model, time is divided into eras and periods. Figure 28.7 includes pictures of organisms and events that characterize the periods. For example, Earth was covered with glaciers during the Ordovician period. Flowering plants evolved during the Cretaceous period. A giant meteor hit Earth at the beginning of the Tertiary period. Scientists believe this event may have ended the existence of the dinosaurs. Modern humans appeared 40,000 years ago during the Cenozoic era. Before these periods of time, the Precambrian era lasted from 4.6 billion to 570 million years ago. During this earliest time period, layers of rock at the bottom of the Grand Canyon were forming and only single-celled organisms lived on Earth.

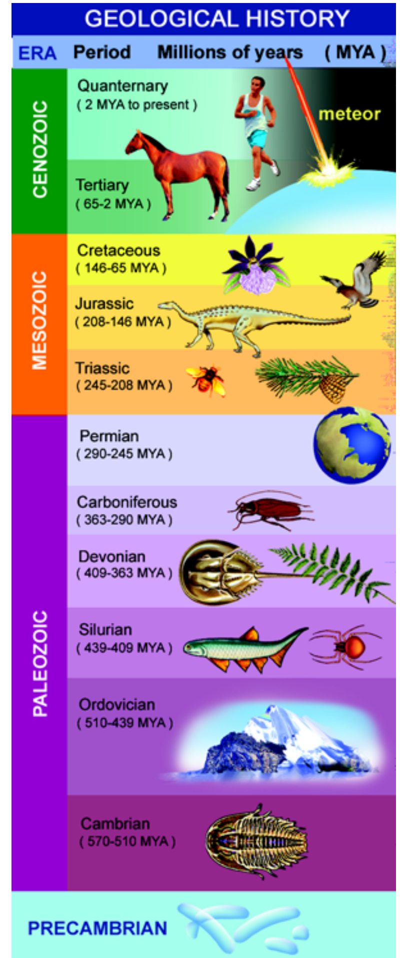



**Figure 28.7:** *Earth's geologic history. Some of the period names are based on the location where fossils from that time were first described. For example, fossils from the Cambrian period were first described in Cambridge, England.*

## Inside Earth

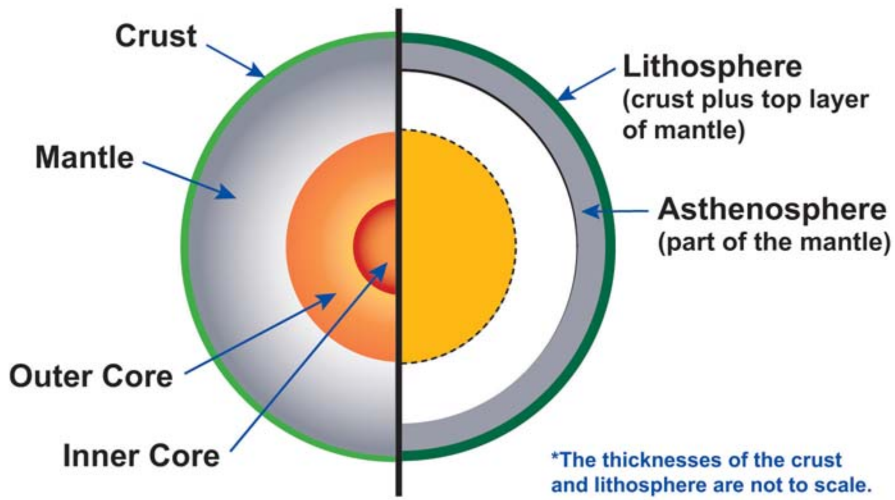
**Earth's beginnings and the formation of layers**

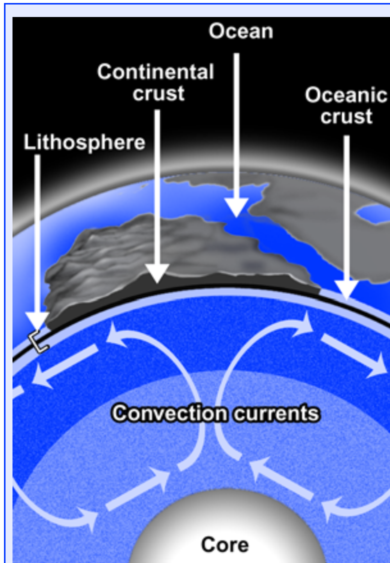
Scientists believe that Earth formed when cosmic particles collected into a sphere due to the gravitational attraction between the particles. As these particles gathered, pressure inside the sphere increased. Iron particles melted and percolated to the core. The "fall" of iron to the core was accompanied by the conversion of potential energy to kinetic energy. This energy transformation generated intense heat that melted other particles in the sphere. At this point in Earth's formation, the densest materials like irb on and nickel sank to Earth's center and formed its core. Layers of less dense material formed the mantle. The least dense elements rose to the outer surface and formed our planet's crust.

**The lithosphere and asthenosphere**

The shallowest 100- to 150-kilometer layer of Earth is the lithosphere (*lithos* is Greek for "stone"). This layer includes the crust and upper mantle. The lithosphere is about two percent of the 12,756-kilometer diameter of Earth—like the skin of an apple compared with the whole apple. Below the lithosphere is the asthenosphere (*asthen* is Greek for "weak"), a layer of the mantle that is composed of material that flows.

### Layers of Earth




**Convection inside Earth**

The rocky material of the mantle moves in very slow convection currents. This movement is related to density and temperature differences in the mantle. Hot material is less dense and rises. Cold material is denser and sinks. Earth's core is a source of heat. Heat from the core warms the deep mantle and causes the material to become less dense and rise toward Earth's surface. At the surface, the hot material cools, becomes more dense, and sinks back to the core where it will be heated again.

## The layers of Earth

**Earth's crust**

Earth's surface is covered with a thin crust. There are two kinds of crust, *continental* and *oceanic* (Figure 28.8). Continental crust is older, thicker, and less dense than oceanic crust. Continental crust is composed primarily of granite, a usually light-colored rock rich in silica. Oceanic crust is made of basalt, a dark-colored rock relatively low in silica and containing iron and magnesium. Both continental and oceanic crusts are brittle and tend to crack when pushed or pulled as pieces of the crust move. A crack in the crust is called a *fault*.

**The mantle**

The mantle of Earth is a 2,900-kilometer-thick layer of molten material between the crust and core. The density of this material is 3.3 g/cm$^3$. The continental and oceanic crusts float on top of the mantle because they are less dense. Blocks of foam and wood floating in water demonstrate the floating of the continental and oceanic crusts in the mantle (Figure 28.9). Being less dense, a foam block floats higher in water than wood. Likewise, continental crust floats higher in the mantle than oceanic crust. The result is that much of the water on Earth has collected on top of the oceanic crust, forming the oceans.

**The core**

Earth has a two-layer core. The inner core is made of *solid* iron and nickel, while the outer core is made of *molten* iron, nickel, and oxygen. Both of these layers are denser than the mantle. The temperature of the core ranges from 2,000°C to 5,000°C. In comparison, the surface of the sun is estimated to be 5,500°C. The density difference between the core and the middle layer of Earth (the mantle) is twice the density difference between the atmosphere and Earth's crust. The core is about one-third of Earth's mass and a little smaller than the moon.

| | Continental crust | Oceanic crust |
|---|---|---|
| **Average thickness** | 10-80 km | 5-10 km |
| **Density** | 2.75 g/cm$^3$ | 3.0 g/cm$^3$ |
| **Oldest known age** | 3.5 billion years | 200 million years |
| **Composition** | mostly granite | basalt |

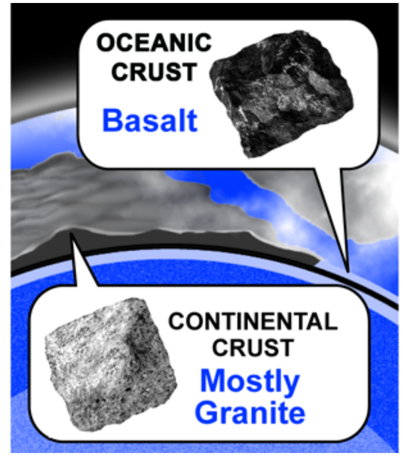



**Figure 28.8:** *The oceanic crust is made of basalt. The continental crust is made mostly of granite.*

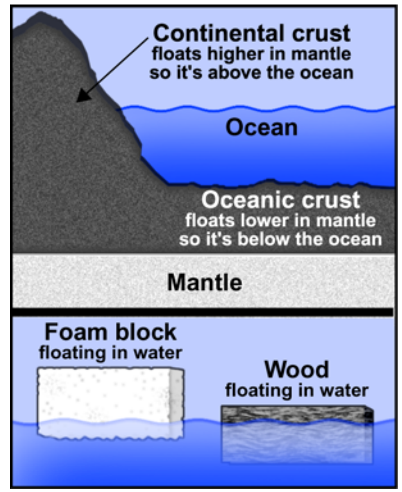



**Figure 28.9:** *Because oceanic crust is denser than continental crust, it floats lower in Earth's mantle. Blocks of foam and wood floating in water demonstrate this phenomenon.*

## Important concepts that will help you understand Earth science

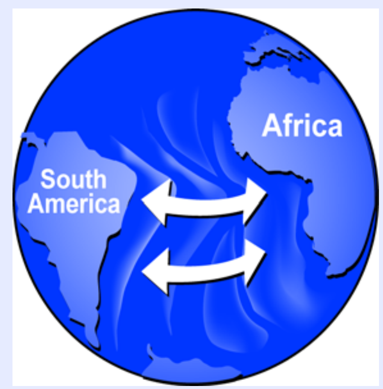
**Concepts you already know**

This section begins your study of the processes that shape Earth. The concepts you have learned in this section will help you understand mountains, earthquakes, volcanoes, and the formation of rocks. As you continue to read, you will see the following familiar concepts.

| Concept | How the concept applies to understanding Earth |
|---|---|
| **Density** | The layers of Earth are separated according to **density**. For example, the core of Earth is much denser than the continental and oceanic crusts. |
| **Viscosity** | The molten material of the mantle is viscous. For example, molasses is much more viscous than water which flows very quickly. The **viscosity** of lava explains the kinds of volcanic eruptions that occur. |
| **Convection currents** | The **convection currents** in the mantle are similar to the convection currents in the atmosphere. |
| **Potential and kinetic energy** | As Earth formed, the fall of iron to the core was accompanied by the conversion of **potential energy** to **kinetic energy**. Heat was produce inside Earth as a result of this energy conversion. Also, earthquakes are caused by a conversion of **potential energy** to **kinetic energy**. |
| **Cycles** | **Cycle** is a term used to describe various processes that move matter from place to place on Earth. Water is transported on Earth via the water cycle. The energy source driving this cycle is the sun. The rock cycle is a set of processes that lead to the formation and recycling of the various kinds of rocks. Energy sources driving this cycle are climate changes (driven by the sun) and convection currents that distribute heat in Earth's mantle. |

### Plate tectonics

In the next section, you will learn about the theory of plate tectonics. It states that large pieces of the lithosphere called *tectonic plates* move on Earth's surface. The theory of plate tectonics explains why South America and Africa fit together like two puzzle pieces. Before reading about plate tectonics, come up with your own ideas to explain how plates move on Earth's surface and what the effects of this movement might be.



# 28.2 Plate Tectonics

If you look at a map of the world, it is easy to imagine the continents like puzzle pieces. In particular, South America and Africa seem to fit together. If the continents were once connected, how did they move apart? The theory of plate tectonics explains the movement of continents and other geological events like earthquakes and volcanoes. In this section, you will learn about the theory of plate tectonics.

## The surface of Earth

**Pangaea and continental drift**

In 1915, Alfred Wegener (1880-1930), a German meteorologist, wrote a book titled *The Origin of Continents and Oceans*. In this book, he proposed that millions of years ago, the land on Earth formed a single, huge landmass. He named it **Pangaea**, a Greek name that means "all lands." Wegener's theory was that pieces of Pangaea moved apart to form the seven continents (Figure 28.10). This idea was called **continental drift**. Wegener's idea was not accepted by all scientists because it did not explain what caused the continents to move.

**Plate tectonics**

How continents moved is explained by a theory called **plate tectonics**. The term *tectonics* means construction or building. The theory of plate tectonics, stated in 1965, refers to the movement of giant pieces of solid rock on Earth's surface called **tectonic plates**. The movement of one plate causes the pulling or pushing of other plates, significantly affecting Earth's surface.

***The movement of tectonic plates affects Earth's surface and causes earthquakes and volcanoes.***

**What is happening now?**

Even today, Earth's surface is changing. For example, the plates on which North America and Europe sit are continuing to separate at a rate between 1 and 10 centimeters a year. For comparison, your fingernails grow at a rate of 2.5 centimeters a year. Though this rate may seem very slow, the Atlantic Ocean is increasing in size. In contrast, the Pacific Ocean is decreasing in size. If the Atlantic continues to grow and the Pacific continues to get smaller, what might Earth look like in 50 million years?

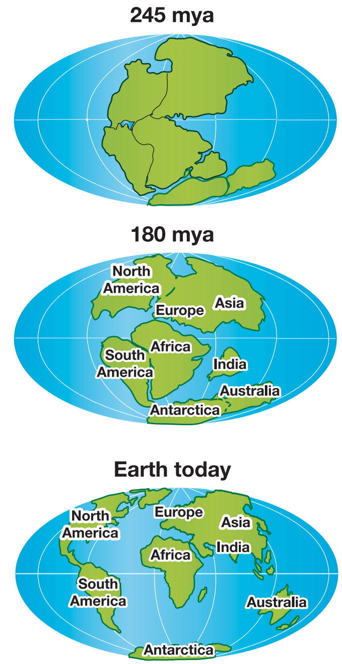
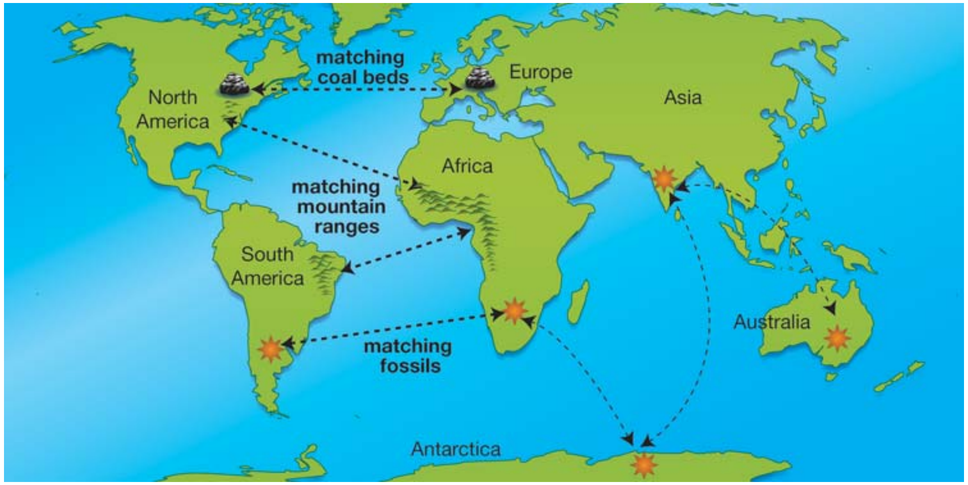



**Figure 28.10:** *About 225 million years ago, the land on Earth was part of one supercontinent called Pangaea. About 200 million years ago, this huge landmass began to split apart into many sections—seven of the largest sections are our continents. It is important to note that the forces that brought Pangaea together had been working for a long time. Before Pangaea, there were other earlier oceans and continents.*

## Continental drift

**Wegener's evidence for continental drift**

For a long time, scientists could not explain why South America and Africa appeared to fit together. Wegener gathered evidence that supported his idea that *all* the continents had been connected.




**Mountains are in certain locations on Earth**

Wegener's scientific colleagues thought it was foolish to propose that continents could move. Instead, they had other ideas to explain features on Earth. One idea was the "dry apple skin" model, which assumed that the Earth is shrinking and mountains are the result of the wrinkling of the crust. If this were true, mountains would be *all over* the surface of Earth. Instead, mountains tend to be in long bands. For example, there are bands of mountains on the west coast of North America and the west coast of South America (Figure 28.11).

**Continental drift was not accepted until the 1960s**

Wegener believed the continents had pushed through the ocean floor. However, he did not have a satisfactory explanation for how this happened. There was no known source of energy large enough to move continents through the sea floor. Also, although scientists had data about the interior of Earth from earthquakes, there were no clues in Earth's crust to show that the continents had broken through the sea floor. Given this lack of evidence to explain the mechanism of continental drift, scientists did not accept this idea. However, in the 1960s, a scientific breakthrough occurred. Evidence showed that the continents and sea floor moved *together* on Earth's surface.

### Continental drift

***Distribution of mountains and coal:***

Mountain ranges on the east coast of South America match mountains on the west coast of Africa. The North American Appalachian Mountains match the Atlas Mountains of northwest Africa. Coal beds in North America match those in Europe.

***Distribution of fossils:***

Fossils of a particular plant are found on continents that are now far apart. This plant only spreads across land, not across oceans.

***The past does not match the present:***

Fossils of tropical plants are found on Antarctic land and glacier scratches are found on rocks near equatorial Africa.


**Figure 28.11:** *Mountain ranges in North and South America.*

## Sea-floor spreading

**Mountain ranges on the sea floor**

The sea floor is mostly flat. However, in the middle of the oceans (namely the Atlantic, Pacific, and Indian), there are more than 50,000 kilometers of mountain ranges called the **mid-ocean ridges**. The average height of the mountains at the ridges is 4,500 meters or about 2.8 miles above the sea floor. The ridges are split in the middle by either a valley or by a *rise* (see sidebar). The valleys can be as much as 800 kilometers across. However, they are usually less than 50 kilometers across for slow-spreading ocean ridges.

**Echo sounding**

Scientists first described the appearance of the sea floor using echo sounders. An echo sounder on a ship sends and collects sound waves. These waves bounce off objects and the sea floor. The data collected by an echo sounder is used to determine the depth of the sea floor. The combined depth readings for an area are used to make a profile of the sea floor (Figure 28.12).

**Sea-floor spreading**

In the early 1960s, Henry Hess (1906-69), a geologist and former commander of a Navy ship equipped with an echo sounder, used the profile of the sea floor to propose that it was spreading at the mid-ocean ridges. Around the same time, Robert Dietz (1914-95), a scientist with similar ideas, coined the term **sea-floor spreading**. Sea-floor spreading describes the sea floor on either side of a mid-ocean ridge as moving away from the ridge and creating a rise or valley. Hot fluid from the mantle (called *magma*) enters the rise or valley and cools, creating new sea floor (also called oceanic crust).

**Proving sea floor spreading**

Not every scientist accepted the idea of sea-floor spreading. If you were going to prove this idea, what would you do? What kind of evidence would you need to prove that the sea floor was spreading apart at the ridges?

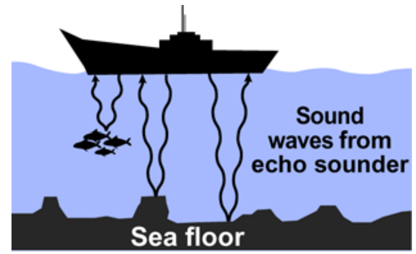
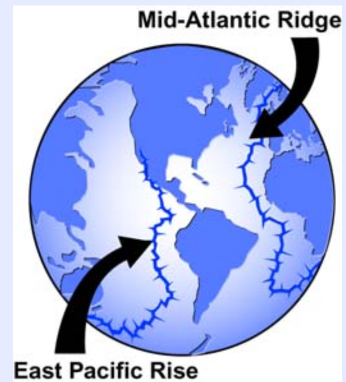




**Figure 28.12:** *An echo sounder is used to make a profile of the sea floor.*

### Mid-ocean ridges



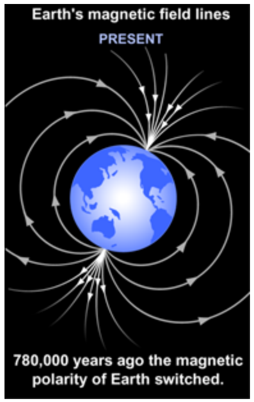

The region near the mid-ocean ridges is elevated with respect to the rest of the sea floor because it is warm and less dense. The elevated parts form the mountainous ridges. Just what the ridges look like depends on the rate of sea-floor spreading. Wide, steep-sided valleys occur at the Mid-Atlantic Ridge because the spreading is slow. Spreading at the East Pacific Rise is faster, so a shallow valley or a *rise* occurs. A *rise* is a long mound of pushed-up crust.

## Magnetic patterns on the sea floor

**Earth is a giant magnet**

Like a giant magnet, Earth has a magnetic north and south pole. Scientists believe Earth's magnetism is due to convection currents in the liquid outer core. These currents generate a magnetic field around Earth. Not only does this magnetic field provide us with a means of navigation, but it also blocks some of the sun's harmful electromagnetic radiation from reaching Earth's surface.

**Earth's polarity has switched over time**




Over geologic time, the magnetic polarity of Earth has switched. Scientists believe the poles switch because of a magnetic interaction between the planet's inner and outer core. Eventually, the interaction diminishes the magnetic field to a point that encourages the poles to reverse. This reversal recharges the magnetic field. The last time Earth's polarity switched was about 780,000 years ago. Rocks on Earth act as a record of these switching events. When molten lava cools and becomes a rock, the grains in the rock are oriented with the magnetic polarity of Earth.

**Magnetic patterns on the sea floor**

In the 1950s and 1960s, scientists discovered that the rocks of the sea floor have a very interesting magnetic pattern. Figure 28.13 illustrates what this pattern looks like. Stripes of rock with a *north-south orientation* (normal) alternate with stripes of rock with a *south-north orientation* (reversed). Scientists also discovered that the pattern of stripes matches on either side of a mid-ocean ridge (Figure 28.13).

**Evidence for sea-floor spreading**

On the previous page, you were asked how you would prove that the sea floor was spreading apart at the mid-ocean ridges. Now, you have some new information. First of all, you know the polarity of Earth switches over time. Second, you know that newly formed rock records Earth's polarity. Thirdly, you know that the rocky sea floor on either side of mid-ocean ridges has a matching pattern of magnetic stripes. Together, this information provides evidence for sea-floor spreading. The matching striped pattern shows that Earth's polarity was recorded on *either side* of the ridge as lava oozed from the ridge and cooled. Since the mid-ocean ridge is a site where new sea floor is made, the newest rock is always near the ridge and the oldest rock is always far from the ridge (Figure 28.13).

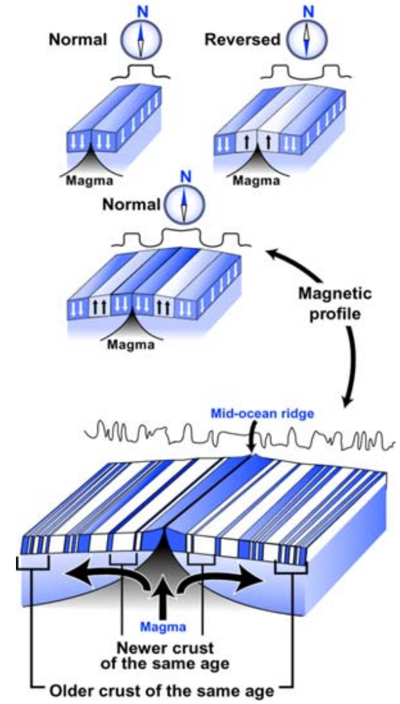



**Figure 28.13:** *Magnetic patterns on the sea floor show the reversal of Earth's magnetic field and provide evidence of sea-floor spreading. The blue and white stripes you see in the figure are an interpretation of a magnetic profile.*

**Think about it**

The sea floor is a record of geologic time. Given this, what does the thickness of each magnetic stripe mean?

## The theory of plate tectonics

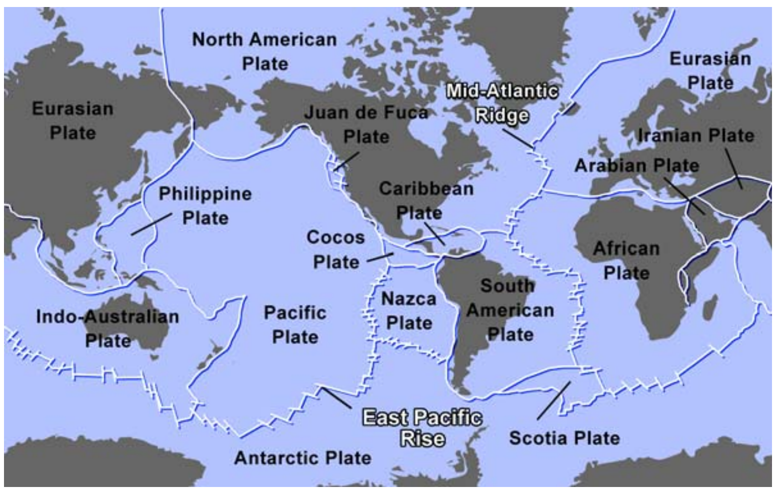
**The theory of plate tectonics**

The theory of plate tectonics is consistent with the observed magnetic patterns on the sea floor, sea-floor spreading, continental drift, and the idea that the lithosphere is divided into tectonic plates. This theory also provides possible explanations for many things about Earth's geology such as mountain-building, earthquakes, and volcanoes.

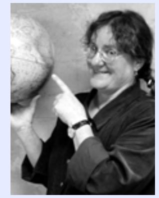
**Plates are pieces of the lithosphere**

The tectonic plates that cover Earth's surface are pieces of the lithosphere that fit together and float on the asthenosphere (a part of the mantle). There are a number of large tectonic plates on Earth's surface, and smaller plates are being identified all the time. Below is a list of the bigger plates. Find these plates on the graphic below. Then find the plate that goes with each of the seven continents. Many of the plates are made up of both continental and oceanic crust. Can you identify which of the plates are only made of oceanic crust?

| The biggest tectonic plates | | | | |
|---|---|---|---|---|
| Eurasian | Philippine | North American | Juan de Fuca | African |
| Arabian | Iranian | Antarctic | Scotia | South American |
| Cocos | Caribbean | Nazca | Pacific | Indo-Australian |




### Tanya Atwater



Tanya Atwater's love for art, maps, and the outdoors led her to study geology. When she entered graduate school in 1967, many exciting discoveries were being made. The concept of sea floor spreading was emerging, leading to the current theory of plate tectonics.

Atwater's research on sea floor spreading involved twelve trips to the ocean floor in the tiny submarine Alvin. Using a mechanical arm, she and her crew collected samples on the ocean floor nearly two miles underwater! In the 1980's Atwater researched propagating rifts. Propagating rifts are created when sea floor spreading centers realign themselves in response to changes in plate motion or magma supplies. She mapped these odd rift patterns and used them to decipher ancient plate motions.

Atwater has taught at the University of California-Santa Barbara for over 25 years. She also works with media, museums, and teachers and she creates educational animations to teach people about Earth.

## Describing plate boundaries

**Faults**

Whenever one tectonic plate moves, another is affected. Most geologic activity occurs at plate boundaries. There are three main kinds of plate boundaries: divergent, convergent, and transform. These boundaries are illustrated below and described on the following pages. Each of these boundaries is associated with faults. Faults are breaks and cracks in Earth's crust where two pieces of the crust become offset. The build up and release of pressure at a fault causes earthquakes. Large earthquakes tend to be more frequent near convergent plate boundaries than at divergent plate boundaries. The San Andreas fault is a transform plate boundary that extends 600 mile along California's coast (Figure 28.14). Earthquakes occur frequently in regions near this kind of boundary.

**Zones of activity at plate boundaries**

At a plate boundary, crust can be created, consumed, or crumpled into mountains. In some cases, plates slide past each other. With all that can happen at a boundary, the effects occur over a region or *zone* rather than on a single line. The zone of activity at a plate boundary can range from tens to hundreds of kilometers wide. For example, the zone of activity for a divergent boundary spans about 30 kilometers on the sea floor and 100 to 200 kilometers on a continent.

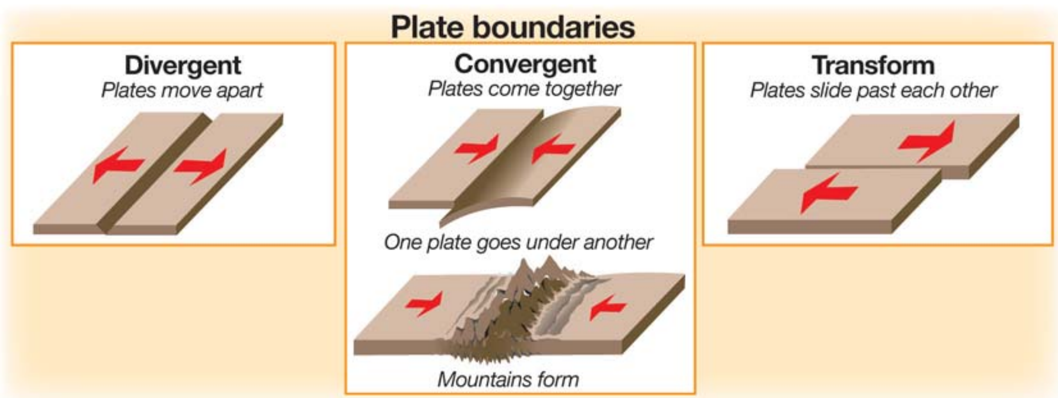




**Figure 28.14:** *The San Andreas fault is a transform plate boundary. The arrow shows the movement of the Pacific plate relative to the North American plate.*

### Where do earthquakes and volcanoes occur?

Earthquakes occur at all plate boundaries. Volcanoes are associated with divergent and convergent plate boundaries. Volcanoes are not associated with transform plate boundaries, where the plates are sliding past each other. However, transform boundaries are often near divergent boundaries where there is volcanic activity.

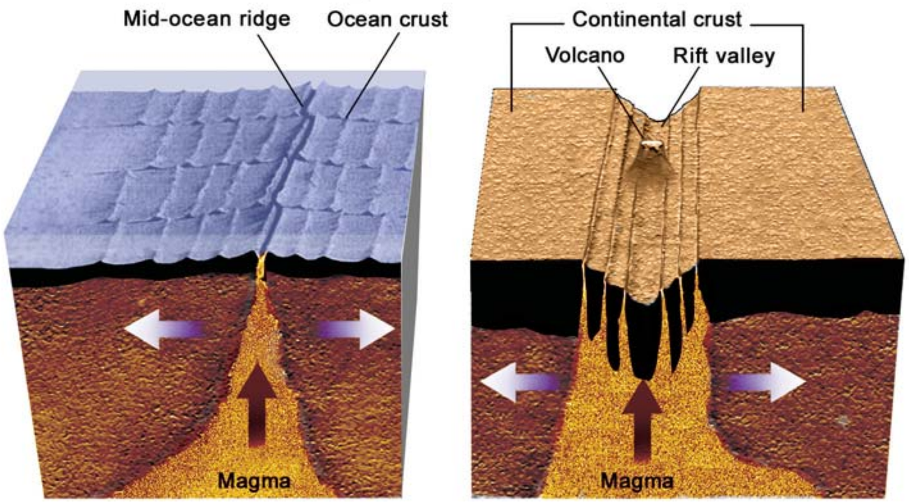
## Divergent plate boundaries

**Description** Divergent plate boundaries are places where plates move apart. Divergent boundaries are sites of earthquakes and volcanic activity. As molten material from the mantle reaches Earth's surface at these boundaries, new crust is created.

***Diverging plates move apart. New crust forms.***

**Examples** Mid-ocean ridges and associated sea-floor spreading occur at *divergent plate boundaries*. Magma from the mantle erupts along cracks created by the separation of plates along the mid-ocean ridge. In effect, a mid-ocean ridge is like a very long volcano. A continental version of a divergent plate boundary is the Great Rift Valley in East Africa. The Great Rift Valley is 6,400 kilometers long and averages 48 to 64 kilometers across. It is the largest continental rift in the world and extends from Jordan to Mozambique. As plates pull apart at the Great Rift Valley, the land sinks, forming a valley that may eventually fill with ocean water. Once underwater, the Great Rift Valley would become part of the mid-ocean ridge system. Although scientists think that eastern Africa could become a site for a new ocean, this will not happen for a very long time.


Divergent Plate Boundaries




| Divergent Plate Boundary | |
|---|---|
| Description | Place where plates are separating; new crust is created. |
| Earthquake activity? | Yes |
| Volcanic activity? | Yes |
| Examples | *Mid-Atlantic Ridge*<br>*East Pacific Rise*<br>*Great Rift Valley* |

### Why doesn't Earth get bigger and bigger?

Even though new crust is created at mid-ocean ridges, the Earth does not get bigger because crust is consumed at convergent plate boundaries (see next page). As new crust is formed at divergent plate boundaries, old, dense crust sinks and melts in the mantle. The balance between creating new crust and melting old crust also explains the increasing size of the Atlantic Ocean and the decreasing size of the Pacific Ocean.

## Convergent plate boundaries

**Subduction and trenches**

**Convergent plate boundaries** occur where two plates approach each other. One result of two plates converging is **subduction**. In subduction, a denser plate slides under a less dense plate and enters the mantle, where it melts or becomes part of the mantle. Subduction can occur between an oceanic plate and a continental plate or between two oceanic plates. In either case, the subducting plate causes volcanic activity on the less dense plate. When an oceanic plate subducts under a continental plate, volcanoes occur on the continental plate such as the volcanic Cascade Mountains in the northwestern United States. When an oceanic plate subducts under another oceanic plate, an arc of volcanic islands is formed such as the Caribbean Islands. A deep oceanic *trench* marks the boundary between a subducting and an overriding plate at a convergent boundary.

| Convergent Plate Boundary | |
|---|---|
| Description | Place where plates meet; mountains form or plates are consumed by subduction. |
| Earthquake activity? | Yes |
| Volcanic activity? | Yes |
| Features at this boundary | *Mariana Trench*<br>*Caribbean Islands*<br>*Himalayan Mountains* |

***Converging plates meet. Subduction occurs or mountains form.***

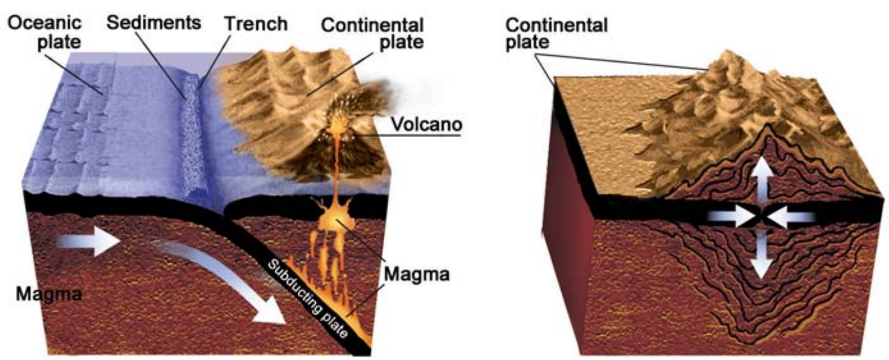
**Mountain building**

The collision of two continental plates is a third kind of convergent boundary. Because both plates resist sinking in the mantle, they crumple. The crust is pushed upward forming mountain peaks and downward forming deep mountain “roots.” The Himalayan Mountains are the result of colliding continental plates.

### Deep oceanic trenches

The Mariana trench at the boundary of the Philippine and Pacific plates is the deepest trench in the world. It is 11 kilometers to the bottom. Compare this depth to the highest mountains on Earth. Mauna Loa, a volcanic mountain in Hawaii, is 10.3 kilometers from its sea floor base to its peak. Mount Everest is 8.84 kilometers high.

Convergent Plate Boundaries



## Transform plate boundaries

**Transform plate boundaries**

At **transform plate boundaries,** two plates slide by each other and crust is not created or consumed (Figure 28.15). The San Andreas fault in California is a well-known transform plate boundary. The build up of friction and pressure between sliding plates often results in earthquakes. Volcanic activity is not associated with transform plate boundaries; however, divergent plate boundaries which are sites of volcanic activity often occur near transform plate boundaries.

***Plates slide past each other at transform plate boundaries. Crust is not created or consumed.***

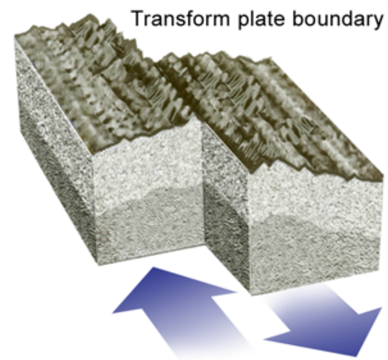



**Figure 28.15:** *At transform plate boundaries, plates slide past each other. Crust is not created or consumed at these boundaries.*

| Transform Plate Boundary | |
|---|---|
| Description | Place where plates slide past each other; no crust is created or consumed |
| Earthquake activity? | Yes |
| Volcanic activity? | No (but divergent plate boundaries and their associated volcanoes are often near transform boundaries) |
| Example | *The San Andreas fault* |

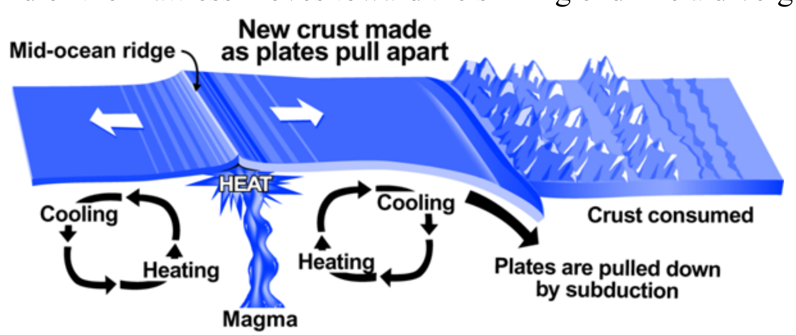
## Movement of plates

**How plates move**

The movement of tectonic plates is related to the distribution of heat by convection currents in the mantle. At the mid-ocean ridges where new crust is forming, a plate is relatively hot and less dense. Away from the ridges, a plate begins to subduct because it is cooler and denser. The subduction of a plate causes the pulling apart of plates at the mid-ocean ridge. Scientists believe that this pulling effect, which depends on heat distribution, causes the interaction and movement of the plates on Earth's surface.

**An analogy to explain how plates move**

An air mattress floating in a pool can illustrate the motion of a plate on the mantle. If you sit on one end of the mattress, it sinks (or *subducts*) underwater. As a result, the other end of the mattress moves toward the sinking end like a divergent plate.



# 28.3 Earthquakes

The majority of earthquakes occur at the edges of tectonic plates. For example, Japan's location near convergent plate boundaries (Figure 28.16) explains why earthquakes occur regularly in that country. If you mark the locations of earthquakes on a world map, you see the outlines of Earth's tectonic plates. This section is all about earthquakes and how they are related to plate tectonics.


**Figure 28.16:** *These recent moderate earthquakes in Japan are associated with subduction occurring at plate boundaries.*

## What is an earthquake?

**Energy and earthquakes** As tectonic plates move, friction causes the rocks at plate boundaries to stretch or compress. Like a stretched rubber band or a compressed spring, these rocks store energy. When the rocks break, change shape, or decrease in volume, the stored energy is suddenly converted to movement energy and an earthquake occurs.

***Potential (stored) energy in rocks transformed to ground-shaking kinetic (movement) energy causes an earthquake.***

**The focus** Earthquakes begin in the lithosphere at a point called a **focus** typically no more than 50 kilometers deep (Figure 28.17). At this depth, rock breaks easily under pressure. Earthquakes usually do not occur deeper than this because the rock is closer to the mantle, very hot, and more flexible. Deeper earthquakes (about 700 kilometers) occur at subduction zones when a subducting plate breaks.

**Seismic waves** The conversion of potential energy in rocks to kinetic energy results in **seismic waves**. Seismic waves radiate from the focus, traveling through the ground about 20 times faster than the speed of sound (about 5 kilometers per second). These waves can be slowed or bent depending on the properties of rock they encounter.

**The epicenter** Seismic waves reach Earth's surface at a point above the focus called the **epicenter**. The amount of ground-shaking is generally greatest near the epicenter, but depends on the type of rock and soil present.

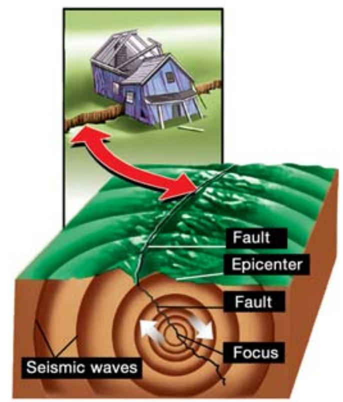



**Figure 28.17:** *The focus, epicenter, and seismic waves of an earthquake occurring at an active fault.*

## Seismic waves

On the previous page, you learned about seismic waves. There are two main kinds of seismic waves: *body waves* and *surface waves*.

**Body waves** — **Body waves** originate from the focus of an earthquake. There are two kinds of body waves that travel through Earth (Figure 28.18). **P-waves** (primary waves) are compression waves that push and pull rock as they move through it. These waves travel about 5 kilometers per second. P-waves move through water and other liquids. **S-waves** (secondary waves) move sideways and up and down, traveling about 3 kilometers per second. S-waves do not travel through liquids.

**Surface waves** — Once body waves reach the epicenter of an earthquake, they become **surface waves**. These waves move more slowly (about 10 percent slower than S-waves), but can be very damaging. When these waves have a lot of energy, the ground rolls like the surface of the ocean. Surface waves can also move side to side and cause buildings to collapse.

**What we can learn from seismic waves** — People who record and interpret seismic waves are called **seismologists**. Seismic waves are recorded and measured by a *seismograph* (Figure 28.19). A worldwide network of seismographs at stations on land and in the oceans record earthquakes. The amplitudes of the recorded waves are related to the rating of the earthquake on the Richter scale (see next page). In addition to measuring earthquakes, seismologists use seismic waves to study Earth's internal structure. This is similar to how a doctor uses X rays to look at bone structure. P-waves and S-waves are able to travel through the Earth's interior (Figure 28.18). However, there is evidence that S-waves do not pass through the outer core. Since S-waves do not travel through liquids, this indicates to seismologists that the outer core is liquid.

**What happens during an earthquake?** — During the earthquake, there is a strong burst of shaking that lasts for a few minutes. The longest ever recorded earthquake occurred in 1964 in Alaska and lasted for four minutes. *Foreshocks* are small bursts of shaking called tremors that may precede a large earthquake. Foreshocks occur days to minutes before the earthquake hits. *Aftershocks* are small tremors that follow an earthquake. These may last for hours to days after the earthquake. The frequency of foreshocks and aftershocks is greatest just before and just after the earthquake.

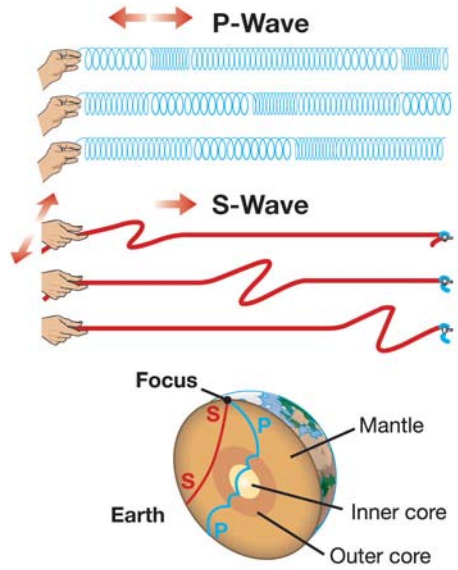



**Figure 28.18:** *P- and S-waves.*

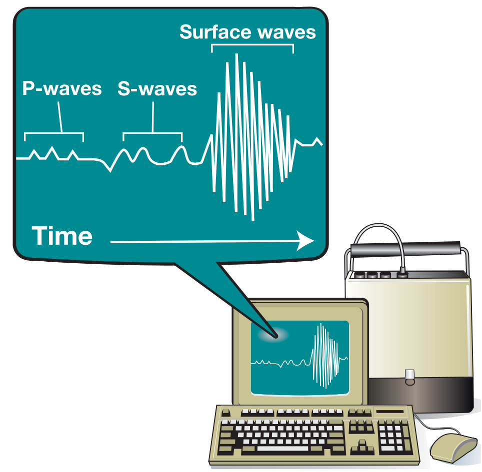



**Figure 28.19:** *A seismograph showing recorded seismic waves.*

## Measuring the magnitude of an earthquake

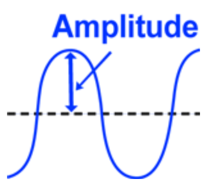
**The magnitude of an earthquake**

The magnitude or size of an earthquake is based on the energy of the seismic waves produced and the amount of ground movement and damage that results. Earthquake rating scales are described below.

**The Mercalli scale**

The Mercalli scale has 12 descriptive categories. Each category is a rating of the damage caused to buildings, to the ground, and to people. Because earthquake damage can be different from place to place, a single earthquake may have different Mercalli numbers in each location where the quake is recorded.

**The Richter scale**




Richter scale ratings relate to the amplitude of seismic waves recorded on a seismograph. Each level of the scale indicates a tenfold increase in earthquake magnitude measured as a tenfold increase in the amplitude of the recorded waves (Figure 28.20). Unlike the Mercalli scale, the Richter scale does not describe the amount of damage from an earthquake. The Richter scale provides accurate measurements for earthquakes that are near, but not for those that are far away.

**The Moment Magnitude scale**

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

**Using seismographs to understand Earth**

Seismographs show the kinds of waves that occur, their amplitude, and the timing of these waves. Using the network of seismographic stations and combining data from many different locations, scientists can also create a scan of Earth to distinguish hot and cool places in the planet's interior. In hot places, seismic waves travel slower. In cool places, seismic waves travel faster. This information has been used to figure out that magma from Earth's mantle is associated with mid-ocean ridges. Today, seismologists cannot reliably predict the date and exact time of an earthquake, but they can identify which areas are likely to have an earthquake in the next 10 or more years. Seismographs are also used to tell the difference between an earthquake and a nuclear explosion. Nuclear testing, which is banned world-wide, causes unique seismic waves to travel through Earth.

**The Richter scale**

| Rating | Effects | Energy in terms of tons of TNT |
|---|---|---|
| < 3.5 | Barely felt; recorded on seismographs. | < 73 |
| 3.5-5.4 | Felt; objects toppled. | 73 to 80,000 |
| 5.5-6.0 | People run outside; damage to poorly built buildings. | 80,000 to 1 million |
| 6.1-6.9 | Damage over a large area. | 1 million to 32 million |
| 7.0-7.9 | Major earthquake; serious damage over a large area. | 32 million to 1 billion |
| > 8.0 | Great earthquake; tragic damage over an area hundreds of kilometers across. | 1 billion to trillions |

**Figure 28.20:** *The Richter scale with a description of the effects at each magnitude and the amount of energy released in terms of tons of the explosive TNT. The largest earthquake recorded occurred in Chile in 1960. It was off the Richter scale; seismologists estimated this quake to be 9.5.*

## Where do earthquakes occur?

**Where are earthquakes?** The majority of earthquakes occur at the boundaries of tectonic plates. The map below illustrates these boundaries and the general positions of earthquakes in the world. At the boundaries, chunks of rock below the surface are disturbed and move, causing an earthquake. Important world cities that experience earthquakes include Mexico City (Mexico), Tokyo (Japan), San Salvador (El Salvador), Santiago (Chile), and Istanbul (Turkey). Individual earthquakes also occur where there is a *fault*. A fault is a place in Earth's crust such as a crack or a *transform plate boundary*. In California, the San Andreas fault is a big fault along which lie the cities of Los Angeles and San Francisco (Figure 28.21).



**Figure 28.21:** *Earthquakes occur along the San Andreas fault.*

| Worldwide earthquakes | | |
|---|---|---|
| **Place** | **Date** | **Richter mag** |
| Ceram Sea, near Indonesia | 1998 | 7.8 |
| Vanuatu, South Pacific island | 1999 | 7.5 |
| New Guinea | 2000 | 8.0 |
| Peru, off Pacific coast | 2001 | 8.4 |
| Hindu Kush region, Afganistan | 2002 | 7.4 |
| South-central Alaska | 2002 | 7.9 |

**Figure 28.22:** *Recent earthquakes and their Richter scale magnitude. These earthquakes are all associated with subduction zones.*

## Earthquakes in the United States

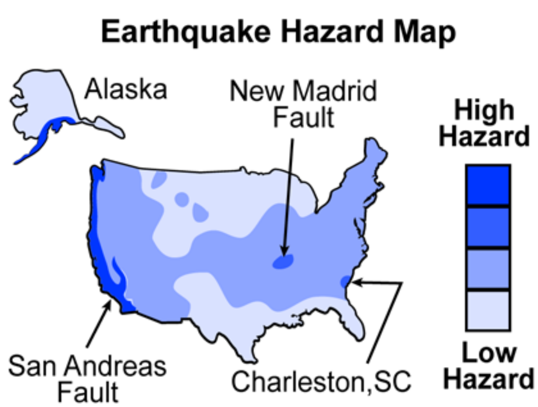
**Earthquakes in the United States**

The west coast of the United States, including Alaska, experiences frequent earthquakes because those regions are near the San Andreas fault and a plate boundary. By comparison, the Midwest and eastern United States experience earthquakes only rarely. These regions are not near a plate boundary. The last time a major earthquake occurred in the Midwest was 1895. The last time that a strong earthquake occurred in the eastern U.S. was in 1886 when a 6.6 (Richter scale) quake hit Charleston, South Carolina.

**The New Madrid fault**

The New Madrid fault is a 250-mile long fault located in the Midwest. Scientists believe this fault and earthquakes in the Midwest are related to processes at plate boundaries or glaciers that once covered North America. These glaciers were so heavy that they pushed down on Earth's surface in this region. Now that these glaciers are gone, scientists believe that the surface is slowly moving back into place, with earthquakes the result.

**Concern about earthquakes**




There are three main concerns if a big earthquake were to occur in the eastern or midwestern United States. First, these regions are centered on the North America Plate, where seismic waves can travel a long way without losing much energy. As a result, more earthquake damage can occur over a larger area. For example, when the Charleston quake struck in 1886, it was felt in New York City, Boston, Milwaukee, Canada, and Cuba. A second concern is that there have been no earthquakes in this region for a long time. This means that the faults may have a lot of potential energy that could release a lot of kinetic energy and cause a big earthquake. Finally, few buildings in the Midwest and East are built to withstand earthquakes, whereas buildings in the West now must be built to withstand quakes.

**Frequency of Earthquakes**

| Description | Richter mag | Avg. # per year |
|---|---|---|
| Great | > 8 | 1 |
| Major | 7-7.9 | 18 |
| Strong | 6-6.9 | 120 |
| Moderate | 5-5.9 | 800 |
| Light | 4.-4.9 | ~6,200 |
| Minor | 3.0-3.9 | ~49,000 |
| Very minor | 1 - 2.9 | ~9000/ day |

**Figure 28.23:** *The frequency of earthquakes worldwide. (Information provided by US Geological Survey.)*

### The importance of minor earthquakes

Minor earthquakes release stored energy in small, less destructive amounts. Rocks in areas that do not experience frequent small earthquakes may have a lot of stored energy. When this potential energy is finally converted to kinetic energy, the earthquake could be big.

## What do seismologists do?

**Locating an epicenter**

Seismographic stations are set up around the world. These stations can measure the arrival time and speed of seismic waves but not the direction from which they are coming. For this reason, it is important to have data from three of these stations (Figure 28.24). At each station, the difference in arrival time between the P-waves (which arrive first) and the S-waves is recorded. The greater the difference in arrival time between P- and S- waves, the farther away an epicenter is from the site of recording. The next step is to use the collected data to figure out the distance to the epicenter. Once the distances are known for the three different sites, circles are drawn around each seismographic station on a map. The radius of each circle is directly related to the difference in arrival time of the P- and S-waves. The point where the three circles intersect is the estimated location of the epicenter.

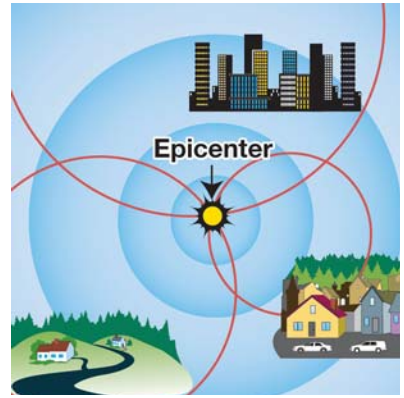



**Figure 28.24:** *An epicenter is identified using data collected from seismographic stations in three different locations.*

**Locating epicenters with computers**

For any earthquake, seismologists locate the epicenter and find out when a series of seismic waves started. Seismologists are also able to identify the focus of the earthquake. Up until the 1960s, they used graphical techniques like the one described above to locate these earthquake features. Then scientists began to take advantage of the development of high-speed computers. They wrote computer programs that could be used to detect epicenters. As these programs improved, they were also used to identify and map the boundaries of plates.

**Creating artificial seismic waves**

Our understanding of seismic waves has also led to creating them artificially in order to explore shallow, internal structures of our planet. Seismic vibrator trucks are designed to create artificial seismic waves by hitting the ground (Figure 28.25). As the ground is "thumped" by the truck, seismologists record the resulting seismic waves. They use this data to study underground rock structures. This information is often used by companies who are looking for oil and gas deposits. Oil and gas exploration also occurs in the oceans. Seismic waves are generated in the ocean by a gun that sends out a blast of compressed air or water from a ship. As the seismic waves bounce back to the ship, they are recorded by a hydrophone that is towed about 5 to 10 kilometers behind the ship.

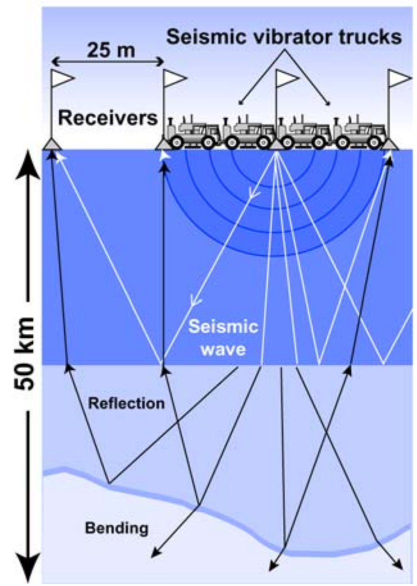



**Figure 28.25:** *Seismic waves created by seismic vibrator trucks.*

## Problem solving: How to determine the distance to an epicenter

Data collected at three seismographic stations includes the speed of the P- and S-waves and the time between the arrival of the P- and S-waves. At each station the speed of the P-wave is 5 kilometers per second and the speed of the S-wave is 3 kilometers per second. The time between the arrival of the waves is recorded in the table at right. Given this information, what is the distance traveled by the waves from the earthquake's epicenter?

| Station # | Time between arrival of P- and S- waves |
|---|---|
| 1 | 75 seconds |
| 2 | 100 seconds |
| 3 | 90 seconds |

Step 1: To calculate the distance to the epicenter for each station, use the equation: distance = rate x time. This equation is a rearranged version of the rate (or speed) equation: speed = distance/time.

Step 2: Use the variables listed in the bottom table at right to solve this problem.

Step 3: The distances traveled by the P- and S-waves are equal, therefore:

$d_p = d_s$

$r_p \times t_p = r_s \times t_s$

Step 4: Since the travel time for S-waves is longer than the travel time for P-waves, then:

$t_s = t_p + (\text{extra travel time})$

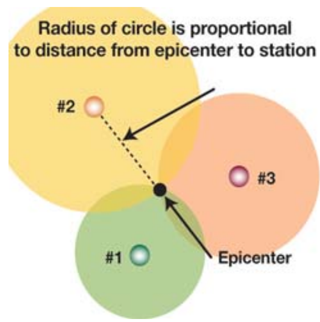
Step 5: Plug this information into a equation and solve for $t_p$. Use the data for Station 1:

$5\ \text{km/sec} \times t_p = 3\ \text{km/sec} \times (t_p + 75\ \text{sec})$

$(5\ \text{km/sec})t_p = (3\ \text{km/sec})t_p + 225\ \text{km}$

$(2\ \text{km/sec})t_p = 225\ \text{km}$

$t_p = 112.5\ \text{seconds}$




Step 6: Substitute the value for $t_p$ into the equation: distance = speed x time.

$d_p = 5\ \text{km/sec} \times 113\ \text{seconds}$

$d_p = 565\ \text{km}$ (This is the same distance that S-waves travel.)

Step 7: Find the calculated distance for the other two stations. These distances are given in the sidebar. Then, draw a circle around each seismic station on a map that shows the locations of the stations. The radius of each circle should be proportional to the distance from the station to the epicenter. The location of the epicenter is where the circles intersect.

| Variables | |
|---|---|
| $d_p$ | distance traveled by P-waves |
| $r_p$ | speed of P-waves |
| $t_p$ | travel time of P-waves |
| $d_s$ | distance traveled by S-waves |
| $r_s$ | speed of S-waves |
| $t_s$ | travel time of S-waves |

**Answers**

**Distances to the epicenter:**

**Station 1: 565 km**

**Station 2: 750 km**

**Station 3: 675 km**

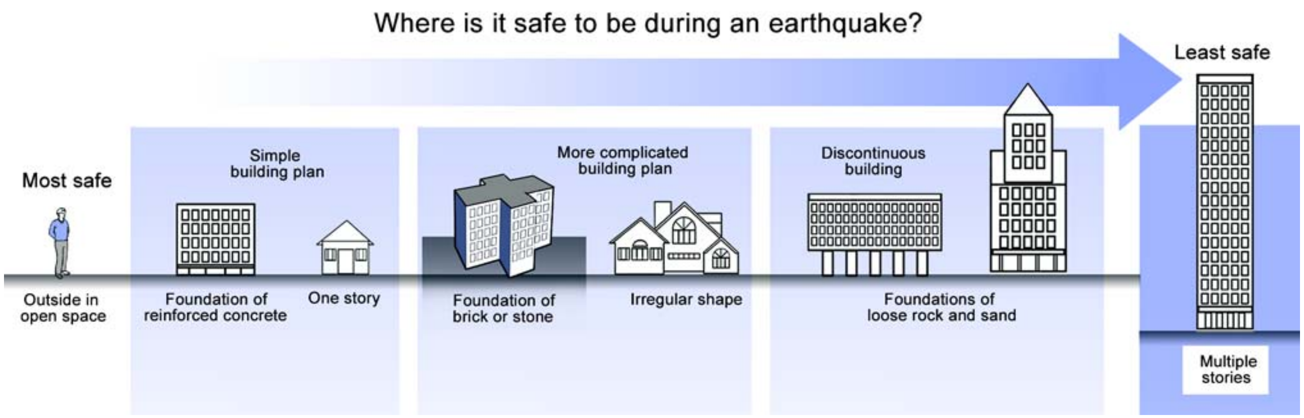
## Preventing earthquake damage

**Earthquake damage**

The shaking ground during an earthquake is not very dangerous. If you were standing in an open space when an earthquake hit, you might fall when the ground moved, but you would be all right. What makes earthquakes dangerous is that the shaking causes buildings, bridges, and roads to collapse and crack. Additional side effects of an earthquake are fires that result from broken gas pipes, huge waves called *tsunamis*, and massive erosion events like mudslides and avalanches.

**Damage prevention for buildings**

How can buildings be built to survive an earthquake? First of all, the building foundation is very important. A structure built on loose soil will sustain more damage during an earthquake. Structures built on land that has a layer of rock below it (called bedrock) will better withstand earthquakes. Strong supports in building frames can keep a building together as it is shaken. Also, engineers have learned that structures can be built to move with the ground. When buildings are too rigid, they are brittle and thus are more likely to crack in an earthquake. Brittle materials are rock, concrete, brick, and glass. When a building is flexible, it can move with the ground as it shakes. Flexible buildings are better able to survive an earthquake. Flexible materials are wood, steel, and fiberglass. How would you design a building to withstand an earthquake? The graphic below compares the safety of certain locations during an earthquake.




### Earthquake safety tips

*In 1995, a 7.2 earthquake struck Kobe, Japan. During the quake, two college students from California quickly ran to stand in a door frame to be safe. They were surprised to see each other. They had never met before. Simply knowing how to be safe during an earthquake brought them together.*

Follow these safety tips in the event of a earthquake:

Getting outside is the safest thing you can do. Once you are outside:

- Get to an open area, far from buildings and objects that could fall.
- Sit down to avoid falling.

If you are inside:

- **Drop, cover, and hold:** Get under a heavy table and hold on to it to keep it from moving away from you.
- If there isn't a heavy table, stand in a door frame or near an inside wall. Protect your head and neck from falling objects.
- Stay away from windows and mirrors.

## Preparing for earthquakes: tsunamis and seismic networks

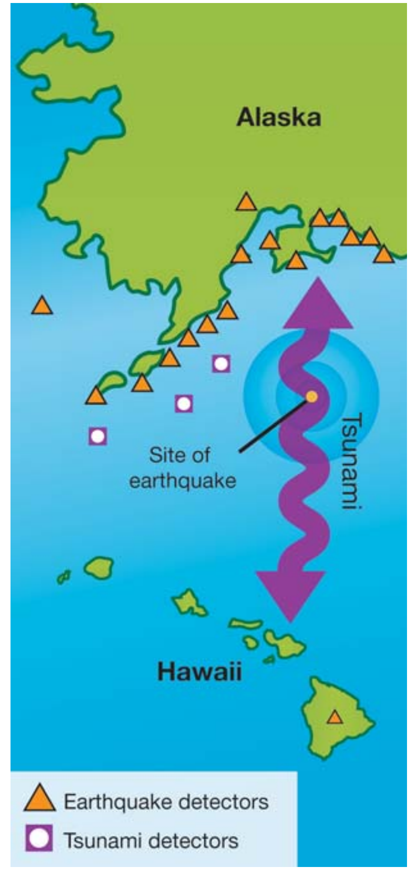



**Figure 28.26:** *A tsunami that occurs in the Pacific Ocean can affect shorelines in both Alaska and Hawaii.*

**What are tsunamis?**

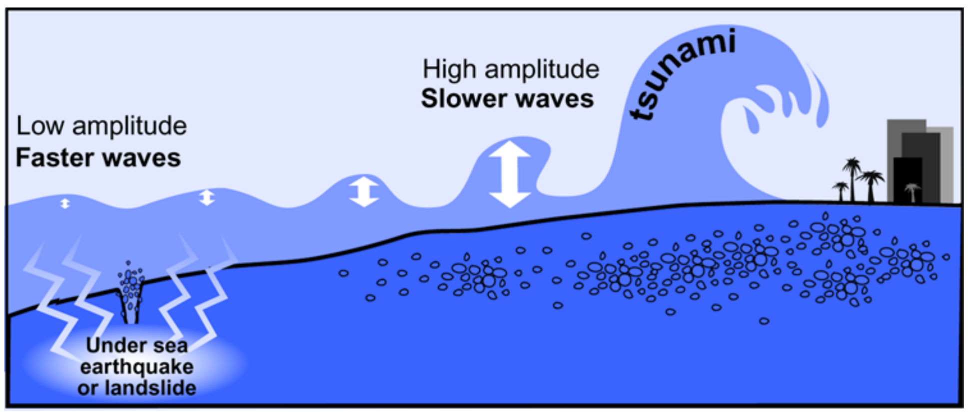
A huge wave generated by an underwater earthquake or landslide is called a **tsunami**. The speed at which this wave travels can be about 700 kilometers per hour. In the open ocean, you would not notice this wave. However, as the wave reaches a shallow area, the water piles up so that the wave may get as high as 25 meters. Tsunamis cause serious flooding and the power of their waves wrecks buildings and can cause loss of life.

**Where do tsunamis occur?**

Tsunamis occur in coastal areas that experience earthquakes. In particular, tsunamis occur in the Pacific Ocean and can affect countries like Japan and Indonesia. Alaska and Hawaii are also affected by tsunamis. When an earthquake happens in the area near Alaska, a tsunami may affect both the Alaskan shoreline and Hawaii (Figure 28.26).

**How do scientists predict tsunamis?**

Around the Pacific coastline of Alaska and the west coast of the Lower 48 states, there are ocean-bound tsunami detectors and seismographs. Scientists use information from the detectors and seismographs to forecast tsunamis. Because scientists know how fast a tsunami can travel after it has been triggered by an earthquake, they can warn people in coastal places to evacuate to higher ground. In December, 2004, in the Indian ocean, two undersea earthquakes ocurred (one at 9.0 magnitude and one at 7.3 magnitude). The tsunamis that resulted killed almost 200,000 people because of the lack of seismic networks in the Indian ocean.



# Chapter 28 Review

## Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

### Set One

| | | | |
|---|---|---|---|
| 1. | paleontologist | a. | The idea that the continents were once a super-continent called Pangaea. |
| 2. | cross-cutting relationships | b. | For a layered rock, the youngest layer is on top and the oldest layer is on the bottom. |
| 3. | superposition | c. | A scientist who studies fossils. |
| 4. | relative dating | d. | A method used to determine the order in which geologic events happened. |
| 5. | continental drift | e. | The vein of rock is younger than the rock surrounding the vein. |
| | | f. | A rock embedded in another rock is older. |

### Set Two

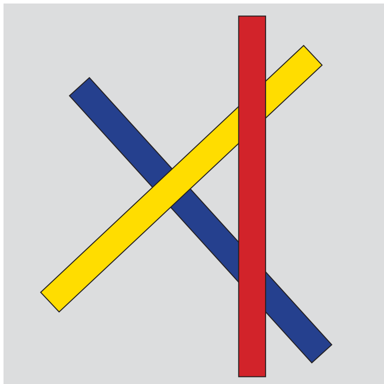
| | | | |
|---|---|---|---|
| 1. | lithosphere | a. | A process that occurs at diverging tectonic plates. |
| 2. | asthenosphere | b. | An ocean mountain range that occurs where tectonic plates diverge. |
| 3. | sea-floor spreading | c. | The layer of the mantle below the lithosphere. |
| 4. | mid-ocean ridge | d. | Earth's crust plus the rigid, upper layer of the mantle. |
| 5. | original horizontality | e. | Sediment forms horizontal layers under the influence of gravity. |
| | | f. | A feature at converging tectonic plates. |

## Concept review

1. Define superposition and lateral continuity. Why are these ideas useful in interpreting how the Grand Canyon formed?
2. Compare the convection currents within the mantle to those in the atmosphere. What energy source drives each current?
3. Compare and contrast the *asthenosphere* and the *lithosphere*.
4. Which of the largest tectonic plates are mainly made of oceanic crust and do not include major continents? Use the diagram of the tectonic plates in the section entitled *Plate Tectonics* to help you answer this question.
5. Describe an example of a divergent plate boundary and a transform plate boundary. Describe two examples of a convergent plate boundary—one example should illustrate where subduction occurs, and the other example should illustrate where mountains occur.
6. What is the difference between the focus and the epicenter of an earthquake?
7. Draw a diagram that shows the difference between a P-wave and an S-wave. Describe the differences between these two kinds of earthquake waves.

## Problems

1. This diagram shows a series of three lines that have been drawn on top of each other. Which line was drawn first? Which line was drawn last? Use relative dating to identify the order in which each line was drawn.



2. North America and Europe are separating at a rate of about 2.5 centimeters a year. How much farther apart will these continents be in 75 million years? Record your answer in kilometers.

3. The geologic time scale covers a very long period. To help you make sense of this length of time, compare the lengths of *each of the periods* with the lengths of something you are familiar with (e.g., a football field, a mile, or the distance from school to your house).
*For example, compare history of the planet with a football field, which is 100 yards long (not including the end zones). If the age of Earth is 4.6 billion years and Homo sapiens have been on Earth for 40,000 years, where on the football field would humans have appeared?*

4. Explain why the following examples support the theory of continental drift: (1) Fossils of an ancient and aquatic reptile (Lystrosaurus) have been found in rocks of the same age on the continents of Antarctica, Africa, and South America. (2) Today, you can find the same species of earthworm in southern Africa and South America.

5. The average density of Earth is 5.52 g/cm$^3$. You learned that the densities of the continental crust and the oceanic crust were 2.75 g/cm$^3$ and 3.0 g/cm$^3$, respectively. Come up with a hypothesis to explain why the average density of Earth is greater than the density of its crust.

6. A seismograph records the arrival of the P-waves of an earthquake and then, 3 1/2 minutes later, the arrival of the S-waves. If the P-waves were traveling at 8 kilometers per second and the S-waves were traveling at 60 percent of the speed of the P-waves, how far away is the epicenter of the earthquake?

7. Seismic waves are about 20 times faster than the speed of sound. If the speed of a seismic wave is 5 kilometers per second, would it be possible to hear an earthquake coming? Given the information provided, calculate an estimate of the speed of sound in units of meters per second.

## Applying your knowledge

1. The terms *density*, *potential energy*, and *kinetic energy* were used in this unit. Each of these terms was presented in previous units. Define each term in your own words and explain why they are important for understanding earth science.

2. Review some recent popular science magazines to find out about the present day activities of geologists and paleontologists. Write a short paragraph that describes a current topic of research in the area of either geology or paleontology.

3. Another important figure in developing the field of geology is Charles Lyell (1797-1875), a Scottish geologist. Like James Hutton, Lyell was important in establishing the idea that the events in the present explain events of the past. Lyell's term for this concept was uniformitarianism. Further research the scientific contributions of both scientists on the Internet or in your local library. Explain their contributions in the form of an one-minute advertisement for television. Write the script for your advertisement and present it to your class. You may use props and other actors in your advertisement.

4. The geologic time scale shown in the section titled *Understanding Earth* illustrates some of the events that have occurred over geologic time. By doing research on the Internet or in your local library, identify when the following events occurred during Earth's geologic history: (1) the appearance of the first trees, (2) the formation of Mount Everest, and (3) the formation of the Mediterranean Sea.

5. Compare Wegener's theory of continental drift with the theory of plate tectonics. Explain why one theory became accepted while the other theory did not.

6. At the site of the Great Rift Valley in Africa, three plates are pulling apart. An eventual consequence of this is that an ocean will form between these plates. When this happens, what will this divergent plate boundary become? Hint: The Atlantic Ocean has this feature.

7. Your property and your neighbor's is separated by a newly formed fault. A year ago, an earthquake occurred at the site of this fault. A month ago, your neighbor discovered a vein of gold on her property. The location of this vein is shown on this diagram. Assuming that the vein continues on to your property, where would you start looking for it? Choose the probable location (either A, B, C, or D) and explain why you chose it. The direction of movement along the fault is shown in the diagram.


8. An earthquake in the eastern hemisphere of Earth is recorded in the western hemisphere. However, only P-waves are recorded. Review what you know about P- and S-waves and come up with an explanation for this data.

9. Define the work of a geologist, paleontologist, and seismologist, each in your own words. If you had to choose to be one of these kinds of scientists, which would you be and why?

# UNIT 10

## Earth Science

# Chapter 29

# Formation of Rocks

Slow, powerful processes are involved in recycling and moving rocky material from place to place on the planet. Deep within Earth, magma rises up and erupts on to the surface. When cooled, this molten rock may become a hand-sized piece of rock, part of a volcanic mountain, or part of the sea floor. Erosion of the land by water, wind, and glaciers is another way that matter moves from place to place. Erosion removes particles off rocks and minerals and moves them to another place where they may become another rock formation. The movement of tectonic plates on Earth's surface can cause rock to be pulled back into the mantle or fold into mountains. The rock cycle summarizes the history of rocks and rock formations.

**29.1** **Volcanoes** *Why do some volcanoes erupt explosively?*

This Investigation expands your understanding of volcanoes. You will be given information about active volcanoes and their magma composition. You will use this information to predict the geographic location of an active volcano.

**29.2** **The Surface of Earth** *How have meteors affected Earth's surface?*

The surface of Earth has endured a lot of erosion over it's 4.6-billion year history. By comparison, the moon's surface has remained relatively unchanged over this time. In this Investigation, you will count the number of meteor impacts for a region of the moon and extrapolate those effects for Earth.

**29.3** **Rocks and Minerals** *How can we interpret the stories within rocks?*

In this Investigation, you will simulate the processes that lead to the formation of the three main kinds of rocks—igneous, sedimentary, and metamorphic. You will also practice interpreting rock formations.

## Learning Goals

In this chapter, you will:

- ✔ Learn about the role of plate tectonics in causing volcanoes and learn what causes eruptions to be gentle or highly explosive.
- ✔ Identify the main types of volcanoes: shield volcanoes, stratovolcanoes, and cinder cones.
- ✔ Learn about other forms of volcanic activity such as geysers, hot springs, hydrothermal vents, and geothermal energy.
- ✔ Learn about the constructive and destructive processes on Earth's surface like mountain-building, and erosion by wind, water, and ice.
- ✔ Learn how to interpret and use geologic hazard maps.
- ✔ Understand human impacts such as urban sprawl on Earth's surface.
- ✔ Learn how to identify the three main kinds of rocks: igneous, sedimentary, and metamorphic.
- ✔ Learn how to identify common minerals using Mohs hardness scale.
- ✔ Apply your understanding of the rock cycle to explain the properties of rocks and to interpret rock formations.

## Vocabulary

| | | | |
|---|---|---|---|
| caldera | geothermal energy | metamorphic rock | soil profile |
| cinder cone volcano | glacier | mineral | stratovolcano |
| cleavage plane | hydrothermal vent | Mohs hardness scale | urban sprawl |
| crater | igneous rock | Ring of Fire | vent |
| erosion | lava | rock cycle | weathering |
| fault-block mountain | magma | sedimentary rock | |
| fold mountain | magma chamber | shield volcano | |

# 29.1 Volcanoes

The eruption of Mount St. Helens in 1980 reduced the height of this mountain in southwest Washington state from 2,932 meters (9,677 feet) to 2,535 meters (8,364 feet) (Figure 29.1). Before then, scientists had monitored earthquake tremors and closely watched the development of a huge bulge at the top of the mountain. Early in the morning of May 18, 1980, an earthquake triggered a landslide that caused the bulge to eject magma, water, and gases.

Mount St. Helens provided scientists with an opportunity to see what happens before, during, and after a volcanic eruption. Why do you think recording earthquakes was a good way to monitor the mountain before it erupted? What do you think caused the bulge on the top? In this section, you will learn the answers to these questions and more about volcanoes.

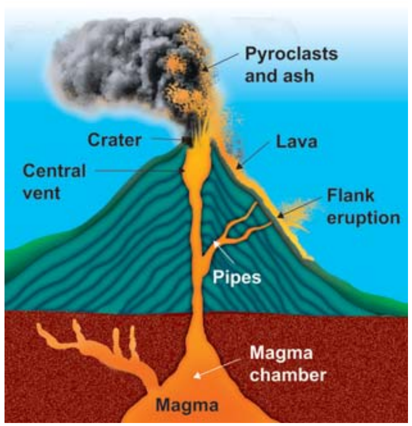

**Figure 29.1:** *Mount St. Helens before and after its eruption. Images courtesy of USGS/Cascades Volcano Observatory.*

## What is a volcano?

**Magma and lava**

Volcanoes are sites where molten rock and other materials from Earth's mantle are released. Molten rock below Earth's surface is called magma. The magma that reaches the surface and erupts out of a volcano is called lava. Volcanoes also release gases and rock fragments into the air. Large rock fragments are called *pyroclasts*. Dust particle-sized fragments are called *ash*.

**Parts of a volcano**




Magma is less dense than Earth's crust so it naturally rises and enters cracks in the surface. Below ground, magma pools in pockets called magma chambers. The pathways that magma takes to Earth's surface are called *pipes*. Areas where magma reaches the surface are called vents. A *flank eruption* occurs on the sides of a volcano where lava spills out of a vent. With each eruption of a volcano, layers of lava and ash build up and form a volcanic mountain. A crater is a depression at the top of a volcanic mountain that forms after an eruption.

### Travel to Earth's core

In 1864, Jules Verne wrote "Journey to the Center of Earth." In this fictional tale, the characters begin and end their travels by entering and exiting a volcano. As you might imagine, a journey to the center of Earth, if it were possible, would involve enduring extremes of temperature and pressure. Earth's core is about as hot as the sun. The pressure would be very great because of the huge weight of rock layers.

## How magma forms

**The mantle is made of solid rock**

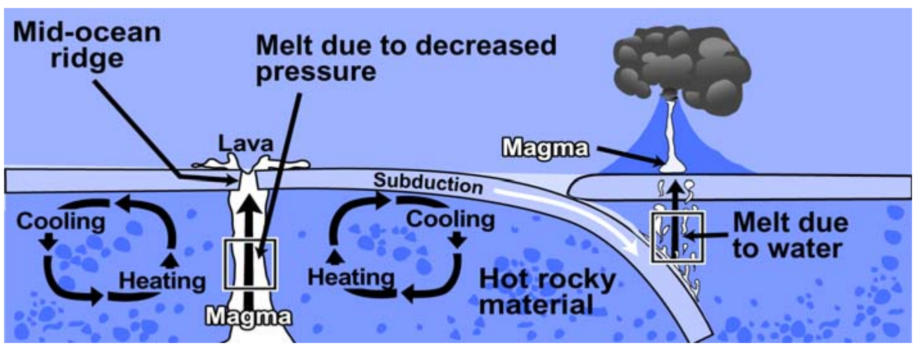
The mantle is composed of very hot, rocky material that moves in very slow convection currents. For the most part, this rocky material is in a solid form even though it is very hot in the mantle. This solid rock melts and becomes magma under certain conditions that lower the melting point of the material (Figure 29.2).

**Decreased pressure lowers the melting point**

The high pressures in the mantle prevent melting. However, because of convection currents, pressure decreases occur, especially near the mid-ocean ridges. At these locations, the rocky material can rise and replace the lava that is becoming new sea floor. Sea-floor spreading creates a void that gets filled by magma from the mantle. This process affects the deeper mantle by causing a decrease in pressure. The first stage of melting is called *partial melt*. The rocky material experiences partial melt because it is composed of various minerals, each with a different melting point. When the minerals melt, the resulting magma is less dense. This is another factor that contributes to magma's ability to rise to Earth's surface.

**The addition of water lowers the melting point**

At subduction zones, water is the key for solid rock to melt and become magma. When subduction occurs, some water is brought in with subducted sediments. Water is also evaporated from minerals like hornblende. The water lowers the melting point of surrounding rock so that magma forms. In other words, the addition of water means that rock will melt and become magma at a lower temperature. Because of water, subduction zones are sites of volcanic activity. The Ring of Fire is the result of subduction zones surrounding much of the Pacific Ocean.



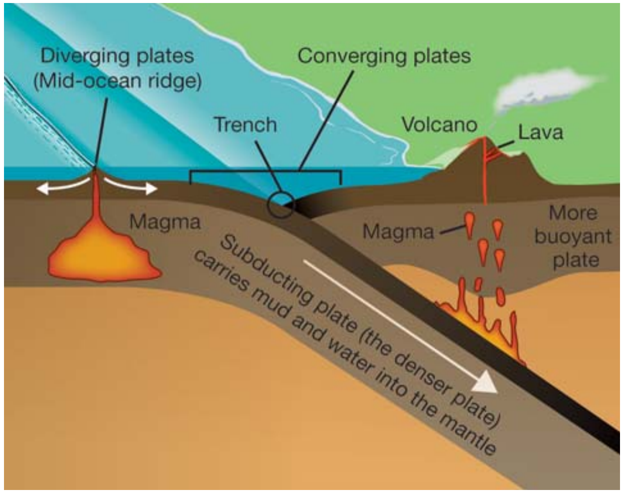

| Solid rock | Melted rock (magma) |
|---|---|
| High pressure | Low pressure |
| No water | Water |

**Figure 29.2:** *This table summarizes the conditions under which the rocky material in the mantle is solid or melted. Rocky material melts and becomes magma when the pressure is lowered or when water is present.*

### Volcanic eruptions

Magma pools near Earth's surface in a magma chamber. Over time, pressure builds up within a chamber as the magma begins to cool and dissolved gases and water vapor are released. Any trigger that releases this pressure—like a small earthquake or a weakness in the volcano itself—results in the sudden, explosive, escape of gases, lava, pyroclasts, and ash.

## Where do volcanoes occur?

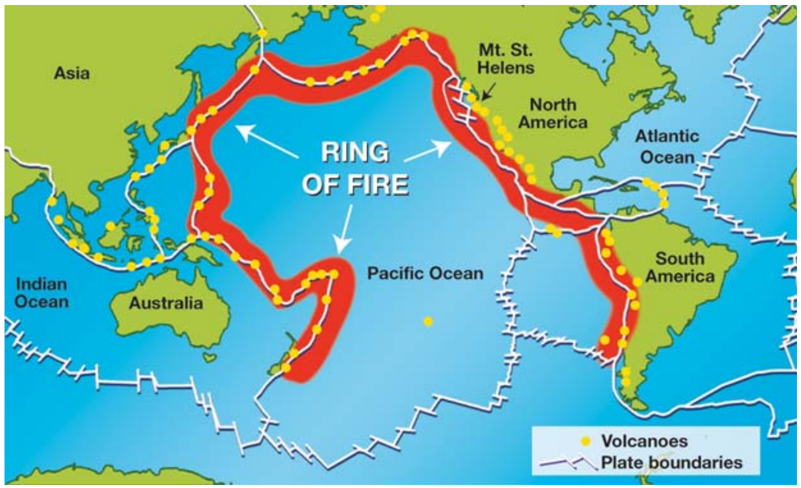



As with earthquakes, most volcanic activity is found at the edges of tectonic plates, namely at *divergent* and *convergent plate boundaries*. Unlike earthquakes, volcanic activity does not occur at *transform plate boundaries*. The mid-ocean ridges, where plates diverge, are like very long volcanoes. Volcanoes also occur at convergent plate boundaries such as where one plate subducts under another.

### The Ring of Fire

About half of the active volcanoes on Earth occur along the boundary of the Pacific Ocean. This region, called the Ring of Fire, includes both volcanic activity and earthquakes. The Ring of Fire coincides with regions where the oceanic crust of the Pacific plate is subducting under other plates. The graphic at left shows how volcanoes (represented by the blue dots) are associated with plate boundaries.

Mount St. Helens is one of the volcanoes within the Ring of Fire. This volcanic mountain is part of the Cascade Mountain range. Mount St. Helens formed when the Juan de Fuca plate subducted under the North American plate.




***Most volcanic activity is associated with plate boundaries. About half of Earth's active volcanoes occur within the Ring of Fire.***

## Features of volcanoes

**Viscosity of lava**

The shape of a volcano depends on the material that comes out of it. Volcanoes emit lava, pyroclasts, ash, and gases. Most importantly, the shape is related to the thickness or *viscosity* of the lava. Viscosity is a measure of a fluid's flow rate. Fluids with high viscosity flow slowly. Fluids with low viscosity flow quickly. Lava's viscosity depends on how much silica it contains. The higher the silica content, the greater the viscosity of the lava.

**Types and shapes of volcanoes**

Low viscosity, fast-flowing lava is associated with shield volcanoes. Because this lava easily flows down hill, shield volcanoes are gently sloped and flattened. In general, these volcanoes range in height from 500 to 10,000 meters high. High viscosity lava is associated with stratovolcanoes (also called composite volcanoes). Stratovolcanoes are cone-shaped, steep-sided mountains made of layers of lava and ash. These volcanoes are around 3,000 meters high. Cinder cone volcanoes are steep stacks of loose pyroclasts (clumps and particles of lava). Cinder cones are rarely higher than 300 meters.

**The explosiveness of a volcano**

Lava viscosity also determines how explosive an eruption will be. Explosive eruptions occur when the lava has a lot of water and dissolved gases (carbon and sulfur dioxide and hydrogen sulfide). This happens when lava is very viscous, as in cinder cones and stratovolcanoes. These volcanoes occur on the continents so their lava contains dissolved granite-like rock (called andesite and rhyolite) that is high in silica. Gentle eruptions are associated with fast-flowing lava from oceanic crust. This lava contains basalt which has less silica, less water, and fewer dissolved gases. Shield volcanoes produce this kind of lava.

**Descriptions of lava**

| Silica content | Low (45-54% silica) | High (54-73% silica) |
|---|---|---|
| Rock composition | Melted basalt | Melted granite-like rock (andesite or rhyolite) |
| Viscosity | Low: flows quickly (~16 km/hour) | High: flows slowly |
| Kind of eruption | Gentle; less water and dissolved gas | Explosive; more water and dissolved gas |
| Associated volcanoes | Shield volcanoes | Stratovolcanoes and cinder cones |

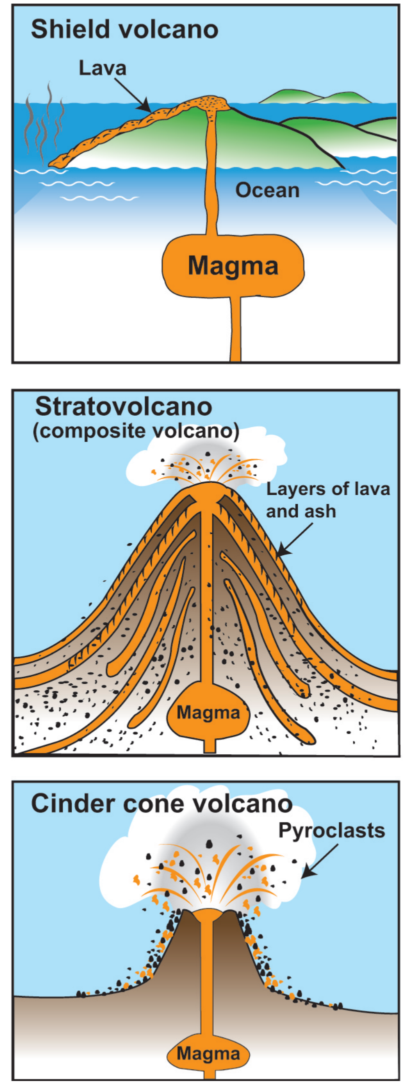



**Figure 29.3:** *The three main types of volcanoes.*

## Shield volcanoes

**More about shield volcanoes**

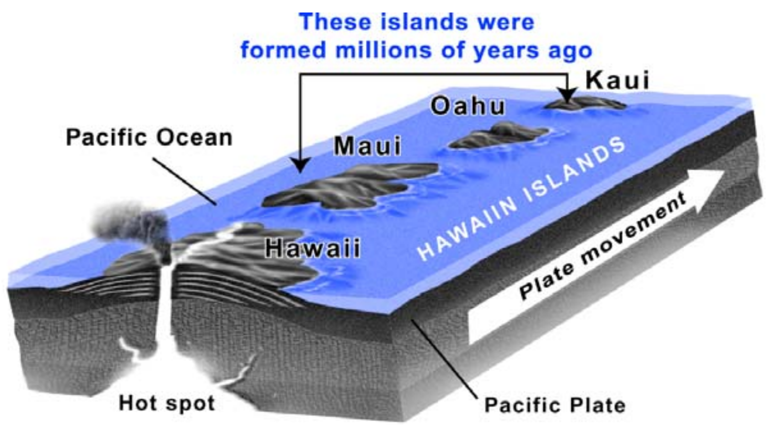
Shield volcanoes are made of fast-flowing, basaltic lava. Although these volcanoes can become very large, their overall shape is flattened because the lava flows too quickly to accumulate on top. Most of these volcanoes form over *hotspots*. The eruptions of shield volcanoes are usually mild because the lava has low viscosity. However, if water enters the main vent, an explosive eruption may occur.

**How shield volcanoes form**

Scientists believe that heat from the outer core warms the lower mantle. At certain places, a blob of magma forms at the boundary between the outer core and the mantle. When the blob gets big enough, it rises toward Earth's surface as a *mantle plume* and becomes a *hotspot* (Figure 29.4). *Hotspots* originate under the lithosphere so they are nearly stationary or move at rates slower than overriding plates.

**Hawaiian Islands**

As an oceanic plate moves over a hotspot (over millions of years), a series of volcanoes form. The Hawaiian Islands were formed in this way. The oldest of the islands is Kaui; the biggest, Hawaii (called the Big Island), is still being formed. Hawaii alone has five shield volcanoes on it, three of them are "world record holders." Mauna Kea is the highest mountain (10.3 kilometers, measured from the seafloor; Mount Everest is 8.84 kilometers above sea level), Mauna Loa is the largest mountain by volume, and Kilauea is the most active volcano.



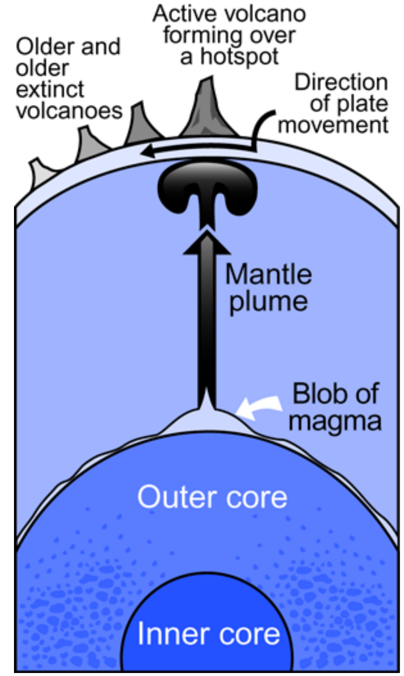




**Figure 29.4:** *How a hotspot forms.*

### Hotspot volcanoes

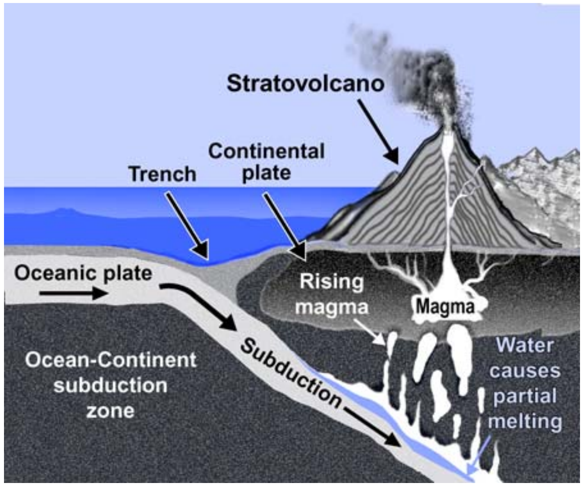
The Galapagos Islands are shield volcanoes that formed over a hot spot in the Pacific Ocean. Yellowstone National Park features volcanic activity related to a continental hotspot. Iceland is an island formed by the volcanic activity of a hotspot and the Mid-Atlantic Ridge.

## Stratovolcanoes (Composite volcanoes)

**The Ring of Fire and subduction**

The majority of the world's volcanoes are stratovolcanoes. Unfortunately, these tend to be the most explosive and destructive kind. In particular, these volcanoes are found within the Ring of Fire, which is associated with subduction zones. At some of the edges of the Pacific Ocean, thinner, denser, oceanic plates are sliding under continental plates. Stratovolcanoes are formed at these locations.

**How stratovolcanoes form**




When the subducting oceanic plate encounters hot mantle, water is released. This water reduces the melting point of the surrounding rock so that it melts at a lower temperature. Because the magma is less dense than the surrounding solid rock, it rises to Earth's surface. As the magma passes through the overlying continental and oceanic crust, it dissolves continental rock which is high in silica and becomes very viscous.

**Eruption of stratovolcanoes**

Eventually, a significant amount of this thick magma collects in a magma chamber. As the magma rises and begins to cool, gases are released and create excess pressure in the magma chamber. This pressure is relieved when cracks occur in the overlying crust and creating passageways to the surface. If a lot of gases are present, then the result is an explosive eruption. The intensity of the eruption is amplified by the conversion of water to steam. Additionally, as magma rises to the surface, gas bubbles become larger. These expanding bubbles contribute to the intensity of the volcanic explosion.

**Examples of stratovolcanoes**

The Cascade Range near the west coast of the United States includes Mount St. Helens among its stratovolcanoes. They are also found in Indonesia and along the west coast of South America in the Andes Mountains of Chile.

### Nuée ardentes

A *nuée ardente* is a "glowing cloud" of hot volcanic debris that is often associated with the eruption of a stratovolcano. The cloud is made of lava which floats on top of volcanic gases. After an eruption, the cloud races down the slope of the volcano at speeds greater than 60 miles per hour, smothering everything in its path.

## Cinder cones

**More about cinder cones**

Cinder cones are common, relatively small volcanoes. They can form over a vent in clusters or on the side of a larger volcano. Usually, cinder cones erupt only once. The length of those eruptions, however, can range from about a month to 10 years.

**How cinder cones form**

When water mixes with lava, it can cause an explosive volcanic eruption. The same is true if lava contains a lot of dissolved gases. When a lot of gas and water are mixed into lava, pieces of the lava are blasted out from a vent and solidify in the air. These pyroclasts, called cinders, have numerous air pockets. As the cinders settle back onto the ground, they form the cinder cone. A cinder cone is a loose, cylindrical pile of this pyroclastic material with round crater at the top. Lava from a cinder cone tends to flow out of the base rather than at the top because the cone is made of loose material.

**Parícutin, Mexico cinder cone**

In 1943, a cinder cone volcano was born in a cornfield in Parícutin, Mexico. It began when gas-filled lava erupted from the ground. In a very short time, there was a pile of volcanic material. In the end, Mount Parícutin was a 400-meter high, steep-sided hill of ash and volcanic debris. It was active from 1943 to 1952.

**Wizard Island cinder cone**

Another well-known example of a cinder cone is Wizard Island in Crater Lake National Park in Oregon. This cinder cone formed in a caldera called Crater Lake (see the sidebar at right). This huge depression formed when the summit of Mount Mazama collapsed following a huge explosive eruption about 7,000 years ago. Mount Mazama was a stratovolcano. Its eruption was about 40 times greater than that of Mount St. Helens. After this eruption and the formation of Wizard Island, trillions of gallons of water from melted snow and rain filled Crater Lake. This lake, at about 2000 feet, is one of the deepest lakes in the world.

**Exploiting cinder cones**

Interestingly, cinder cone volcanoes are threatened by the fact that people like to take the materials that make up the cinder cone and use the materials for building roads and for sanding roads in the winter. Cinder cone rock is also used as decorative "lava rocks" for landscaping.


**Figure 29.5:** *Wizard Island in Crater Lake.*

### Calderas

When a volcano erupts, the magma chamber becomes an empty pocket under the overlying rocks. Eventually, the weight of the rocks is too great and the remaining top of the volcano collapses on itself and creates a depression called a caldera.

Calderas are active volcanic sites. Magma underneath a depression continues to heat the ground and underground water. Volcanic activity associated with a caldera includes boiling mud puddles, geysers, and hot springs.

## Additional sites of volcanic activity

**Volcanic activity at ridges**

Most volcanic activity on Earth occurs at mid-ocean ridges where plates are diverging. These regions are like long volcanoes. The Mid-Atlantic Ridge and the East African Rift Valley are slow-spreading ridges. Therefore, these ridges tend to have a valley where the plates are diverging. Volcanoes that form in these valleys are called *rift volcanoes*. An example is Mount Kilimanjaro in Tanzania, East Africa. The East Pacific Rise is a fast-spreading ridge and lacks a valley between the diverging plates. At both the Mid-Atlantic Ridge and the East Pacific Rise, lava forms new seafloor. An above sea-level version of volcanic activity is Iceland, a large island that is part of the Mid-Atlantic Ridge. Near Iceland, a volcanic eruption that started on the ocean floor formed a new island, Surtsey, in 1963 (Figure 29.6). This island experienced volcanic activity until 1967.

**Island arc volcanoes occur at subduction zones**

You have learned that volcanic activity is associated with subduction that occurs when an oceanic plate slides under a continental plate. Volcanoes also form when an oceanic plate slides under another oceanic plate. As the denser oceanic plate is pulled downward and melted in the mantle, magma rises and enters cracks in the non-subducting oceanic plate. The result is the formation of an arc of volcanic islands along the trench at the place where the plates converge. Examples of island arcs are the Caribbean Islands and the islands of Japan.

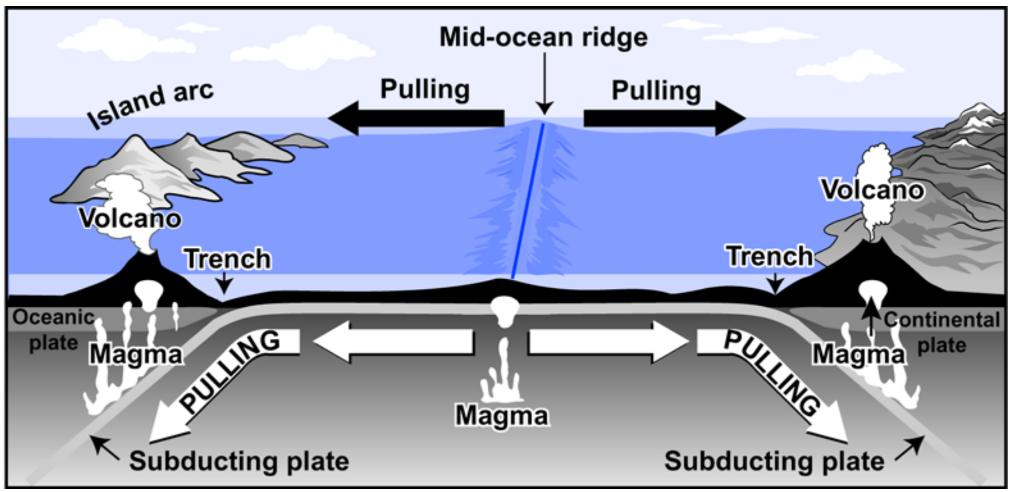




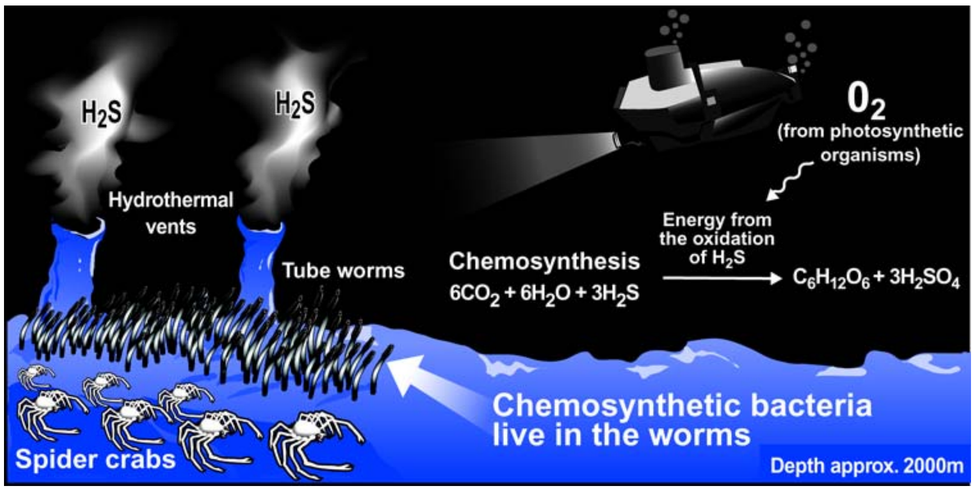
**Figure 29.6:** *The birth of a new island. Surtsey was "born" near Iceland because of a volcanic eruption from the ocean floor.*

**Volcanoes shape Earth**

At mid-ocean ridges and active volcanoes, lava erupts on Earth's surface and cools, resulting in the formation of rocks and new land. Islands, the ocean floor, and the continents are simply solidified lava or magma. The Earth's entire surface is a product of new or ancient volcanic activity.

**Hydrothermal vents**

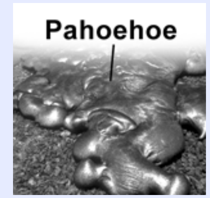
**Hydrothermal vents** are deep sea chimney-like structures that occur along mid-ocean ridges. Seawater that has been heated by magma to high temperatures comes out of the vents. When this hot, mineral-rich water reaches the cold water (about 0°C) at the sea floor, the dissolved materials precipitate and form the chimneys. Sulfur is an important mineral associated with these vents. Living near the vents are giant tube worms that live off bacteria that use hydrogen sulfur to make food. These bacteria use *chemosynthesis*, a process like photosynthesis, to survive. Instead of using the sun's energy to make food and oxygen from carbon dioxide and water, they get their energy from the reaction between oxygen and hydrogen sulfide ($H_2S$). Interestingly, the source of oxygen for chemosynthesis is oxygen from photosynthesis at Earth's surface that has dissolved in the ocean water and circulated down to the deep ocean.




### Volcanoes and the atmosphere

When volcanoes erupt, large amounts of gases and particulates are released into the atmosphere causing natural air pollution. The gases include sulfur dioxide and nitrogen oxides. The dust released by volcanoes may be responsible for temporary cooling of Earth's climate. Additionally, water vapor from volcanoes has been an important source of water for Earth's surface and atmosphere.

### Special names for lava




Because of the volcanic nature of the Hawaiian Islands, some volcanic terms are Hawaiian names.


Two of these are *pahoehoe* (pah HOH ee hoh ee) and *aa* (Ah ah). These terms describe lava with relatively little silica. Pahoehoe flows quickly. When it cools and solidifies it looks like taffy and has long, curvy, wrinkles. Aa is more viscous. When it cools and solidifies it looks very crumbly, like large clumps of granola. Pahoehoe and aa are characteristic of the non-explosive, gentle eruptions on the Hawaiian Islands.

## Products of volcanic activity

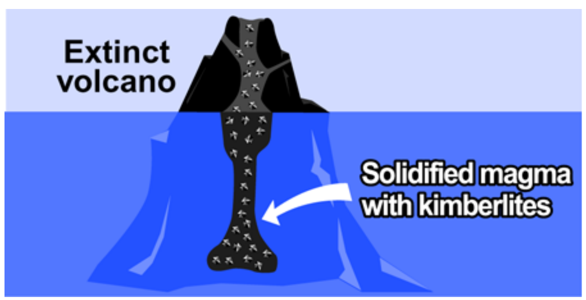
**Geysers and hot springs**


Photo courtesy of Mary Feay

*Geothermal energy* can heat water underground and generate steam. When this steam is released naturally, it is called a *geyser*. In Yellowstone National Park, Old Faithful is a very famous geyser that releases water and steam every 33 to 93 minutes. The geyser occurs when pressure builds up underground and forces a blast of steam and water. *Hot springs* are pools of groundwater that have been heated by pockets of magma. This heated water collects at Earth's surface. In the mountainous regions of Japan, a cold-weather monkey called the Japanese Macaque keeps warm by sitting in hot springs.

**Mineral deposits and diamonds**

Water heated by volcanic activity has dissolved minerals in it. As this water cools, the minerals precipitate, forming rich deposits of economically important minerals such as gold, copper, zinc, and iron. Some gemstones are also associated with volcanic activity. For example, diamonds form at high temperatures deep underground when carbon crystallizes inside rocks called *kimberlites*. Kimberlites reached the surface during violent eruptions of ancient volcanoes. Scientists believe that this magma, which was highly pressurized, moved toward Earth's surface at twice the speed of sound. At the surface, the kimberlites cooled and hardened in volcanic vents and cracks in the crust, becoming today's diamond resources. Diamonds are mined on every continent except Europe and Antarctica where they may exist but remain undiscovered. Regions that are rich in kimberlites include Australia, Russia, and, in Africa, Botswana, the Democratic Republic of Congo (formerly Zaire), and South Africa. In the United States, there are diamond mines on the Colorado-Wyoming border and in North Carolina. The latest discovery of diamonds resources has been in Canada.




### Geothermal energy

Some places on Earth do not rely on fossil fuels to have heat or heated water. This is because they are able to utilize heat and steam that is trapped in Earth's crust. This kind of energy is called *geothermal energy*. Places that use geothermal energy include Iceland, New Zealand, and Northern California.

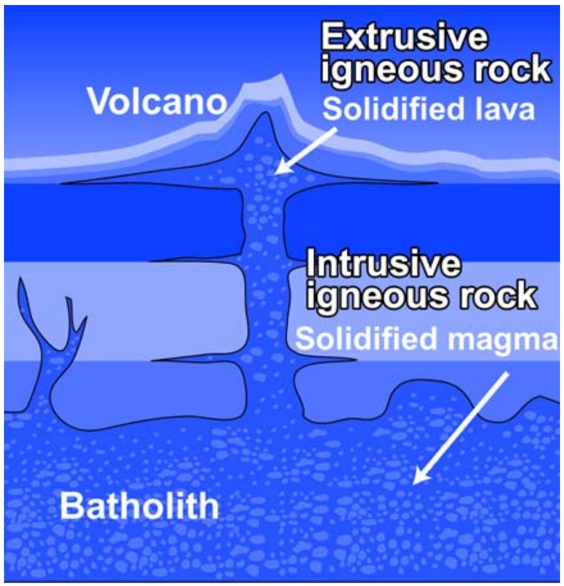
Geothermal energy is the useful product of volcanic activity. When steam from magma collects below ground, it can be tapped just like water in a well. This steam is under pressure which makes it even more useful. In other words, the pressurized steam can be used to generate electricity. The steam is also useful for heating homes.

## Describing volcanoes

**Assessing the status of a volcano**

The scientists who study volcanoes are called *volcanologists*. In addition to trying to predict the timing of a volcanic eruption, they determine how hazardous an eruption might be. Volcanologists spend their time observing and describing volcanic regions. An *active* volcano may soon erupt or has just erupted. Presently, there are about 500 active volcanoes on Earth, causing an average of 60 eruptions per year. A *dormant* volcano does not show signs of erupting, but it may erupt in the future. The time until the next eruption may not be for hundreds or thousands of years. Dormant volcanoes include Campi Flegrei caldera in Italy, Mount Baker and Mount Hood on the West Coast of the United States, and Nisyros, a stratovolcanic island that is part of Greece. An *extinct* volcano is one that has ceased activity. Examples of extinct volcanoes are Mount Kilimanjaro in Tanzania, East Africa; Mount Warning in Australia; 90 volcanoes in the volcanic region of France called Chaine des Puys; and Mount Elbrus in Russia, Europe's tallest mountain at over 5.4 kilometers.

**Describing volcanic rock**




Volcanic activity results in the formation of two kinds of rocks—*extrusive* and *intrusive igneous rocks*. Rocks formed from lava, which has been erupted on the surface, are referred to as *extrusive*. These rocks cool quickly and have fine crystals as a result. Extrusive rocks are associated with volcanic eruptions. When magma cools and solidifies below Earth's surface, *intrusive igneous rocks* are formed. Because these rocks cool more slowly, they have larger crystals. A *batholith* is a large underground rock that formed when a mass of magma cooled underground.

### Can volcanoes be predicted?

It is easier to predict a volcanic eruption than an earthquake because there are many more signs that a volcano might erupt. Predictors of eruptions include:

- Earthquake tremors that result from magma collecting in the ground.
- Heating of water near the volcano.
- The release of gases from the volcano.
- Changes of the volcano's surface

Which of these predictors indicated that Mount St. Helens was going to erupt in 1980?

Scientists can predict that a volcano is active and will erupt in the near future. They cannot predict the exact time it will erupt or how explosive it will be.

# 29.2 The Surface of Earth

A full moon in the night sky gives you a glimpse of what the moon looks like. Unlike Earth, the moon has no plate tectonic activity. Additionally, the moon is nearly free of water and lacks an atmosphere. Without plate tectonics and erosion by wind and water, the surface of the moon has stayed the same for a very long time (Figure 29.7). In comparison, Earth's surface is always changing. In this section, you will learn about forces that cause these changes.

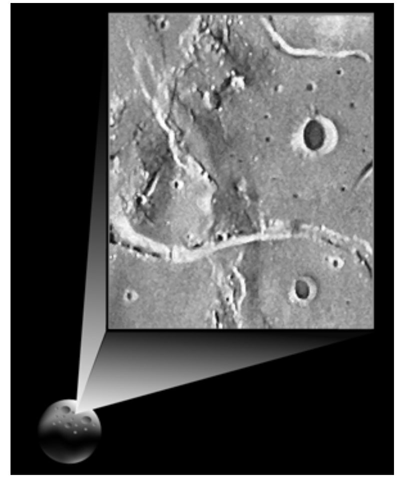


**Figure 29.7:** *The craters on the surface of the moon are the result of impact craters from meteorites. How does the surface of Earth compare with that of the moon?*

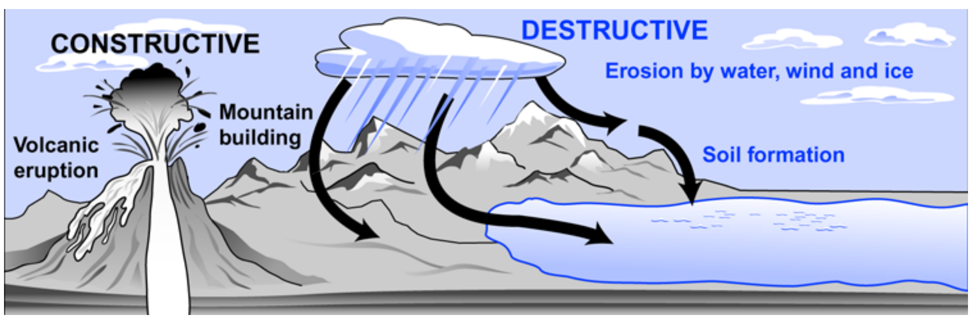
## Earth's lithosphere

Earth's surface is constantly changing

Earth's lithosphere is very thin compared with the whole planet. Pieces of the lithosphere, called tectonic plates, move on Earth's surface. Recall that earthquakes, volcanoes, mountains, and the construction of new lithosphere are events that occur at plate boundaries. These events are changing the appearance of Earth's surface all the time. For example, the slow collision of tectonic plates continues to build mountains. Mountains that are still being built include the Rockies, Himalayas, and Alps (Figure 29.8). Somewhere on Earth, an active volcano is erupting and adding more lava to Earth's surface.

Constructive vs. destructive processes

The features we see on Earth's surface represent the dynamic balance between the *constructive processes* often associated with plate tectonics (volcanoes and mountain-building) versus the *destructive processes* of erosion associated with moving wind, water, and ice. At the same time that mountains and volcanoes are being created, wind and water are gradually wearing down these and other land formations. The eroded bits of rock are then deposited and piled up by wind or water somewhere else on Earth's surface only to become another land formation.



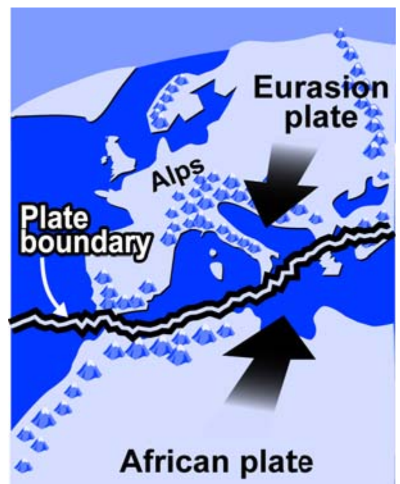



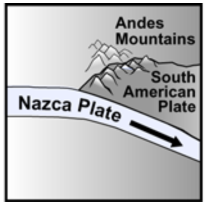

**Figure 29.8:** *The formation of the Alps is still occurring as the African and Eurasian plates converge.*

## Mountain-building, a constructive process

**How mountains form**

Mountain-building is a major constructive process. Mountains form in three main ways: by folding at convergent plate boundaries; by movement of chunks of land at faults; and by volcanic activity.

**Fold mountains**




Scientists explain how fold mountains formed using the theory of plate tectonics (Figure 29.9). The Andes were formed as the Nazca plate subducted under the South American plate. At this convergent boundary between a subducting oceanic plate and a continental plate, mountains formed along the west coast of South America due to folding and faulting (breaking into chunks due to the lithosphere cracking under pressure). Mountains also form when two continental plates collide. For example, the Himalayas are fold mountains that began to form more than 40 million years ago when the Indian and Eurasian plate collided.

**Fault-block mountains**

Sometimes pressure at plate boundaries causes the lithosphere to crack and become a fault. A result of this cracking is a fault-block mountain (Figure 29.10). When cracks occur, pieces of the lithosphere tilt or move. Chunks of rock that slide down create a valley. The chunks that move upward or tilt form mountains. Mountains near the San Andreas fault are examples of fault-block mountains.

**Mountains formed by volcanic activity**

Volcanic mountains occur at subduction zones (e.g., the Ring of Fire) and at hotspots (Figure 29.11). A *volcano* is formed by the extensive layering of lava and volcanic material that builds up over millions of years with each eruption. For this reason, these mountains often stand alone; they are not part of a mountain range. A *dome mountain* is formed by a bulge of magma forcing the lithosphere upward.

### Formation of the Andes Mountains

In the 1830s, Charles Darwin found seashell fossils in the Andes on the west coast of South America. Darwin's interpretation of his findings was that a powerful, slow-moving force from Earth had thrust the bottom of the sea upward and formed the Andes. The Andes are so high that even if the polar ice caps melted, there would not be enough water on Earth to completely cover these mountains. This means the Andes could not have been undersea mountains at one time.

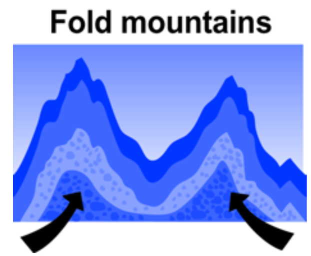



**Figure 29.9:** *Examples of fold mountains include the Andes and the Himalayan Mountains.*

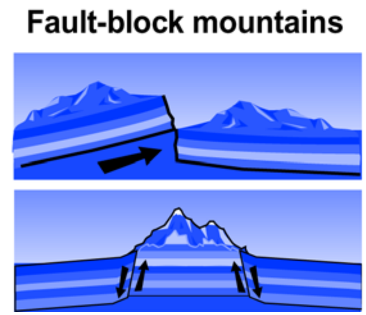



**Figure 29.10:** *Mountains along the San Andreas fault are examples of fault-block mountains.*

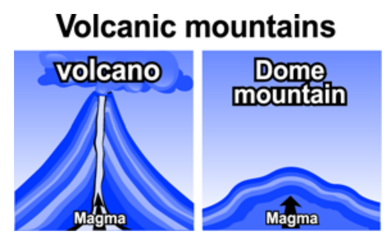



**Figure 29.11:** *There are numerous volcanic mountains along the Ring of Fire. An example of a dome mountain is Mount Rushmore.*

## Erosion, a destructive process

**What is erosion?**

**Erosion** (also known as *weathering*) is a major destructive process. This term describes the continuous physical and chemical events that cause land and rock to wear down. To understand erosion, think of a sand castle. Once you have made your sand castle, it does not take long for water, wind, and people to transform your castle back to a pile of sand. Likewise, mountains are made of rock and soil. They are eroded by wind and water in the form of rain, streams, and ice in the form of **glaciers**. Mountains grow or get higher when they form faster than erosion occurs. However, when the mountain forming process slows down, erosion dominates. The rate of erosion is related to the height and steepness of the mountain—the steeper the mountain is, the faster it erodes because it is easier to push material down a steep slope than a gradual slope. Mountain building is a slow geologic process taking millions of years. Mountain weathering is rapid by comparison.

**Young versus old mountains**

You can tell if a mountain is young or old by the shape of the peaks. Sharp mountain peaks indicate a young mountain. Although the Himalayas began forming more then 40 million years ago, the sharp peaks indicate that these mountains are relatively young. Rounded mountain peaks indicate an old mountain that has worn away for a long time. The Scottish Highlands are old, rounded mountains that are about 250 million years old. The Appalachians, also old rounded mountains, are more than 200 million years old.

**Landforms shaped by water**

Valleys are good examples of the power of water and gravity on land. Rain falls and flows down steep-sided mountains, eventually collecting in a large body of water like a lake or ocean. At the top of a mountain, water runs quickly and carves V-shaped riverbeds. Over time, the river carves out enough room to move side to side and make the valley U-shaped. Valleys can also become U-shaped when a glacier moves through a river valley like a giant ice cream scoop. Near the ocean (or any slower body of water like a lake or pond), a river may spread out and form a delta. A *delta* is a place where a river spreads into a fan shape as it slows down and deposits large amounts of sediment. The Mississippi Delta is a well-known delta in the United States. Another well-known feature that was shaped by a river is the Grand Canyon, created as the Colorado River ran through it.

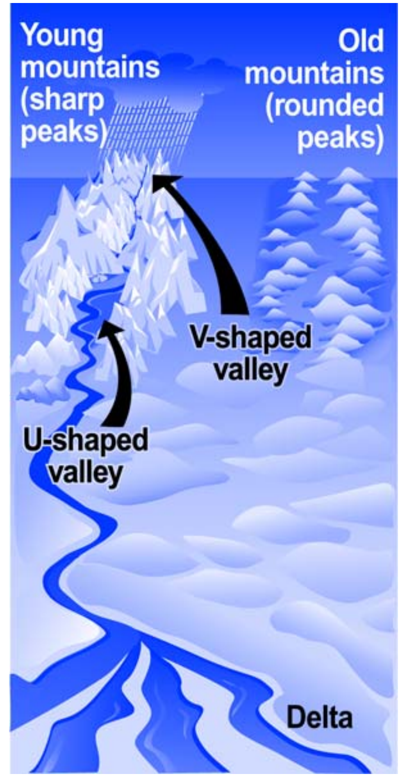



**Figure 29.12:** *An illustration of old versus young mountains and valleys. Older mountains have rounded peaks whereas young mountains have sharp peaks. V-shape valleys tend to be toward the tops of mountains. U-shaped valleys tend to be toward the base of mountains where rivers tend to flow in curvy pathways. A delta is a place where a river fans out as it approaches a slow-moving body of water.*

## Formation of soil

**What is soil?** The formation of soil is the result of erosion. Soil is made of weathered rock and decayed animals and plants. For this reason, it is rich in nutrients and a suitable medium in which plants can anchor their roots and grow. Important compounds and elements would remain trapped in rocks and unavailable to plants in the soil if it was not for erosion. Ultimately, through the food chain, the nutrients are passed on to us.

**The characteristics of soil** The characteristics of soil depend upon the type of rock that is weathered. The main sources of soil are volcanic and mountain rocks. The characteristics of soil also depend on the type of weathering. *Chemical weathering* mostly occurs in hot, wet climates such as tropical rain forests. Examples of chemical weathering are rust formation in iron-containing minerals and erosion by rain which is always a little acidic. Some soil characteristics depend on temperature because some reactions that cause chemical weathering occur faster at warmer temperatures. *Mechanical weathering* mostly occurs in cold, dry climates such as tundras in polar regions and involves breaking up rock into smaller and smaller pieces.

**A soil profile** Figure 29.13 illustrates a soil profile. A soil profile is a cross-section that shows the different layers of soil in the ground. It takes a long time and a lot of weathering for soil to have all the layers you see in this figure. Young soil does not have each of these layers.

- Horizon O: A very thin layer composed of *humus*, an organic, nutrient-rich soil made from the decay and waste products of plants and animals.
- Horizon A: A dark layer called *topsoil* that is composed of more humus and small pieces of rock. It is home to many animals. For example, about 1 billion small and microscopic animals live in one cubic meter of topsoil.
- Horizon B: A layer of clay and small rocks where dissolved minerals collect. The color of this layer depends on the rock and mineral types in the layer.
- Horizon C: A layer of weathered rock pieces and minerals.
- Horizon D: Solid rock called bedrock formed in place over time. This layer is covered by the layers of soil.

### Wind erosion

Like water, wind is a powerful force that causes erosion. Wind carries sediment from place to place. Wind can also increase the erosional effects of water. For example, by the time a raindrop hits the soil, it can be traveling as fast as 32 km/hour. At this speed, raindrops pound away at soil and rock. Wind further increases the speed and erosional effects of raindrops. The effects of water and wind are reduced when plants are growing in the soil. Their roots hold the soil together. Trees can also serve as a protective barrier, reducing the effects of wind.

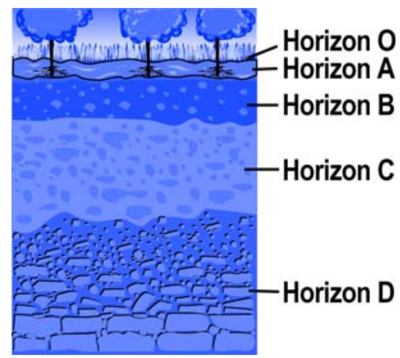



**Figure 29.13:** *A soil profile.*

## Glaciers

**What is a glacier?**

Glaciers at the poles are a frozen form of about 2 percent of *all* the water on Earth. Additionally, about 10 percent of Earth's surface is covered with glaciers. A **glacier** is a huge mass of ice that can be many kilometers thick and thousands of kilometers wide. Glaciers are formed from the accumulation of snow over hundreds or thousands of years. Each year more snow is piled up and does not melt during the warmer summer months. As the snow piles up and pressure increases, it changes into ice. This effect also occurs when you pack snow into a tight snowball. With the buildup of ice, a glacier becomes so thick and heavy that it flows (Figure 29.14). The force that drives this movement is gravity. Near the oceans, pieces of glaciers may break off, float away, and become icebergs.

**Ice ages**

An **ice age** is a period of tens to hundreds of millions of years when the climate of Earth is very cold. During this time, much of the surface is covered with glaciers that repeatedly moved forward and backward from the poles to the equator. There have been four ice ages during Earth's history. Within each ice age, there have been shorter periods of time of thousands of years when the glacial coverage was at its maximum size. These shorter periods of time are called *glaciations*. In our present time, we are experiencing the fourth and most recent ice age that began about 1.5 million years ago. During this time, there have been several glaciations. Presently, we are in a "warm" period between glaciations. This present warm period began about 10,000 years ago.

**The effect of glaciers on land**

About 30 percent of Earth's surface (much of North America and Europe) was covered by glaciers 10,000 years ago. As Earth's climate warmed, the glaciers melted and moved toward the poles and higher elevations, pushing around huge piles of rocks, scratching the surfaces of rocks, and eroding the mountain tops. For example, Long Island was created by a glacier bulldozing and depositing rocks during the last glaciation. The rocky soil of New England is evidence of the movement of glaciers. Scientists also believe that some earthquakes in North America are likely to be the result of the Earth slowly rebounding into place after having been pressed down by glaciers. If the glaciers on Earth continued to melt, sea level would rise about 76 meters and many big coastal cities would be flooded.

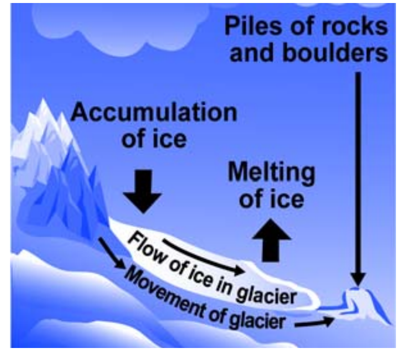



**Figure 29.14:** *A glacier accumulates ice faster than the ice melts. The mass of ice becomes so thick and heavy that it flows.*

### What causes ice ages?

The dominant theory to explain ice ages has to do with the tilt of Earth and its orbit around the sun. Another theory is that continental drift plays a role in cooling Earth. When Antarctica broke away from Pangaea and moved to the south pole, it became covered with ice. Like a giant reflector, ice-covered Antarctica bounces light and heat back into Earth's atmosphere. Scientists believe that this reflection may be one reason why the climate cools for long periods of time.

## Geologic hazard maps

**What are geologic hazard maps?**

Geological hazards are natural events that could result in loss of life and property damage. For this reason, it is very important for builders to consult geologic hazard maps before they begin construction of any building or home. **Geologic hazard maps** indicate the location of faults where earthquakes occur, areas where volcanoes are active, and where landslides, avalanches, floods, or other natural hazards are possible. These maps sometimes indicate the degree of likelihood that hazardous events will occur. They also indicate hazards that are associated with each other. For example, when strong earthquakes occur, water-saturated soil (usually composed of sand and silt) becomes very loose and acts like a viscous liquid. A similar action takes place when you stand in the surf on a beach and wiggle your feet. Your feet quickly sink and are buried by the water-saturated sand. During an earthquake, this effect, called *liquefaction*, results in homes, buildings, bridges, and cars sinking into the ground (Figure 29.15).

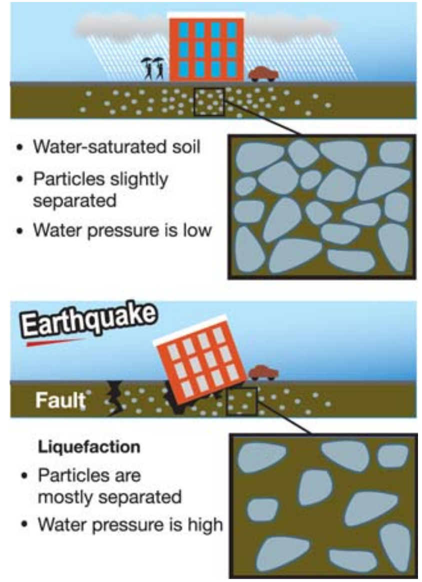
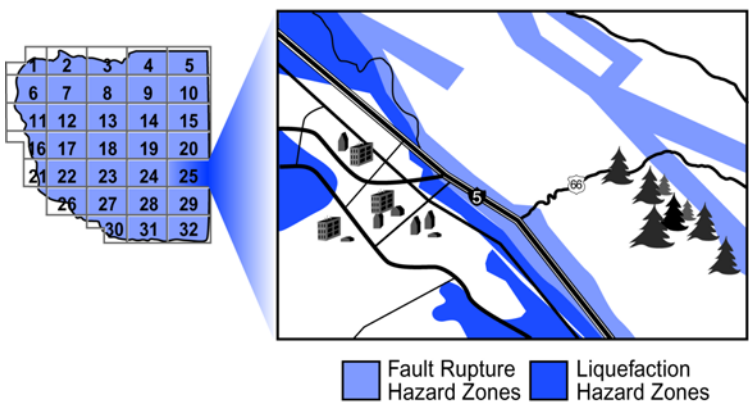



**Figure 29.15:** *Liquefaction occurs when soil is saturated with water. During an earthquake, increasing pressure on the soil increases the water pressure in the soil. This sometimes means that individual soil particles lose contact with each other. The result is that the soil acts like a viscous liquid.*

**An example of a geologic hazard map**

Geologic hazard maps show whether or not hazards occur in a particular region. In communities where geologic hazards are common, a geologic review of the property is required before construction of a building can begin. An example of a geologic hazard map is shown below. The map shows section 25 of a geographic region that has been divided into 32 sections.

**Geologic Hazard Zones**




### Topography

The term topography refers to features and formations, like bodies of water and mountains, that characterize Earth's surface. How would you describe the topography where you live?

## Human impact on Earth's surface

**What is urban sprawl?**

As the human population grows, we take up more space. Sometimes we take up more space than we need. The term urban sprawl refers to how living areas around a city "sprawl" as they grow instead of concentrate near facilities that serve the people of the community (Figure 29.16).

**The environmental impact of urban sprawl**

When urban sprawl occurs, it is more difficult to serve a community using publicly-funded transportation like buses, subways, and commuter rails. As a result, more roads are built and large traffic jams make travel more difficult. Building roads changes the land. Roads and parking lots prevent water from slowly seeping into the ground to replenish the water supply in aquifers. Instead, water quickly runs off the paved surfaces causing the increased flow rate of water in nearby rivers and streams. When water flows quickly, soil and plant life on the banks are washed away and the overall health of the river and stream is reduced.

**Urban sprawl changes local climate**

Another effect of urban sprawl has to do with what happens when trees are cleared to make room for buildings and roads. Rooftops and road surfaces give off a lot of heat such that a region becomes an "urban heat island." When a city is hotter, there tends to be more ozone pollution which causes respiratory problems and inhibits photosynthesis in plants. Additionally, as heat rises and colder air flows into the gap left behind, an unusual number of thunder and lightning storms may occur. Although these storms can clean pollution out of the air, they also cause local flooding because there are fewer greenspaces to absorb water.

**How can the effects of urban sprawl be reduced?**

The first step in making a difference in reducing urban sprawl is to understand what is happening. Once you are aware of a problem, you can take steps to change some habits that create urban sprawl and the problems associated with it. To reduce the need for more roads and reduce air pollution from cars, you can walk, take public transportation, or drive more fuel-efficient cars. Another helpful habit is to maintain cars so that oil and fluids don't leak on to paved surfaces and become pollutants in our water supply. Cities can curb the effects of urban heat islands by adding heat-reflective rooftops to buildings and by planting more trees in urban areas. Trees and plants are natural "air-conditioners" that keep areas cooler through shading and by absorbing heat.

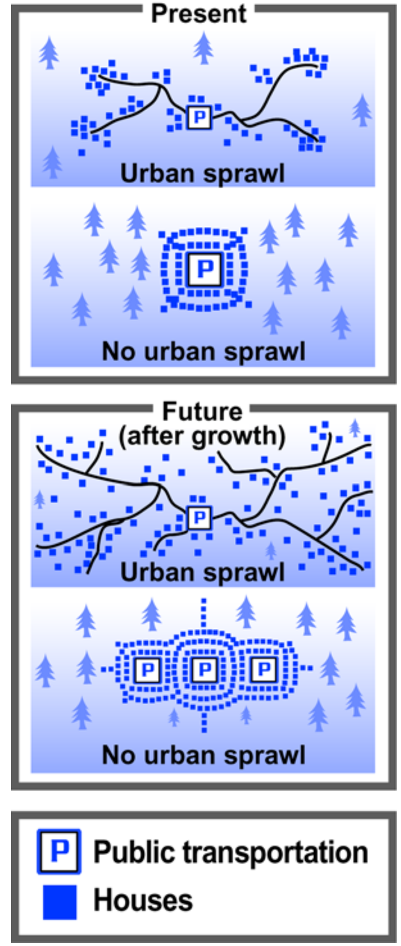



**Figure 29.16:** *Urban sprawl occurs when the growth of a community occurs in a way that is not organized. Growth that is not organized leads to more roads, less greenspace, increased traffic, and greater difficulty in providing public transportation.*

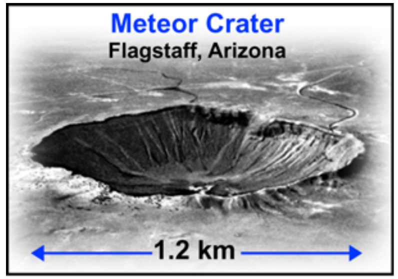
## Extraterrestrial shaping of Earth's surface

**The moon versus Earth**

The surface of the moon is much different from the surface of Earth. Whereas Earth's surface has been in constant change, the surface of the moon has been preserved. In the late 1960s and early 1970s, the Apollo space missions went to the moon. By studying very small pieces of the moon rocks brought back to Earth by these missions, scientists have learned that the moon's surface is about 4 billion years old, nearly as old as the solar system. Because the moon's surface is so well-preserved, it is our best research lab for studying what was happening in the solar system 4 billion years ago.

**Showers of comets and asteroids on Earth and the moon**

Scientists believe that 4.1 to 3.8 billion years ago, the surfaces of the moon and Earth experienced torrential showers of comets and asteroids. The many craters on the moon's surface are evidence of these showers. By comparison, Earth has very few craters. This does not mean that Earth did not get hit by these comets and asteroids. Rather, the constant change of Earth's surface due to plate tectonics and weathering has hidden most of the evidence. There is evidence that Earth was hit in Arizona, at the famous impact crater called the Meteor Crater. This crater, whose diameter is 1.2 kilometers, was formed by an asteroid with a diameter of 24 meters.




**Are there Earth rocks on the moon?**

By studying the moon, scientists estimate that in a 200-million-year period, Earth would have experienced impacts from at least 17,000 asteroids. With such huge impacts, scientists believe it may be possible to find pieces of rock from Earth on the moon; these pieces would had been thrown off Earth on to the moon when an impact occurred. This idea has scientists petitioning NASA to send astronauts back to the moon to bring back more moon rocks for study.

### How do you study moon rocks?

Because of the comet and asteroid showers millions of years ago, some moon rocks were blasted off the moon onto Earth. Scientists have studied these to find out more about Earth's early history.

When an impact occurred on the moon, the impact caused moon rock to melt and release argon gas. At the same time, the impact forced the rock off the moon. This moon rock landed on Earth about a million years later. As the rock traveled through space, radioactive decay in the rock released more argon gas, which became trapped in the rock.

By measuring the amount of argon in these ancient moon rocks, scientists can determine when the rock formed and when the impact occurred.

# 29.3 Rocks and Minerals

When you pick up a rock, you hold a lot of history in your hands. This is because any rock is the result of numerous intense processes that have created it over millions of years. Such processes include the eruption of a volcano, erosion of land by a river, and mountain-building. Each of these processes listed is important in forming one of the three categories of rocks. In this section, you will learn how rocks are classified and formed. Using this knowledge, you will be able to tell the history of a rock.

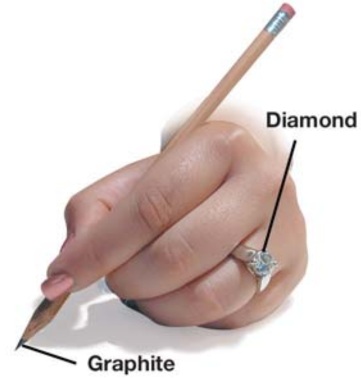


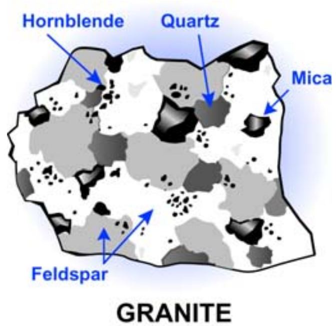

**Figure 29.17:** *Diamonds and graphite are made of carbon. Diamonds form within volcanic rock that explosively reaches Earth's surface. Graphite is made of organic material that has experienced high temperatures and pressures.*

## Rocks are made of minerals

**What is a mineral?**

The history of a rock begins with minerals because they are the building blocks of a rock. A **mineral** is a solid, naturally-occurring object with a *defined* chemical composition. Minerals are inorganic (meaning they do not result from living things) and have a crystalline structure. Usually, a mineral is a compound of two or more elements, but it can be made of a single element. For example, metals like copper and gold are minerals that occur as pure elements. It is important to note that different minerals can have the same chemical composition but have different crystal structure. For example, graphite and diamonds are two different minerals that are made of pure carbon (Figure 29.17). A list of some common minerals and their uses is provided in the table in Figure 29.18.

**About 20 minerals make up Earth's crust**




There are more than 3,000 minerals on Earth. About 20 common minerals make up about 95 percent of Earth's crust and are involved in rock formation. For example, during the underground cooling stage of the formation of a granite rock, different minerals crystallize. These distinct minerals are easy to see in a hand-sized piece of granite. Feldspar and quartz crystals make of the majority of a piece of granite. Mica and hornblende crystals are also visible. These minerals are further described on the next page.

| Some common minerals | |
|---|---|
| **Name (chemical formula)** | **Uses** |
| silver ($Ag$) | jewelry, electrical wire, coins |
| corundum ($Al_2O_3$) | sandpaper, gems (e.g., rubies, sapphires) |
| quartz ($SiO_2$) | glass making, gems (e.g., onyx, amethyst) |
| gypsum ($CaSO_42H_2O$) | used to make Plaster of Paris |

**Figure 29.18:** *Some common minerals and their uses.*

## Common minerals

**What is feldspar?** The *feldspar* in granite is usually white or pink. However, feldspar can also be green or other colors. Feldspar is composed of sodium, calcium, potassium, and silica. Feldspar has **cleavage planes**. A cleavage plane is a region where a rock cleanly splits. The placement of a cleavage plane occurs where there are weak bonds between atoms and molecules in the mineral. Many cleavage planes in the same direction appear as parallel lines (Figure 29.19).

**What is quartz?** *Quartz* crystals are dark gray, white, clear or rosy, and appear to glisten as if they are wet or oily. Unlike feldspar, quartz lacks cleavage planes. When quartz breaks, it does not split along planes. Quartz is made of silicon dioxide ($SiO_2$) and is used in making glass. Gemstones like onyx, agate, and amethyst are made of quartz.

**What is mica?** *Mica* is a silicate ($Si_xO_y$, where $x$ and $y$ represent different numbers of atoms) with various ions of iron, magnesium, and sodium. A piece of mica is like a small stack of paper sheets. A stack of paper sheets and a piece of mica are described as having a single cleavage plane (Figure 29.19). The two main types of mica in granite are *white mica* (called *muscovite*) and *black mica* (called *biotite*).

**What is hornblende?** *Hornblende* is also found in granite. It is a dark mineral made of a mixture of elements including calcium and silicon, along with iron, magnesium, or aluminum.

**More information about minerals** A mineral is a material that is naturally occurring, inorganic, and crystalline. Using this definition, ice is a mineral, but liquid water is not (Figure 29.20). Do you see why? On the other hand, coal is not a mineral because it is made from living things and is not a crystal (Figure 29.20). Most minerals (except metals) also have one or more cleavage planes that also help in determining their identity.

**Recognizing minerals helps identify rocks** Recognizing common minerals is an important step to being able to identify a rock and understand how it formed. The majority of continents are made of granite and the most common mineral in Earth's crust is feldspar. Quartz is the second most common mineral. Since granite is a common rock, it is useful to know how to identify mica and hornblende.

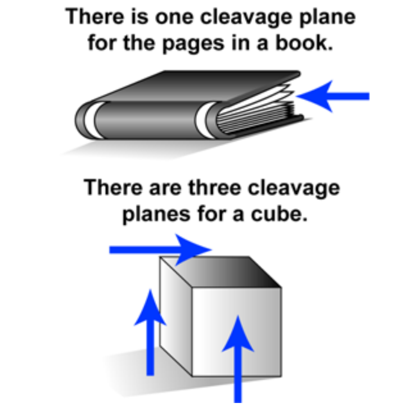



**Figure 29.19:** *Mica has one cleavage plane. The mineral halite has three cleavage planes and breaks into cubes. Halite is made of sodium chloride. Next time you use table salt (also sodium chloride), look at the tiny grains. Each is a miniature cube.*

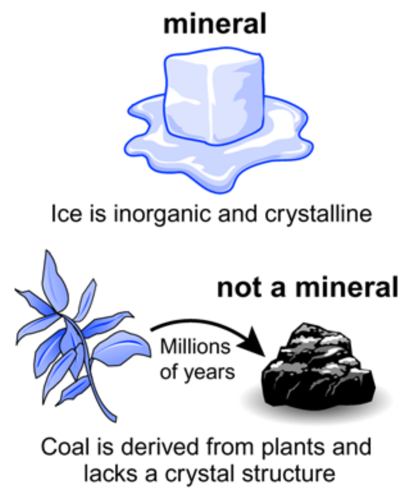



**Figure 29.20:** *Ice is a mineral. Coal is not a mineral.*

## Identifying minerals

**Mohs hardness scale**

**Mohs hardness scale** was developed in 1812 by Friedrick Mohs (an Austrian mineral expert) as a method to identify minerals (Figure 28.2). This scale uses 10 common minerals to represent variations in hardness. You can identify a mineral's place on the hardness scale by whether it can scratch another mineral. For example, gypsum (hardness = 2) scratches talc (hardness = 1). The hardest mineral, a diamond, can scratch all other minerals. Minerals of the same hardness (and without impurities) scratch each other.

**Common items test the hardness of a mineral**

In addition to the minerals listed in Figure 29.21, you can use common items. For example, your fingernail, a penny, and glass can be used to test the hardness of a mineral. The following scenarios illustrate how to use Mohs hardness scale.

- A fingernail scratches gypsum, but gypsum does not scratch the fingernail. The fingernail is scratched by calcite. What is the hardness of a fingernail? *Answer: 2.5*
- A penny is scratched by fluorite, but the penny cannot scratch fluorite. The penny scratches calcite and calcite scratches the penny. What is a penny's hardness? *Answer: 3*
- A piece of glass scratches and is scratched by orthoclase (a type of feldspar). The glass scratches apatite. What is the hardness of glass? *Answer: 6*

| Mohs hardness scale | |
|---|---|
| **Mineral** | **Hardness** |
| talc | 1 |
| gypsum | 2 |
| calcite | 3 |
| fluorite | 4 |
| apatite | 5 |
| orthoclase | 6 |
| quartz | 7 |
| topaz | 8 |
| corundum | 9 |
| diamond | 10 |

**Figure 29.21:** *The Mohs hardness scale is used to help identify minerals.*

## Identifying rocks

**What is a rock?**

A **rock** is a naturally formed solid usually made of one or more minerals. Therefore, being able to recognize common minerals is very useful for identifying a rock. It is important to note that it can be difficult to identify a rock. Scientists sometimes have to rely on special microscopes to be sure about a rock's identity.

**Use your powers of observation to identify a rock**

Your powers of observation are your best tools for identifying a rock. Ask yourself: What does the rock look like? Where was it found? Your answers to these questions may help you determine if the rock is *igneous*, *sedimentary*, or *metamorphic*. The terms igneous, sedimentary, and metamorphic refer to how a rock was formed. You will learn about these terms on the next page.

### Where to go to find out more about rocks

A rock key can help identify a rock by asking a series of questions. Keys also have diagrams or photographs to help you identify rocks. You can find a rock key at your local library. You can also learn about local rocks by contacting your state's geological survey.

## What are igneous, sedimentary, and metamorphic rocks?

Igneous rocks (*ignis* means "fire")

**Igneous rocks** are made of magma or lava, the fiery hot material that originates in Earth's mantle. *Intrusive* igneous rocks are formed from magma that has cooled and solidified below Earth's surface. Deep underground, the temperature is very warm. Therefore, cooling and solidification of rocks takes a long time and large, visible crystals form as a result in intrusive rocks. Intrusive rocks tend to be coarse-grained. Granite is a common intrusive rock. The continents are mostly made of granite. *Extrusive* igneous rocks form from lava, molten material extruded onto Earth's surface. At Earth's surface, cooling and solidification of lava takes place relatively quickly so that very small crystals form. Extrusive rocks tend to be fine-grained. Basalt is a common extrusive rock with very small crystals. The ocean floor is made of basalt.

Sedimentary rocks (*sedimentation* means settling)

**Sedimentary rocks** are made of the products of weathering. Wind or water *weathers* existing rocks in a process called **erosion**. Then, wind and water deposit the eroded particles (called sediment) in layers. Mineral water flows between the particles in the layers as they *compact*. As water is forced out by temperature and pressure, the particles are *cemented*. Over millions of years, compaction and cementing turn layers of sediment into rock. The most important kinds of sedimentary rocks are *clastic*, *organic*, and *chemical*. Clastic rocks result from eroded bits of rocks being pressed together. Organic rocks, like coal, form when *layers of decaying sediments* of once living animals and plants are compacted. Over millions of years, a 20-meter layer of decaying plant material will turn into a one-meter layer of coal. Chemical rocks are formed when a *solution of dissolved minerals evaporates* leaving behind a rock with many mineral crystals. Rock salt (called halite) and gypsum are examples of chemical rocks.

Metamorphic rocks (*metamorphic* refers to a change of form)

A **metamorphic rock** is an igneous, sedimentary, or other metamorphic rock that has been transformed by pressure or frictional heat from deep burial under layers of rock or from the compression that occurs during mountain-building. Rocks that experience this intense pressure and heat are said to be *metamorphosed*. For example, numerous metamorphic rocks formed when India and Asia collided to form the Himalayan Mountains. Metamorphic rocks are often exposed at Earth's surface when layers of sediment above these rocks are eroded.

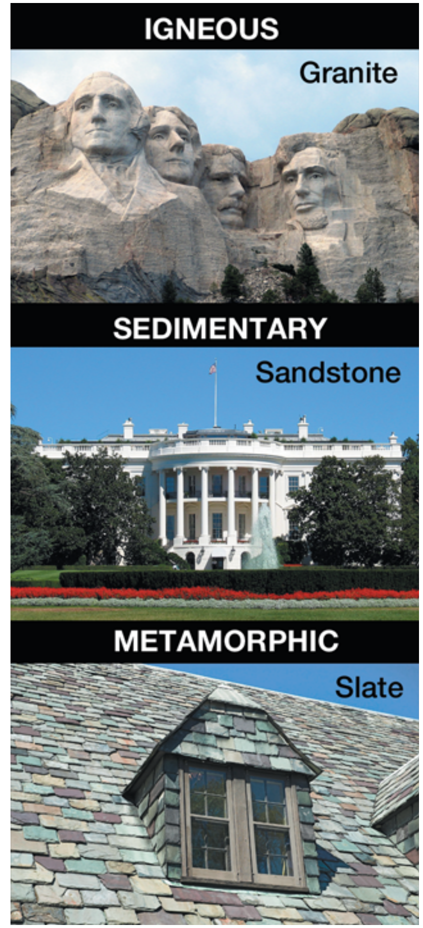



**Figure 29.22:** *Rocks are useful materials for creating structures that last. Mount Rushmore is a famously sculpted mountain of granite, an igneous rock. The United States' White House is made of sandstone, a sedimentary rock. Slate, a metamorphic rock, is a well-known material used in roofing.*

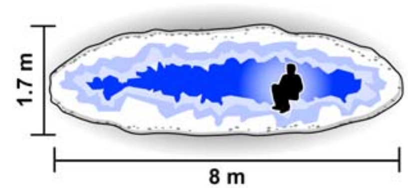
## Identifying a rock

**What does the rock look like?**

When examining a rock, it is helpful to break it open to see the interior. The outside of a rock can be misleading due to color changes that occur with weathering. Next, it is important to look at the *grain* of a rock's texture. Grain refers to the fact that a single rock is made of other rock pieces or mineral crystals of various sizes and shapes and in different patterns. Rocks that are coarse-grained have large particles and the minerals that make up this kind of rock are visible. Rocks that are fine-grained have very small particles that can only be interpreted with a magnifying glass or microscope. Grains can appear as specks, crystals, or as round or angular pieces. The particles and grains in a rock can be randomly placed or organized into straight or wavy layers.

**What is the composition of a rock?**

Using your eyes is the first step to identifying a rock. For example, in some cases the composition of a rock can be determined by looking at its mineral crystals. With practice, you will be able to identify common minerals in rocks. To aid you in identification, you can use a magnifying glass. Often to identify crystals, geologists make thin slices of a rock for viewing under a microscope or a *microprobe*. A microprobe is used to melt a specific crystal in order to identify its chemical composition and properties. Other techniques for identifying minerals include making a streak of the mineral on a ceramic tile. The color of the streak is not always the same as the color of the mineral. For example, silvery hematite used for jewelry will leave a reddish streak. The color of the streak gives you a clue about the identity of the mineral. As you learned earlier, you can identify the relative hardness of the mineral using Mohs hardness test. Also, the smell of the rock can be helpful in identifying if a rock contains sulphur compounds. Finally, an acid test will help you identify whether or not a rock contains calcium carbonate because this substance reacts with acid. How would you determine whether or not a rock contains magnetic metals like iron or nickel? Such a rock would attract a magnet.




### What is a geode?

A geode is a collection of minerals that forms within cavities in volcanic or sedimentary rocks. A geode is not easily classified as an igneous, sedimentary, or metamorphic rock. When you break open a geode, you find gleaming crystals. Typically, you can hold a geode in your hand. However, in May 2002, a geologist discovered a giant geode in Italy that is 8 m x 1.7 m and fits 10 people! Imagine sitting inside a geode lined with large, transparent pieces of crystalline gypsum! Scientists believe the geode may have been formed when the Mediterranean Sea evaporated 5-6 million years ago.

## Identifying igneous, sedimentary, or metamorphic rocks

**How do you tell if a rock is igneous?**

Igneous rocks can often be identified by their texture. For example, igneous rocks have crystals that intersect at angles. However, the grain in these rocks usually does not have a pattern or a uniform orientation of crystals. The size of the grains depends on how fast the rock cooled during its formation. Some igneous rocks are glassy (very fine-grained) because they cooled quickly. Basalt is a fine-grained rock. An example of a slow-cooling igneous rock with large, easy-to-see grains, is granite. Granitic rocks are easy to find in mountainous regions where they have been exposed due to weathering. In flatter regions, this intrusive igneous rock is often buried by sediments. Mount Rushmore in South Dakota is made of granite.

**How do you tell if a rock is sedimentary?**

Sedimentary rocks often appear to have layers of rock pieces. Because the pieces tend to sort by size, a sedimentary rock tends to have same sized pieces or the same sized particles are organized into layers. The boundaries between pieces in a sedimentary rock are not well-defined. Sedimentary rocks are often found in areas where sediment gets deposited. Sedimentary rocks with large pieces tend to form in high-energy environments, like the bed of a fast-moving river (conglomerate rock). Sedimentary rocks with small pieces form in low energy environments like a pond, lake, or the ocean floor (shale). Sedimentary rocks are common and easily seen in the mid- and southwestern United States. For example, the Grand Canyon is a giant land formation made of layers of sedimentary rock that have been exposed by weathering.

**How do you tell if a rock is metamorphic?**

The grains in metamorphic rocks tend to orient themselves based on how the rock was metamorphosed. Rocks that are modified by pressure have grains oriented in lines. An example of this kind of metamorphic rock is slate formed from shale (a sedimentary rock). Rocks that are modified by pressure and heat have grains oriented in foliations (wavy patterns). These rocks appear layered or *foliated*. Examples of foliated rocks are gneiss formed from granite. Examples of nonfoliated rock include some types of marble formed from limestone. Metamorphic rocks tend to be the hardest and most weather-resistant rock of the three kinds. These rocks are often associated with mountains because the pressures that arise from mountain-building cause the formation of these rocks.

### The history of a rock

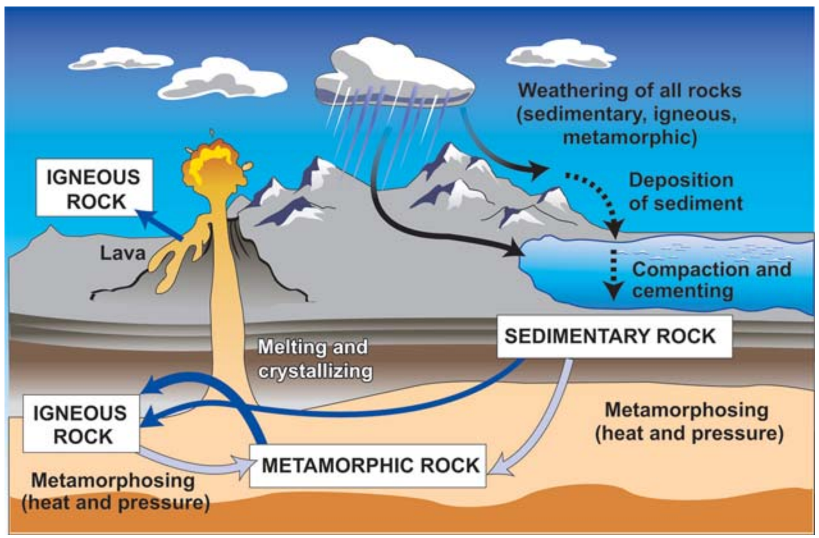
*Marble is a weather-resistant, crystalline rock often used by sculptors. How is marble formed?*

Marble is a metamorphic rock that originates as limestone. It is thousands or millions of years old. Limestone, a sedimentary rock, was formed on the bottom of the ocean. As tiny marine creatures died, their calcium carbonate shells rained down on the ocean floor and became sediments called ooze. In ancient times, compaction and cementing hardened the ooze to limestone and preserved these tiny fossils. The limestone was raised as mountains formed. The heat and pressure created by this movement caused some rock to metamorphose into marble. The green or grey streaks in marble are the result of compounds in the limestone being forced out during metamorphosis.

## The rock cycle

**What is the rock cycle?**

The **rock cycle** illustrates the formation and recycling of rocks by geological processes. Let's begin with a piece of granite that is part of a mountain. This granite is weathered by wind and rain. Sediments from the eroded rock are washed down the mountain where they enter a stream and then a river that empties into the ocean. These sediments are deposited on the ocean floor where they will be covered by other sediments. Eventually, these layers of sediments are compressed and cemented to form a sedimentary rock. As a sedimentary rock becomes buried deeper and deeper by more and more sediment, it experiences intense pressure and becomes a metamorphic rock. Next, this metamorphic rock is pulled down into the mantle at a subduction zone. Now the metamorphic rock melts and becomes magma. Then, the magma rises toward Earth's surface to become a intrusive igneous rock like granite or an extrusive rock like basalt. The magma could also be ejected from a volcano as lava and then cooled to become an extrusive igneous rock like pumice. Either way, the rock cycle continues as another igneous rock weathers to become a sedimentary rock, melts to again become igneous, or metamorphoses into another metamorphic rock.




**Key processes in the rock cycle**

The rock cycle illustrates how matter is recycled. The processes that keep rock material moving through the rock cycle are *weathering*, *compaction* and *cementing*, *melting* and *crystallizing*, and *metamorphosing*. Additionally, the interaction of tectonic plates plays a very important role in the rock cycle. Rocks melt or metamorphose when they are subducted into the mantle. The collisions of tectonic plates create mountains. Were it not for mountain building, the weathering of rocks over time would leave the continents smooth and flattened.

# Chapter 29 Review

## Vocabulary review

Match the following terms with the correct definition. There is one extra definition in the list that will not match any of the terms.

### Set One

1. magma
2. lava
3. Ring of Fire
4. magma chamber
5. crater

a. The pattern of volcanoes and earthquakes that occurs at the boundaries of the Pacific Ocean
b. A glowing cloud of hot volcanic material
c. A place where magma collects underground
d. A bowl-shaped depression at the top of a volcano; also, a large depression that results from an extraterrestrial object hitting land
e. Molten material from the mantle that reaches Earth's surface
f. Molten material that originates in the mantle

### Set Two

1. geothermal energy
2. stratovolcano
3. shield volcano
4. hydrothermal vent
5. rift valley

a. A wide and long depression that occurs where two tectonic plates are diverging
b. An opening on the ocean floor that allows high heat and gases to escape from the mantle
c. A type of volcano that results from a hot spot
d. A violent type of volcano that is related to a buildup of pressure and viscous magma. Many of these volcanoes occur at subduction zones.
e. Energy that is generated from heat and steam in Earth's crust
f. Energy that is generated from water

### Set Three

1. cleavage plane
2. urban sprawl
3. erosion
4. soil profile
5. topography

a. A reduction in greenspace and increased traffic are results of this phenomenon
b. The break down of soil, rocks, and land formations due to climate and seasonal changes
c. A cross-section of ground that shows the layers of sediment
d. A term used to describe the shape of land and the presence of bodies of water and mountains
e. A region in a mineral where it will split cleanly due to weak interactions between molecules
f. The way that crystals are arranged in an igneous rock

### Set Four

1. metamorphic rocks
2. igneous rocks
3. sedimentary rocks
4. rock cycle
5. mineral

a. Rocks that are produced when magma or lava cools and solidifies
b. Rocks that are produced when layers of rock pieces are compacted to form a new rock
c. Examples include quartz and mica
d. Examples include marble, slate, and granite
e. The set of processes that lead to the formation and recycling of the various kinds of rocks
f. Rocks formed from other rocks due to intense heat and pressure

## Concept review

1. Explain the difference between magma and lava.
2. Imagine you are a blob of magma coming up through the Mid-Atlantic Ridge. Describe what might happen to you on your next step in the rock cycle.
3. Write a paragraph that explains how tectonic plates are involved in causing earthquakes and volcanoes.
4. Is erosion a constructive or a destructive force that shapes the land? Explain your answer.
5. When sugar water crystallizes, rock candy is made. Would you describe large crystals of rock candy as a mineral, a rock, or neither? Justify your answer.
6. Compare and contrast the main types of rocks: sedimentary, igneous, and metamorphic. Give an example of each type.
7. List three ways the rock cycle is like the water cycle, and three ways in which these two cycles are not alike.
8. The crust of Earth is mostly which kind of rock—igneous, sedimentary, or metamorphic? Explain your answer.

## Problems

1. A volcanologist finds that the silica content of the volcanic rock near an ancient volcano is 48 percent. From this information, describe the probable type of volcano and its eruption. Where might this volcano be located?
2. Glaciers covered much of North America 30,000 years ago. The average rate at which glaciers move is two meters per day. Assuming this rate is constant, how far would a glacier move in 15,000 years?
3. You are given the task of organizing a collection of minerals used to represent the variations of hardness. Seven of nine minerals have labels. You know that the collection does not contain a diamond. Use the Mohs hardness scale and the information below to identify the two unlabeled minerals.
   a. The first mineral scratches talc and gypsum. This mineral does not scratch fluorite. What is this mineral?
   b. The second mineral scratches topaz and quartz. You guess that a diamond would scratch this mineral. What is it?

| Mohs hardness scale | |
|---|---|
| **Mineral** | **Hardness** |
| talc | 1 |
| gypsum | 2 |
| calcite | 3 |
| fluorite | 4 |
| apatite | 5 |
| orthoclase | 6 |
| quartz | 7 |
| topaz | 8 |
| corundum | 9 |
| diamond | 10 |

4. In Yosemite National Park there is a large granite formation called Half Dome. The distance from the bottom of the valley to the top of Half Dome is one kilometer. The top of Half Dome is rounded instead of peaked the way most mountains look. How do you think Half Dome formed? To develop a hypothesis, answer the following questions.
   a. What kind of rock is granite? Is it intrusive or extrusive?
   b. Did Half Dome form as a result of a volcanic eruption? Did it form as a result of two continents pushing against each other?
   c. Why might Half Dome be rounded?
   d. Develop a hypothesis about Half Dome: In your opinion, how did this rock formation form?
   e. Now research the geology of Half Dome on the Internet or in your local library. How did it form? Compare your research findings with your hypothesis.

Photo courtesy of U.S. Geological Survey

## Applying your knowledge

1. Use what you have learned from this chapter and the previous chapter to come up with a plan for determining the age of an extinct stratovolcano. Write down your plan as a series of steps.

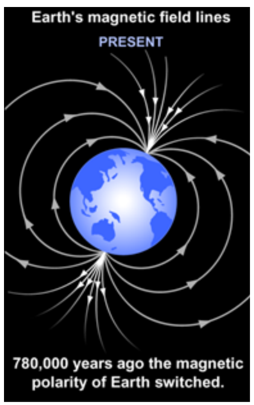
2. Magma and lava have different characteristics based on their silica content. In previous units, you learned about *viscosity* and *solutions*. Review these terms and answer the following questions.
   a. Which is more viscous, magma directly from the mantle or magma that contains dissolved rock from the continental crust? Explain your answer.
   b. Are magma and lava solutions? Explain your answer.

3. Compare the effect of pressure on the change from solid rock to magma to the effect of pressure on the phase change of water from a liquid to a gas.

4. Imagine that your community has an opportunity to build a geothermal power plant and your job is to market geothermal energy to your community. What would you say to convince your community to convert from their present source of energy to geothermal energy? Use your local library or the Internet to research the benefits of using geothermal energy and find out where geothermal energy is being used in the United States. Make a brochure that explains these benefits and answers questions that people might have.

5. Many life forms depend on the ability of plants to convert solar energy to chemical energy through the process of photosynthesis. Why then is it possible for whole ecosystems to survive in the deep sea in the absence of sunlight? Explain how this is possible. Explain whether or not the sun still plays a role in the survival of such ecosystems.

6. Water and human beings each play a role in shaping Earth's surface. Which changes Earth's surface more? Justify your answer.
7. The oldest rocks that we have observed so far on Earth are 4 billion years old. You know that the Earth is 4.6 billion years old. Based on what you have learned in chapters 28 and 29, come up with a hypothesis to explain why the oldest rocks on Earth are younger than the Earth itself. Explain and justify your hypothesis in a detailed paragraph.
8. Could the rock cycle occur if Earth did not experience plate tectonics? Given your answer, explain whether or not there is a rock cycle on the moon.
9. You have learned that the polarity of Earth's magnetic field has switched over time. You also learned that the reversal of the magnetic field is recorded in rocks. If you were going to research this phenomenon, which kind of rock (igneous, sedimentary, metamorphic) would be best to study and why? In your answer, explain why the other kinds of rock would not be useful to study.




10. A geologic hazard map shows that a number of active volcanoes follow the western coastline of South America but there are no volcanoes on the eastern coastline.
    a. Explain the pattern of volcanoes on the South American continent. Predict whether or not this pattern will change in the next 1 million years.
    b. As far as you can tell, will there ever be volcanoes on the east coast of South America? Why or why not?
    c. One of the active volcanoes is Nevado del Ruiz in Colombia. The last time this volcano erupted was 1985. What happened during this eruption? What do you predict will occur if this volcano erupts again? Answer these questions by doing research in your local library or on the Internet.