Earth Science

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CHAPTER 1 MS Earth's Minerals

Chapter Outline

Scientists have discovered more than 4,000 minerals in Earth's crust. Some minerals are found in very large amounts. Most minerals are found in small amounts. Some are very rare. Some are common. Many minerals are useful. Modern society depends on minerals and rocks that are mined. Mining is difficult work, but is necessary for us to have the goods we use.

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1.1 Minerals

Lesson Objectives

- Describe the properties that all minerals share.
- Describe some different crystal structures of minerals.
- Identify the groups in which minerals are classified.

Vocabulary

- atom
- chemical compound
- crystal
- compound
- electron
- element
- ion
- matter
- mineral
- molecule
- neutron
- nucleus
- proton
- silicate

Introduction

You use objects that are made from minerals every day, even if you do not realize it. You are actually eating a mineral when you eat food that contains salt. You are drinking from a mineral when you drink from a glass. You might wear silver jewelry. The shiny metal silver, the white grains of salt, and the clear glass may not seem to have much in common, but they are all made from minerals (**Figure** 1.1). Silver is a mineral. Table salt is the mineral halite. Glass is produced from the mineral quartz.

Just looking at that list you see that minerals are very different from each other. If minerals are so different, what do all minerals have in common?

What is Matter?

To understand minerals, we must first understand matter. **Matter** is the substance that physical objects are made of.

FIGURE 1.1
Silver is used to make sterling silver jewelry. Table salt is the mineral halite. Glass is produced from the mineral quartz.

Atoms and Elements

The basic unit of matter is an **atom**. At the center of an atom is its **nucleus**. **Protons** are positively charged particles in the nucleus. Also in the nucleus are **neutrons** with no electrical charge. Orbiting the nucleus are tiny electrons. **Electrons** are negatively charged. An atom with the same number of protons and electrons is electrically neutral. If the atom has more or less electrons to protons it is called an **ion**. An ion will have positive charge if it has more protons than electrons. It will have negative charge if it has more electrons than protons.

An atom is the smallest unit of a chemical **element**. That is, an atom has all the properties of that element. All atoms of the same element have the same number of protons.

Molecules and Compounds

A **molecule** is the smallest unit of a **chemical compound**. A compound is a substance made of two or more elements. The elements in a chemical compound are always present in a certain ratio.

Water is probably one of the simplest compounds that you know. A water molecule is made of two hydrogen atoms and one oxygen atom (**Figure** 1.2). All water molecules have the same ratio: two hydrogen atoms to one oxygen atom.

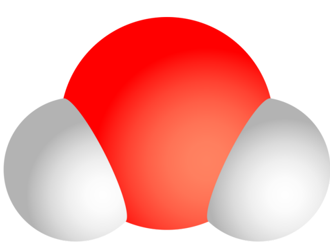

FIGURE 1.2
A water molecule has two hydrogen atoms (shown in gray) bonded to one oxygen molecule (shown in red).

What are Minerals?

A **mineral** is a solid material that forms by a natural process. A mineral can be made of an element or a compound. It has a specific chemical composition that is different from other minerals. One mineral's physical properties differ from others'. These properties include crystal structure, hardness, density and color. Each is made of different elements. Each has different physical properties. For example, silver is a soft, shiny metal. Salt is a white, cube-shaped crystal. Diamond is an extremely hard, translucent crystal.

Natural Processes

Minerals are made by natural processes. The processes that make minerals happen in or on the Earth. For example, when hot lava cools, mineral crystals form. Minerals also precipitate from water. Some minerals grow when rocks are exposed to high pressures and temperatures.

Could something like a mineral be made by a process that was not natural? People make gemstones in a laboratory. Synthetic diamond is a common one. But that stone is not a mineral. It was not formed by a natural process.

Inorganic Substances

A mineral is an inorganic substance. It was not made by living organisms. Organic substances contain carbon. Some organic substances are proteins, carbohydrates, and oils. Everything else is inorganic. In a few cases, living organisms make inorganic materials. The calcium carbonate shells made by marine animals are inorganic.

Definite Composition

All minerals have a definite chemical makeup. A few minerals are made of only one kind of element. Silver is a mineral made only of silver atoms. Diamond and graphite are both made only of the element carbon.

Minerals that are not pure elements are made of chemical compounds. For example, the mineral quartz is made of the compound silicon dioxide, or SiO_2. This compound has one atom of the element silicon for every two atoms of the element oxygen.

Each mineral has its own unique chemical formula. For example, the mineral hematite has two iron atoms for every three oxygen atoms. The mineral magnetite has three iron atoms for every four oxygen atoms. Many minerals have very complex chemical formulas that include several elements. However, even in more complicated compounds, the elements occur in definite ratios.

Solid Crystals

Minerals must be solid. For example, ice and water have the same chemical composition. Ice is a solid, so it is a mineral. Water is a liquid, so it is not a mineral.

Some solids are not crystals. Glass, or the rock obsidian, are solid but not crystals. In a **crystal**, the atoms are arranged in a pattern. This pattern is regular and it repeats. **Figure** 1.3 shows how the atoms are arranged in halite (table salt). Halite contains atoms of sodium and chlorine in a pattern. Notice that the pattern goes in all three dimensions.

The pattern of atoms in all halite is the same. Think about all of the grains of salt that are in a salt shaker. The atoms are arranged in the same way in every piece of salt.

Sometimes two different minerals have the same chemical composition. But they are different minerals because they have different crystal structures. Diamonds are beautiful gemstones because they are very pretty and very hard.

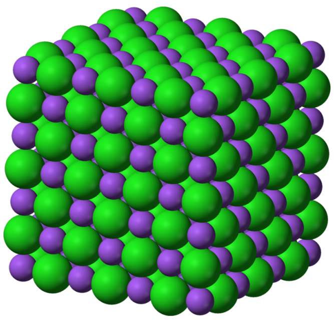

FIGURE 1.3
Sodium ions (purple balls) bond with chloride ions (green balls) to form halite crystals.

Graphite is the "lead" in pencils. It's not hard at all! Amazingly, both are made just of carbon. Compare the diamond with the pencil lead in **Figure** 1.4. Why are they so different? The carbon atoms in graphite bond to form layers. The bonds between each layer are weak. The carbon sheets can just slip past each other. The carbon atoms in diamonds bond together in all three directions. This strong network makes diamonds very hard.

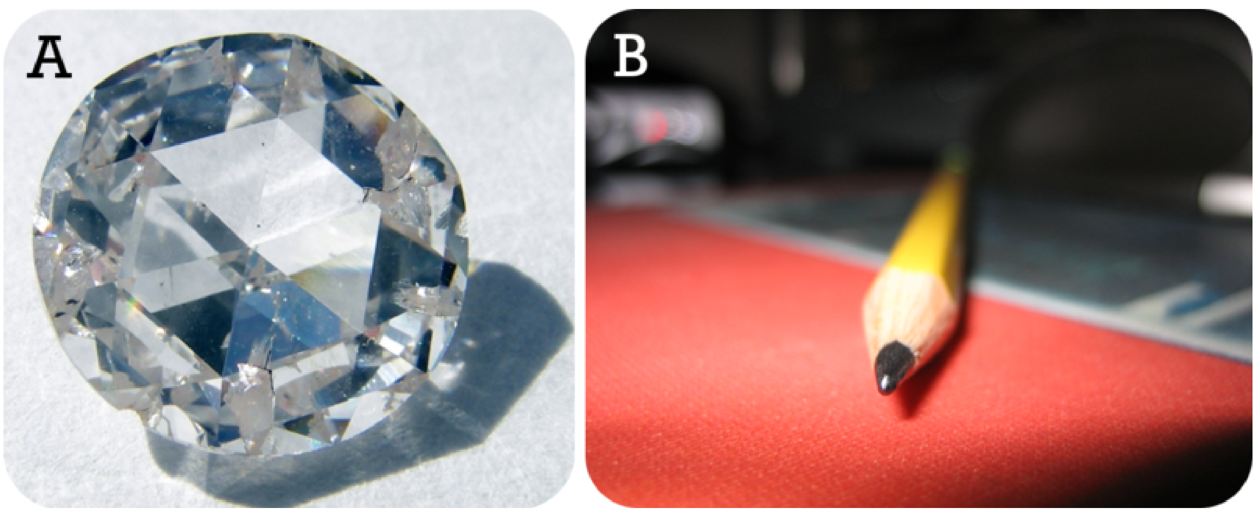

FIGURE 1.4
Diamonds (A) and graphite (B) are both made of only carbon, but they're not much alike.

Physical Properties

The patterns of atoms that make a mineral affect its physical properties. A mineral's crystal shape is determined by the way the atoms are arranged. For example, you can see how atoms are arranged in halite in **Figure** 1.3. You can see how salt crystals look under a microscope in **Figure** 1.5. Salt crystals are all cubes whether they're small or large.

Other physical properties help scientists identify different minerals. They include:

- Color: the color of the mineral.
- Streak: the color of the mineral's powder.

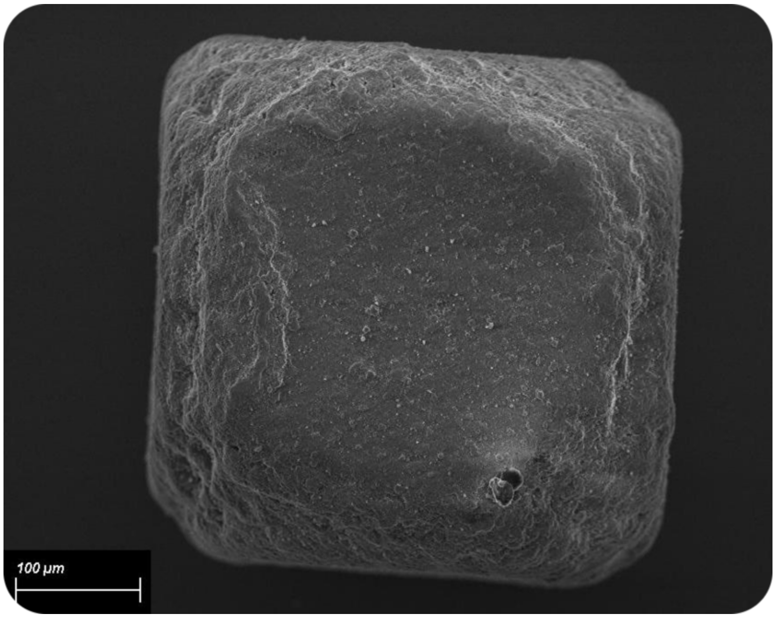

FIGURE 1.5
Under a microscope, salt crystals are cubes.

- Luster: the way light reflects off the mineral's surface.
- Specific gravity: how heavy the mineral is relative to the same volume of water.
- Cleavage: the mineral's tendency to break along flat surfaces.
- Fracture: the pattern in which a mineral breaks.
- Hardness: what minerals it can scratch and what minerals can scratch it.

Groups of Minerals

Imagine you are in charge of organizing more than 100 minerals for a museum exhibit. People can learn a lot more if they see the minerals together in groups. How would you group the minerals together in your exhibit?

Mineralogists are scientists who study minerals. They divide minerals into groups based on chemical composition. Even though there are over 4,000 minerals, most minerals fit into one of eight mineral groups. Minerals with similar crystal structures are grouped together.

Silicate Minerals

About 1,000 silicate minerals are known. This makes silicates the largest mineral group. Silicate minerals make up over 90 percent of Earth's crust!

Silicates contain silicon atoms and oxygen atoms. One silicon atom is bonded to four oxygen atoms. These atoms form a pyramid (**Figure** 1.6). The silicate pyramid is the building block of silicate minerals. Most silicates contain other elements. These elements include calcium, iron, and magnesium.

Silicate minerals are divided into six smaller groups. In each group, the silicate pyramids join together differently. The pyramids can stand alone. They can form into connected circles called rings. Some pyramids link into single and double chains. Others form large, flat sheets. Some join in three dimensions.

Feldspar and quartz are the two most common silicates. In beryl, the silicate pyramids join together as rings. Biotite is mica. It can be broken apart into thin, flexible sheets. Compare the beryl and the biotite shown in **Figure** 1.7.

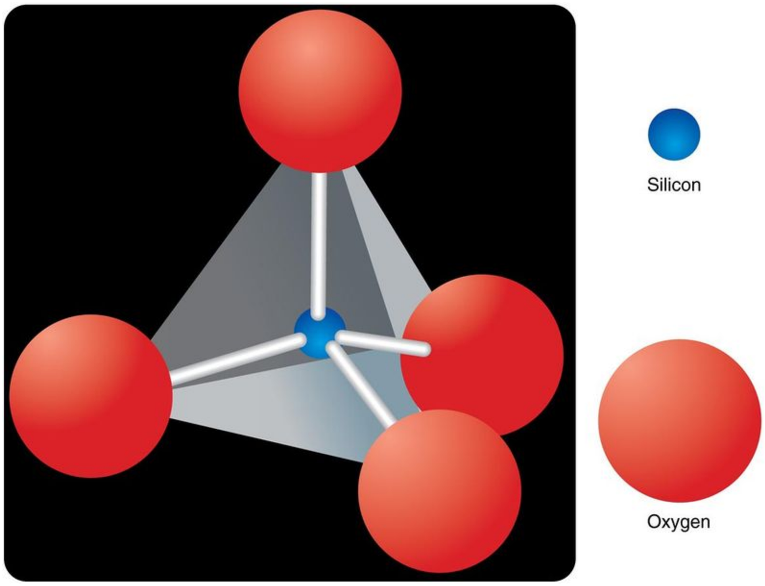

FIGURE 1.6
One silicon atom bonds to four oxygen atoms to form a pyramid

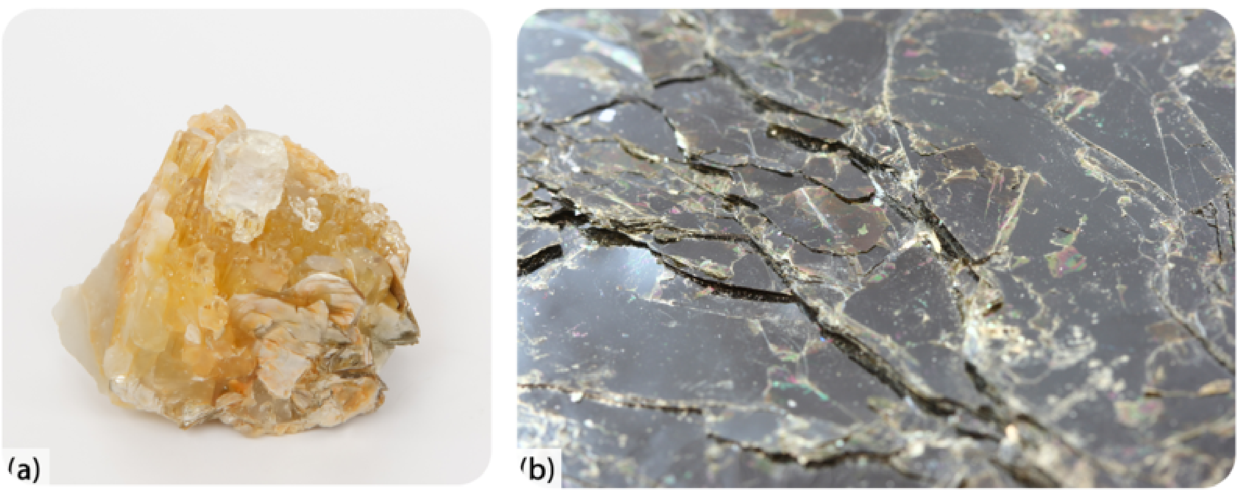

FIGURE 1.7
Beryl (a) and biotite (b) are both silicate minerals.

Native Elements

Native elements contain only atoms of one type of element. They are not combined with other elements. There are very few examples of these types of minerals. Some native elements are rare and valuable. Gold, silver, sulfur, and diamond are examples.

Carbonates

What do you guess **carbonate** minerals contain? If you guessed carbon, you would be right! All carbonates contain one carbon atom bonded to three oxygen atoms. Carbonates may include other elements. A few are calcium, iron, and copper.

Carbonate minerals are often found where seas once covered the land. Some carbonate minerals are very common. Calcite contains calcium, carbon, and oxygen. Have you ever been in a limestone cave or seen a marble tile? Calcite is in both limestone and marble. Azurite and malachite are also carbonate minerals, but they contain copper instead of calcium. They are not as common as calcite. They are used in jewelry. You can see in **Figure** 1.8 that they are very colorful.

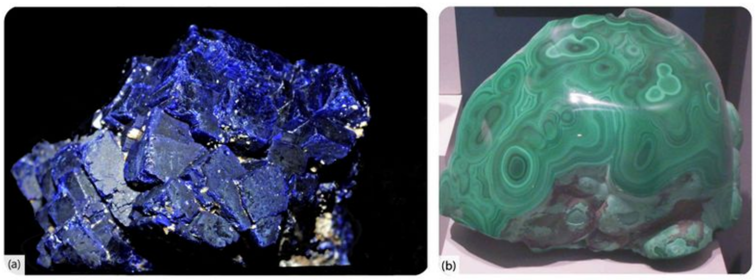

FIGURE 1.8
The deep blue mineral is azurite and the green is malachite. Both of these carbonate minerals are used for jewelry.

Halides

Halide minerals are salts. They form when salt water evaporates. This mineral class includes more than just table salt. Halide minerals may contain the elements fluorine, chlorine, bromine, or iodine. Some will combine with metal elements. Common table salt is a halide mineral that contains the elements chlorine and sodium. Fluorite is a type of halide that contains fluorine and calcium. Fluorite can be found in many colors. If you shine an ultraviolet light on fluorite, it will glow!

Oxides

Earth's crust contains a lot of oxygen. The oxygen combines with many other elements to create oxide minerals. Oxides contain one or two metal elements combined with oxygen. Oxides are different from silicates because they do not contain silicon. Many important metals are found as oxides. For example, hematite and magnetite are both oxides that contain iron. Hematite (Fe_2O_3) has a ratio of two iron atoms to three oxygen atoms. Magnetite (Fe_3O_4) has a ratio of three iron atoms to four oxygen atoms. Notice that the word "magnetite" contains the word "magnet". Magnetite is a magnetic mineral.

Phosphates

Phosphate minerals have a structure similar to silicates. In silicates, an atom of silicon is bonded to oxygen. In phosphates, an atom of phosphorus, arsenic, or vanadium is bonded to oxygen. There are many types of phosphate mineral, but still phosphate minerals are rare. The composition of phosphates is complex. For example, turquoise contains copper, aluminum, and phosphorus. The stone is rare and is used to make jewelry.

Sulfates

Sulfate minerals contain sulfur atoms bonded to oxygen atoms. Like halides, they can form in places where salt water evaporates. Many minerals belong in the sulfate group, but there are only a few common sulfate minerals. Gypsum is a common sulfate mineral that contains calcium, sulfate, and water. Gypsum is found in various forms. For example, it can be pink and look like it has flower petals. However, it can also grow into very large white crystals. Gypsum crystals that are 11 meters long have been found. That is about as long as a school bus! Gypsum also forms at the Mammoth Hot Springs in Yellowstone National Park, shown in **Figure** 1.9.

FIGURE 1.9
Gypsum is the white mineral that is common around hot springs. This is Mammoth Hot Springs in Yellowstone National Park.

Sulfides

Sulfides contain metal elements combined with sulfur. Sulfides are different from sulfates. They do not contain oxygen. Pyrite is a common sulfide mineral. It contains iron combined with sulfur. Pyrite is also known as "fool's gold." Gold miners have mistaken pyrite for gold because pyrite has a greenish gold color.

Lesson Summary

- A mineral is a naturally occurring inorganic solid. It has a definite composition and crystal structure.
- The atoms in minerals are arranged in regular, repeating patterns.
- These patterns are responsible for a mineral's physical properties.
- Minerals are divided into groups. The groups are based on their chemical composition.
- Silicates are the most common minerals.

Lesson Review Questions

Recall

1. What is matter?

2. What are atoms and what are they made of?

3. What is a molecule? What substances do molecules make?

4. Go through the eight mineral groups. List the elements that are contained by all minerals in each group.

Apply Concepts

5. Quartz is made of one silicon atom and two oxygen atoms. If you find a mineral and find that it is made of one silicon atom and one oxygen atom is it quartz?

6. Why is water ice considered a mineral?

7. A shady looking character offers you a valuable mineral made of carbon. You know that diamonds are made of carbon so you give him $100 for one. Have you gotten yourself a good deal? Why or why not?

Think Critically

8. Why are diamonds "a girls best friend?" What other uses might diamonds have?

9. Coal is made of ancient plant parts that were squeezed together and heated. Is coal a mineral? Explain.

Points to Consider

- What is one way you could tell the difference between two different minerals?
- Why would someone want to make minerals when they are found in nature?
- Why are minerals so colorful? Can color be used to identify minerals?

1.2 Identification of Minerals

Lesson Objectives

- Explain how minerals are identified.
- Describe how color, luster, and streak are used to identify minerals.
- Summarize specific gravity.
- Explain how the hardness of a mineral is measured.
- Describe the properties of cleavage and fracture.
- Identify additional properties that can be used to identify some minerals.

Vocabulary

- cleavage
- density
- fracture
- hardness
- luster
- streak

Introduction

How could you describe your shirt when you are talking to your best friend on the phone? You might describe the color, the way the fabric feels, and the length of the sleeves. These are all physical properties of your shirt. If you did a good job describing your shirt, your friend would recognize the shirt when you wear it. Minerals also have physical properties that are used to identify them.

How are Minerals Identified?

Imagine you were given a mineral sample similar to the one shown in **Figure** 1.10. How would you try to identify your mineral? You can observe some properties by looking at the mineral. For example, you can see that its color is beige. The mineral has a rose-like structure. But you can't see all mineral properties. You need to do simple tests to determine some properties. One common one is how hard the mineral is. You can use a mineral's properties to identify it. The mineral's physical properties are determined by its chemical composition and crystal structure.

FIGURE 1.10
You can use properties of a mineral to identify it. The color and rose-like structure of this mineral mean that it is gypsum.

Color, Streak, and Luster

Diamonds have many valuable properties. Diamonds are extremely hard and are used for industrial purposes. The most valuable diamonds are large, well-shaped and sparkly. Turquoise is another mineral that is used in jewelry because of its striking greenish-blue color. Many minerals have interesting appearances. Specific terms are used to describe the appearance of minerals.

Color

Color is probably the easiest property to observe. Unfortunately, you can rarely identify a mineral only by its color. Sometimes, different minerals are the same color. For example, you might find a mineral that is a gold color, and so think it is gold. But it might actually be pyrite, or "fool's gold," which is made of iron and sulfide. It contains no gold atoms.

A certain mineral may form in different colors. **Figure** 1.11 shows four samples of quartz, including one that is colorless and one that is purple. The purple color comes from a tiny amount of iron. The iron in quartz is a chemical impurity. Iron is not normally found in quartz. Many minerals are colored by chemical impurities. Other factors can also affect a mineral's color. Weathering changes the surface of a mineral. Because color alone is unreliable, geologists rarely identify a mineral just on its color. To identify most minerals, they use several properties.

Streak

Streak is the color of the powder of a mineral. To do a streak test, you scrape the mineral across an unglazed porcelain plate. The plate is harder than many minerals, causing the minerals to leave a streak of powder on the plate. The color of the streak often differs from the color of the larger mineral sample, as **Figure** 1.12 shows.

Streak is more reliable than color to identify minerals. The color of a mineral may vary. Streak does not vary. Also, different minerals may be the same color, but they may have a different color streak. For example, samples of hematite and galena can both be dark gray. They can be told apart because hematite has a red streak and galena has a gray streak.

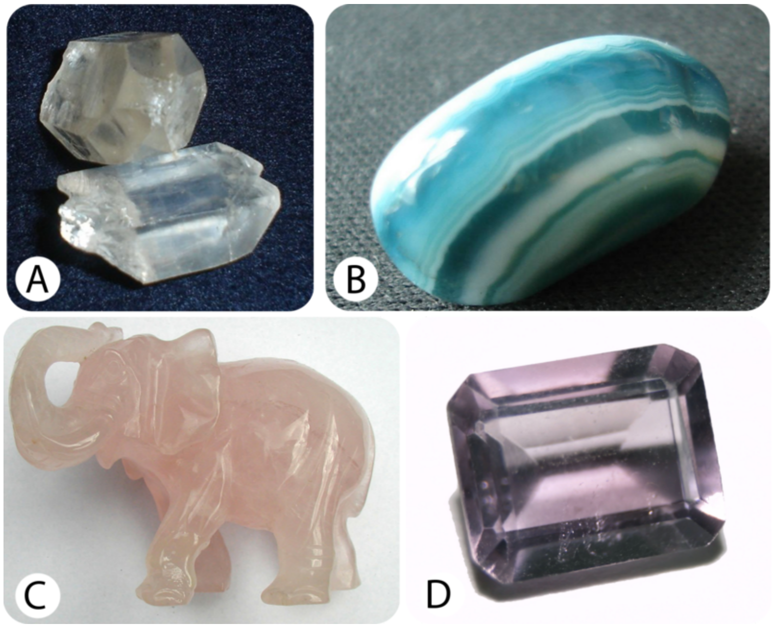

FIGURE 1.11
Quartz comes in many different colors including: (A) transparent quartz, (B) blue agate, (C) rose quartz, and (D) purple amethyst.

FIGURE 1.12
Rub a mineral across an unglazed porcelain plate to see its streak. The hematite shown here has a red streak.

Luster

Luster describes the way light reflects off of the surface of the mineral. You might describe diamonds as sparkly or pyrite as shiny. But mineralogists have special terms to describe luster. They first divide minerals into metallic and non-metallic luster. Minerals that are opaque and shiny, like pyrite, are said to have a "metallic" luster. Minerals with a "non-metallic" luster do not look like metals. There are many types of non-metallic luster. Six are described in **Table** 1.1.

TABLE 1.1: Minerals with Non-Metallic Luster

Non-Metallic Luster	Appearance
Adamantine	Sparkly
Earthy	Dull, clay-like
Pearly	Pearl-like
Resinous	Like resins, such as tree sap
Silky	Soft-looking with long fibers
Vitreous	Glassy

Can you match the minerals in **Figure** 1.13 with the correct luster from **Table** 1.1 without looking at the caption?

Density

You are going to visit a friend. You fill one backpack with books so you can study later. You stuff your pillow into another backpack that is the same size. Which backpack will be easier to carry? Even though the backpacks are the same size, the bag that contains your books is going to be much heavier. It has a greater density than the backpack with your pillow.

Density describes how much matter is in a certain amount of space. Substances that have more matter packed into a given space have higher densities. The water in a drinking glass has the same density as the water in a bathtub or swimming pool. All substances have characteristic densities, which does not depend on how much of a substance you have.

Mass is a measure of the amount of matter in an object. The amount of space an object takes up is described by its volume. The density of an object depends on its mass and its volume. Density can be calculated using the following equation:

$$\text{Density} = \text{Mass}/\text{Volume}$$

Samples that are the same size, but have different densities, will have different masses. Gold has a density of about 19 g/cm^3. Pyrite has a density of only about 5 g/cm^3. Quartz is even less dense than pyrite, and has a density of 2.7 g/cm^3. If you picked up a piece of pyrite and a piece of quartz that were the same size, the pyrite would seem almost twice as heavy as the quartz.

Hardness

Hardness is a mineral's ability to resist being scratched. Minerals that are not easily scratched are hard. You test the hardness of a mineral by scratching its surface with a mineral of a known hardness. Mineralogists use the Mohs Hardness Scale, shown in **Table** 1.2, as a reference for mineral hardness. The scale lists common minerals in order of their relative hardness. You can use the minerals in the scale to test the hardness of an unknown mineral.

Mohs Hardness Scale

As you can see, diamond is a 10 on the Mohs Hardness Scale. Diamond is the hardest mineral; no other mineral can scratch a diamond. Quartz is a 7. It can be scratched by topaz, corundum, and diamond. Quartz will scratch minerals

FIGURE 1.13
(A) Diamonds have an adamantine luster. These minerals are transparent and highly reflective. (B) Kaolinite is a clay with a dull or earthy luster. (C) Opal's luster is greasy. (D) Chalcopyrite, like its cousin pyrite, has metallic luster. (E) Stilbite (orange) has a resinous luster. (F) The white ulexite has silky luster. (G) Sphalerite has a submetallic luster. (H) This Mayan artifact is carved from jade. Jade is a mineral with a waxy luster.

that have a lower number on the scale. Fluorite is one. Suppose you had a piece of pure gold. You find that calcite scratches the gold. Gypsum does not. Gypsum has a hardness of 2 and calcite is a 3. That means the hardness of gold is between gypsum and calcite. So the hardness of gold is about 2.5 on the scale. A hardness of 2.5 means that gold is a relatively soft mineral. It is only about as hard as your fingernail.

TABLE 1.2: Mohs Scale

Hardness	Mineral
1	Talc

TABLE 1.2: (continued)

Hardness	Mineral
2	Gypsum
3	Calcite
4	Fluorite
5	Apatite
6	Orthoclase feldspar
7	Quartz
8	Topaz
9	Corundum
10	Diamond

Cleavage and Fracture

Different types of minerals break apart in their own way. Remember that all minerals are crystals. This means that the atoms in a mineral are arranged in a repeating pattern. This pattern determines how a mineral will break. When you break a mineral, you break chemical bonds. Because of the way the atoms are arranged, some bonds are weaker than other bonds. A mineral is more likely to break where the bonds between the atoms are weaker.

Cleavage

Cleavage is the tendency of a mineral to break along certain planes. When a mineral breaks along a plane it makes a smooth surface. Minerals with different crystal structures will break or cleave in different ways, as in **Figure** 1.14. Halite tends to form cubes with smooth surfaces. Mica tends to form sheets. Fluorite can form octahedrons.

FIGURE 1.14
Minerals with different crystal structures have a tendency to break along certain planes.

Minerals can form various shapes. Polygons are shown in **Figure** 1.15. The shapes form as the minerals are broken along their cleavage planes. Cleavage planes determine how the crystals can be cut to make smooth surfaces. People who cut gemstones follow cleavage planes. Diamonds and emeralds can be cut to make beautiful gemstones.

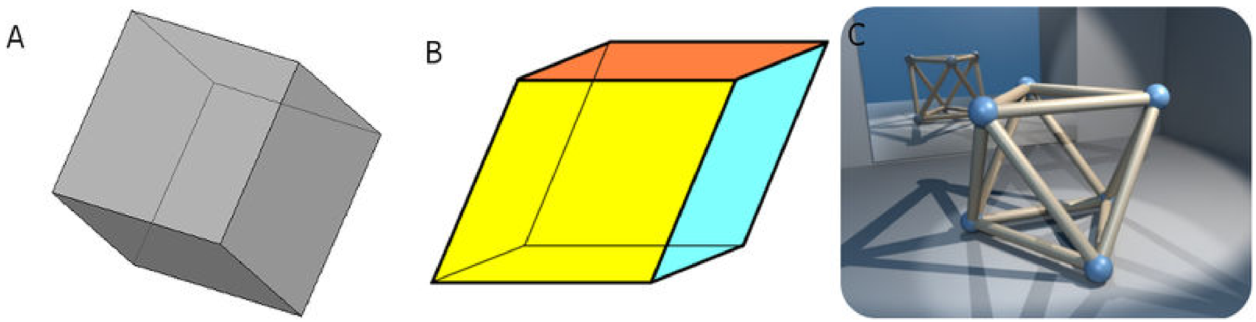

FIGURE 1.15
Cubes have six sides that are all the same size square. All of the angles in a cube are equal to 90°. Rhombohedra also have six sides, but the sides are diamond-shaped. Octahedra have eight sides that are all shaped like triangles.

Fracture

Fracture describes how a mineral breaks without any pattern. A fracture is uneven. The surface is not smooth and flat. You can learn about a mineral from the way it fractures. If a mineral splinters like wood, it may be fibrous. Some minerals, such as quartz, fracture to form smooth, curved surfaces. A mineral that broke forming a smooth, curved surface is shown in **Figure** 1.16.

Other Identifying Characteristics

Minerals have other properties that can be used for identification. For example, a mineral's shape may indicate its crystal structure. Sometimes crystals are too small to see. Then a mineralogist may use a special instrument to find the crystal structure.

Some minerals have unique properties. These can be used to the minerals. Some of these properties are listed in **Table** 1.3. An example of a mineral that has each property is also listed.

TABLE 1.3: Special Mineral Properties

Property	Description	Example of Mineral
Fluorescence	Mineral glows under ultraviolet light	Fluorite
Magnetism	Mineral is attracted to a magnet	Magnetite
Radioactivity	Mineral gives off radiation that can be measured with Geiger counter	Uraninite
Reactivity	Bubbles form when mineral is exposed to a weak acid	Calcite
Smell	Some minerals have a distinctive smell	Sulfur (smells like rotten eggs)

FIGURE 1.16
This mineral formed a smooth, curved surface when it fractured.

Lesson Summary

- You can identify a mineral by its appearance and other properties.
- The color and luster describe the appearance of a mineral, and streak describes the color of the powdered mineral.
- Each mineral has a characteristic density.
- Mohs Hardness Scale is used to compare the hardness of minerals.
- The way a mineral cleaves or fractures depends on the crystal structure of the mineral.
- Some minerals have special properties that can be used to help identify the mineral.

Lesson Review Questions

Recall

1. What is cleavage? What is fracture? If you are looking at a mineral face, how can you tell them apart?

2. What is color? When would you use color to identify a mineral?

3. What is streak? Why would you use streak instead of color to identify a mineral?

Apply Concepts

4. What type of luster do gemstones mostly have? Why do you think this type of luster is popular for jewelry?

5. If a mineral has a unique property that only that type of mineral has is it good for identifying that mineral? Is there any time that it might not be?

Think Critically

6. You are trying to identify a mineral sample. Apatite scratches the surface of the mineral. Which mineral would you use next to text the mineral's hardness—fluorite or feldspar? Explain your reasoning.

7. You have two mineral samples that are about the size of a golf ball. Mineral A has a density of 5 g/cm^3. Mineral B is twice as dense as Mineral A. What is the density of Mineral B?

Points to Consider

- Some minerals are colored because they contain chemical impurities. How did the impurities get into the mineral?
- What two properties of a mineral sample would you have to measure to calculate its density?

1.3 Formation of Minerals

Lesson Objectives

- Describe how melted rock produces minerals.
- Explain how minerals form from solutions.

Vocabulary

- lava
- magma
- rocks

Introduction

Minerals are all around you. They are used to make your house, your computer, even the buttons on your jeans. But where do minerals come from? There are many types of minerals, and they do not all form in the same way. Some minerals form when salt water on Earth's surface evaporates. Others form from water mixtures that are seeping through rocks far below your feet. Still others form when molten rock cools.

Formation from Magma and Lava

You are on vacation at the beach. You take your flip-flops off so you can go swimming. The sand is so hot it hurts your feet. You have to run to the water. Now imagine if it were hot enough for the sand to melt.

Some places inside Earth are so hot that rock melts. Melted rock inside the Earth is called magma. **Magma** can be hotter than 1,000°C. When magma erupts onto Earth's surface, it is known as **lava**, as **Figure** 1.17 shows. Minerals form when magma and lava cool.

Formation from Solutions

Most water on Earth, like the water in the oceans, contains elements. The elements are mixed evenly through the water. Water plus other substances makes a solution. The particles are so small that they will not come out when you filter the water. But the elements in water can form solid mineral deposits.

FIGURE 1.17
Lava is melted rock that erupts onto Earth's surface.

Minerals from Salt Water

Fresh water contains a small amount of dissolved elements. Salt water contains a lot more dissolved elements. Water can only hold a certain amount of dissolved substances. When the water evaporates, it leaves behind a solid layer of minerals, as **Figure** 1.18 shows. At this time, the particles come together to form minerals. These solids sink to the bottom. The amount of mineral formed is the same as the amount dissolved in the water. Seawater is salty enough for minerals to precipitate as solids. Some lakes, such as Mono Lake in California, or Utah's Great Salt Lake, can also precipitate salts.

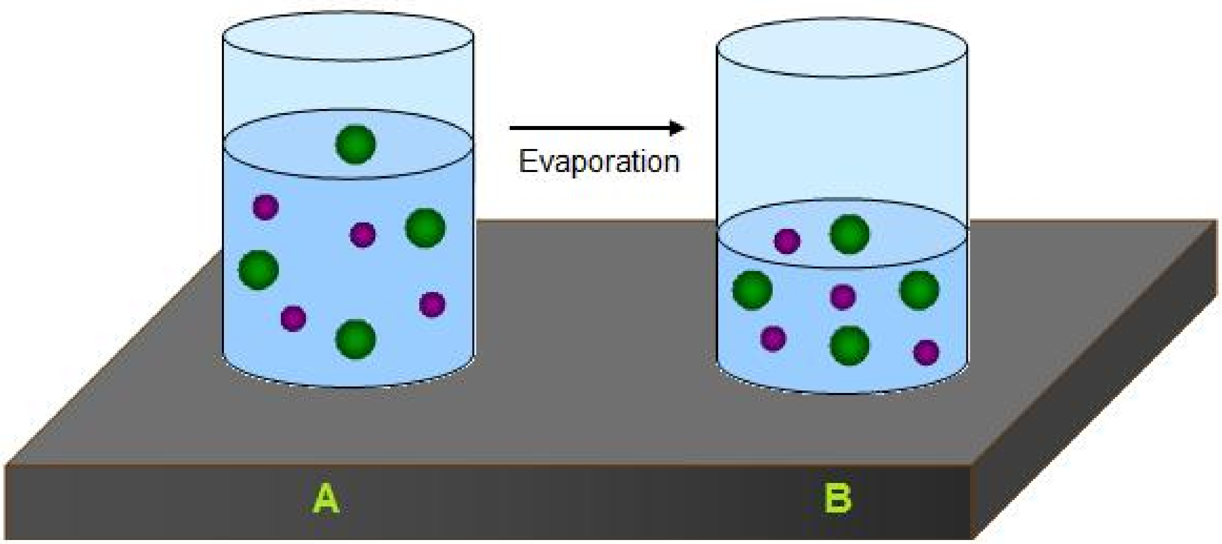

FIGURE 1.18
When the water in glass A evaporates, the dissolved mineral particles are left behind.

Salt easily precipitates out of water, as does calcite, as **Figure** 1.19 shows. The limestone towers in the figure are made mostly of the mineral calcite. The calcite was deposited in the salty and alkaline water of Mono Lake, in California. Calcium-rich spring water enters the bottom of the lake. The water bubbles up into the alkaline lake. The

calcite “tufa” towers form. When the lake level drops, the tufa towers are revealed.

FIGURE 1.19
Tufa towers are found in interesting formations at Mono Lake, California.

Minerals from Hot Underground Water

Underground water can be heated by magma. The hot water moves through cracks below Earth’s surface. Hot water can hold more dissolved particles than cold water. The hot, salty solution has chemical reactions with the rocks around it. The water picks up more dissolved particles. As it flows through open spaces in rocks, the water deposits solid minerals. When a mineral fills cracks in rocks, the deposits are called “veins.” **Figure** 1.20 shows a white quartz vein. When the minerals are deposited in open spaces, large crystals grow. These rocks are called geodes. **Figure** 1.20 shows a “geode” that was formed when amethyst crystals grew in an open space in a rock.

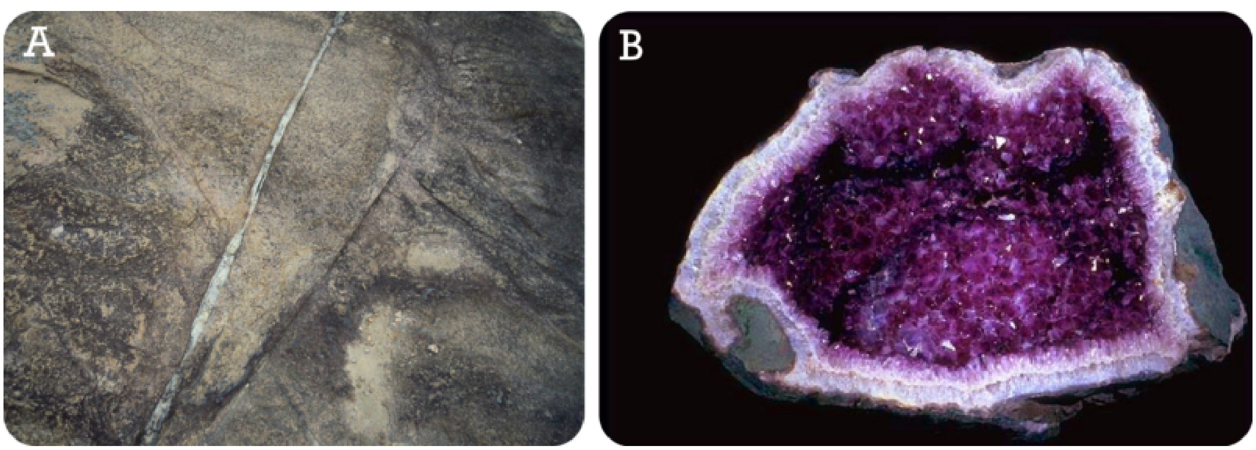

FIGURE 1.20
(A) A quartz vein formed in this rock. (B) Geodes form when minerals evaporate out in open spaces inside a rock.

Lesson Summary

- Mineral crystals that form when magma cools are usually larger than crystals that form when lava cools.
- Minerals are deposited from salty water solutions on Earth's surface and underground.

Lesson Review Questions

Recall

1. How does magma differ from lava?

2. What happens to elements in salt water when the water evaporates?

Apply Concepts

3. Describe how minerals can form out of salt water. What are all the steps in the process?

Think Critically

4. You are handed a rock with large and form beautiful crystals. Another rock is made of the same mineral type but the crystals are small and not well formed. How is the way the two sets of that mineral formed different?

Points to Consider

- When most minerals form, they combine with other minerals to form rocks. How can these minerals be used?
- The same mineral can be formed by different processes. How can the way a mineral forms affect how the mineral is used?

1.4 Mining and Using Minerals

Lesson Objectives

- Explain how minerals are mined.
- Describe how metals are made from mineral ores.
- Summarize the ways in which gemstones are used.
- Identify some useful minerals.

Vocabulary

- gemstone
- ore

Introduction

When you use a roll of aluminum foil or some baby powder, you probably don't think about how the products were made. We use minerals in many everyday items.

Minerals have to be removed from the ground and made into the products. All the metals we use start out as an ore. Mining the ore is just the first step. Next, the ore must be separated from the rest of the rock that is mined. Then, the minerals need to be separated out of the ore.

Ore Deposits

A mineral deposit that contains enough minerals to be mined for profit is called an **ore**. Ores are rocks that contain concentrations of valuable minerals. The bauxite shown in the **Figure** 1.21 is a rock that contains minerals that are used to make aluminum.

Finding and Mining Minerals

Ores have high concentrations of valuable minerals. Certain places on Earth are more likely to have certain ores. Geologists search for the places that might have ore deposits. Some of the valuable deposits may be hidden underground. To find an ore deposit, geologists will go to a likely spot. They then test the physical and chemical properties of soil and rocks. Ore deposits contain valuable minerals. They may also contain other chemical elements that indicate an ore deposit is nearby.

FIGURE 1.21
Aluminum is made from the minerals in rocks known as bauxite.

After a mineral deposit is found, geologists determine how big it is. They outline the deposit and the surrounding geology on a map. The miners calculate the amount of valuable minerals they think they will get from the deposit. The minerals will only be mined if it is profitable. If it is profitable, they must then decide on the way it should be mined. The two main methods of mining are surface mining and underground mining. Placers are a type of surface deposit.

Surface Mining

Surface mining is used to obtain mineral ores that are near the surface. Blasting breaks up the soil and rocks that contain the ore. Enormous trucks haul the broken rocks to locations where the ores can be removed. Surface mining includes open-pit mining, quarrying, and strip mining.

As the name suggests, open-pit mining creates a big pit from which the ore is mined. **Figure** 1.22 shows an open-pit diamond mine in Russia. The size of the pit grows as long as the miners can make a profit. Strip mines are similar to open-pit mines, but the ore is removed in large strips. A quarry is a type of open-pit mine that produces rocks and minerals that are used to make buildings and roads.

Placer Mining

Placer minerals collect in stream gravels. They can be found in modern rivers or ancient riverbeds. California was nicknamed the Golden State. This can be traced back to the discovery of placer gold in 1848. The amount of placer gold brought in miners from around the world. The gold formed in rocks in the Sierra Nevada Mountains. The rocks also contained other valuable minerals. The gold weathered out of the hard rock. It washed downstream and then settled in gravel deposits along the river. Currently, California has active gold and silver mines. California also has mines for non-metal minerals. For example, sand and gravel are mined for construction.

FIGURE 1.22
This diamond mine is more than 500 m deep.

Underground Mining

If an ore is deep below Earth's surface it may be too expensive to remove all the rock above it. These deposits are taken by underground mining. Underground mines can be very deep. The deepest gold mine in South Africa is more than 3,700 m deep (that is more than 2 miles)! There are various methods of underground mining. Underground mining is more expensive than surface mining. Tunnels must be blasted into the rock so that miners and equipment can get to the ore. Underground mining is dangerous work. Fresh air and lights must be brought in to the tunnels for the miners. The miners breathe in lots of particles and dust while they are underground. The ore is drilled, blasted, or cut away from the surrounding rock and taken out of the tunnels. Sometimes there are explosions as ore is being drilled or blasted. This can lead to a mine collapse. Miners may be hurt or killed in a mining accident.

Making Metals from Minerals

Most minerals are a combination of metal and other elements. The rocks that are taken from a mine are full of valuable minerals plus rock that isn't valuable. This is called waste rock. The valuable minerals must be separated from the waste rock. One way to do this is with a chemical reaction. Chemicals are added to the ores at very high temperatures.

For example, getting aluminum from waste rock uses a lot of energy. This is because temperatures greater than 900^{o}C are needed to separate out the aluminum. It also takes a huge amount of electricity. If you recycle just 40 aluminum cans, you will save the energy in one gallon of gasoline. We use over 80 billion cans each year. If all of these cans were recycled, we would save the energy in 2 billion gallons of gasoline!

Uses of Ore Minerals

We rely on metals, such as aluminum, copper, iron, and gold. Look around the room. How many objects have metal parts? Metals are used in the tiny parts inside your computer, in the wires of anything that uses electricity, and to make the structure of a large building, such as the one shown in the **Figure** 1.23.

FIGURE 1.23
The dome of the capital building in Hartford, Connecticut is coated with gold leaf.

Gemstones and Their Uses

Some minerals are valuable simply because they are beautiful. Jade has been used for thousands of years in China. Native Americans have been decorating items with turquoise since ancient times. Minerals like jade, turquoise, diamonds, and emeralds are gemstones. A **gemstone** is a material that is cut and polished to use in jewelry. Many gemstones, such as those shown in **Figure** 1.24, are minerals.

FIGURE 1.24
Gemstones come in many colors.

Gemstones are beautiful, rare, and do not break or scratch easily. Generally, rarer gems are more valuable. If a gem

is popular, unusually large or very well cut, it will be more valuable.

Most gemstones are not used exactly as they are found in nature. Usually, gems are cut and polished. **Figure** 1.25 shows an uncut piece of ruby and a ruby that has been cut and polished. The way a mineral splits along a surface allows it to be cut to produce smooth surfaces. Notice that the cut and polished ruby sparkles more. Gems sparkle because light bounces back when it hits them. These gems are cut so that the most amount of light possible bounces back. Other gemstones, such as turquoise, are opaque, which means light does not pass through them. These gems are not cut in the same way.

FIGURE 1.25
Ruby is cut and polished to make the gemstone sparkle. Left: Ruby Crystal. Right: Cut Ruby.

Gemstones also have other uses. Most diamonds are actually not used as gemstones. Diamonds are used to cut and polish other materials, such as glass and metals, because they are so hard. The mineral corundum, which makes the gems ruby and sapphire, is used in products like sandpaper. Synthetic rubies and sapphires are also used in lasers.

Other Useful Minerals

Metals and gemstones are often shiny, so they catch your eye. Many minerals that we use everyday are not so noticeable. For example, the buildings on your block could not have been built without minerals. The walls in your home might use the mineral gypsum for the sheetrock. The glass in your windows is made from sand, which is mostly the mineral quartz. Talc was once commonly used to make baby powder. The mineral halite is mined for rock salt. Diamond is commonly used in drill bits and saw blades to improve their cutting ability. Copper is used in electrical wiring, and the ore bauxite is the source for the aluminum in your soda can.

Mining and the Environment

Mining provides people with many resources they need, but mining can be hazardous to people and the environment. Miners should restore the mined region to its natural state. It is also important to use mineral resources wisely. Most ores are non-renewable resources.

Land Reclamation

After the mining is finished, the land is greatly disturbed. The area around the mine needs to be restored to its natural state. This process of restoring the area is called “reclamation.“ Native plants are planted. Pit mines may be refilled or reshaped so that they can become natural areas again. The mining company may be allowed to fill the pit with

water to create a lake. The pits may be turned into landfills. Underground mines may be sealed off or left open as homes for bats.

Mine Pollution

Mining can cause pollution. Chemicals released from mining can contaminate nearby water sources. **Figure** 1.26 shows water that is contaminated from a nearby mine. The United States government has mining standards to protect water quality.

FIGURE 1.26
Scientists test water that has been contaminated by a mine.

Lesson Summary

- Geologists look for mineral deposits that will be profitable to mine.
- Ores that are close to the surface are mined by surface mining methods. Ores that are deep in Earth are mined using underground methods.
- Metals ores must be melted to make metals.
- Many gems are cut and polished to increase their beauty.
- Minerals are used in a variety of ways.

Lesson Review Questions

Recall

1. What are placers? How do placer deposits form?

2. What makes an ore deposit valuable?

Apply Concepts

3. Why would a mining company choose to do a surface mine? Why would it choose to do an underground mine?

4. Once the ore rocks are taken to a refinery, what happens to get the ore out?

Thinking Critically

5. What are some disadvantages of underground mining?
6. What is the bottom line when it comes to deciding how what and how to mine?
7. How is land reclaimed after mining? Is it ever fully recovered?
8. How might the history of the Golden State been different if placers had not been found in its rivers?

Points to Consider

- Are all mineral deposits ores?
- An open-pit diamond mine may one day be turned into an underground mine. Why would this happen?
- Diamonds are not necessarily the rarest gem. Why do people value diamonds more than most other gems?

1.5 References

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2. Necklace: Flickr:Tikanchay handcrafted jewelry from Peru; Salt mill: User:ElinorD/Wikimedia Commons; Glass: Will Murray (User:Willscrlt/Wikimedia Commons); Silver: Courtesy of US Geological Survey and Mineral Information Institute; Salt: Courtesy of US Geological Survey and Mineral Information Institute; Quartz: Courtesy of Ken Hammond/US Department of Agriculture. Necklace: http://www.flickr.com/photos/29874248@N06/2811981846/; Salt mill: http://commons.wikimedia.org/wiki/File:Saltmill.jpg; Glass: http://commons.wikimedia.org/wiki/File:Highball_Glass_%28Tumbler%29.svg; Silver: http://commons.wikimedia.org/wiki/File:SilverUSGOV.jpg; Salt: http://commons.wikimedia.org/wiki/File:ImgSalt.jpg; Quartz: http://commons.wikimedia.org/wiki/File:USDA_Mineral_Quartz_Crystal_93c3951.jpg . Necklace: CC BY 2.0; Rest: Public Domain
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CHAPTER 2 MS Rocks

Chapter Outline

Have you ever heard the phrase "rock solid?" Something is rock solid if it does not and cannot change. It will not fail or go wrong. A rock-solid plan is a sure bet. A rock-solid idea is sure to be doable. Devil's Tower in Wyoming looks rock solid. It looks like it would not change or move. Even in a million years it would look just like it does now.

In this chapter you will find out that rocks do change. Rocks can change from one type to another. Rocks can alter to have different characteristics but still be the same type. Most changes in rocks take place over long periods of time. More rarely the changes take only a short time. This rock formation's days are numbered… and a diamond is not forever.

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2.1 Types of Rocks

Lesson Objectives

- Define rock and describe what rocks are made of.
- Know the three main groups of rocks.
- Explain how each of these three rock types are formed.
- Describe the rock cycle.

Vocabulary

- deposited
- sediments

Introduction

There are three major rock types. Rock of any of these three rock types can become rock of one of the other rock types. Rock can also change to a different rock of the same type. Rocks give good clues as to what was happening in a region during the time that rock formed.

The Rock Cycle

All rocks on Earth change, but these changes usually happen very slowly. Some changes happen below Earth's surface. Some changes happen above ground. These changes are all part of the rock cycle. The rock cycle describes each of the main types of rocks, how they form and how they change. **Figure** 2.1 shows how the three main rock types are related to each other. The arrows within the circle show how one type of rock may change to rock of another type. For example, igneous rock may break down into small pieces of sediment and become sedimentary rock. Igneous rock may be buried within the Earth and become metamorphic rock. Igneous rock may also change back to molten material and re-cool into a new igneous rock.

Rocks are made of minerals. The minerals may be so tiny that you can only see them with a microscope. The minerals may be really large. A rock may be made of only one type of mineral. More often rocks are made of a mixture of different minerals. Rocks are named for the combinations of minerals they are made of and the ways those minerals came together. Remember that different minerals form under different environmental conditions. So the minerals in a rock contain clues about the conditions in which the rock formed (**Figure** 2.2).

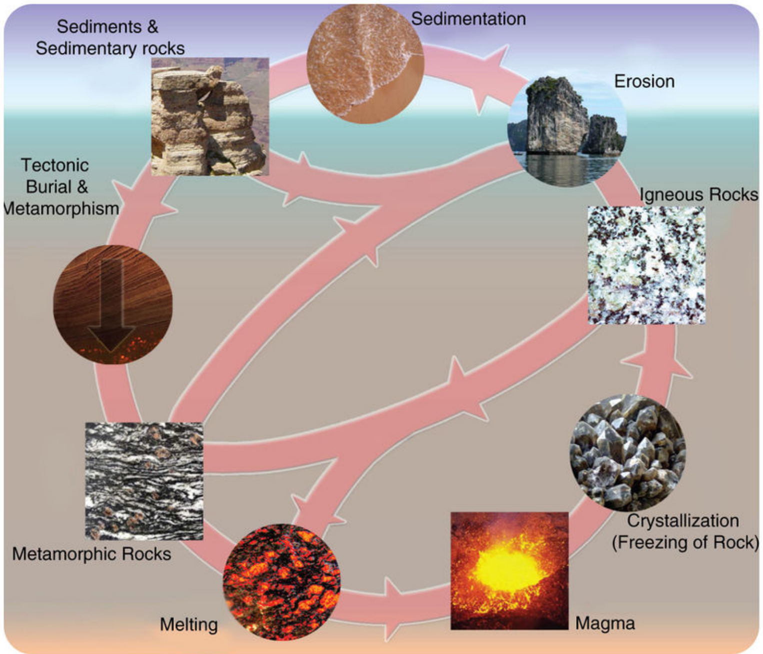


FIGURE 2.1
The rock cycle.

FIGURE 2.2
Rocks contain many clues about the conditions in which they formed. The minerals contained within the rocks also contain geological information.

Three Main Categories of Rocks

Geologists group rocks based on how they were formed. The three main kinds of rocks are:

1. Igneous rocks form when magma cools below Earth's surface or lava cools at the surface (**Figure** 2.3).

2. Sedimentary rocks form when sediments are compacted and cemented together (**Figure** 2.4). These sediments may be gravel, sand, silt or clay. Sedimentary rocks often have pieces of other rocks in them. Some sedimentary rocks form the solid minerals left behind after a liquid evaporates.

3. Metamorphic rocks form when an existing rock is changed by heat or pressure. The minerals in the rock change but do not melt (**Figure** 2.5). The rock experiences these changes within the Earth.

FIGURE 2.3
Lava is molten rock. This lava will harden into an igneous rock.

FIGURE 2.4
This sandstone is an example of a sedimentary rock. It formed when many small pieces of sand were cemented together to form a rock.

Rocks can be changed from one type to another, and the rock cycle describes how this happens.

Processes of the Rock Cycle

Any type of rock can change and become a new type of rock. Magma can cool and crystallize. Existing rocks can be weathered and eroded to form sediments. Rock can change by heat or pressure deep in Earth's crust. There are three main processes that can change rock:

- Cooling and forming crystals. Deep within the Earth, temperatures can get hot enough to melt rock. This molten material is called magma. As it cools, crystals grow, forming an igneous rock. The crystals will grow larger if the magma cools slowly, as it does if it remains deep within the Earth. If the magma cools quickly, the crystals will be very small.
- Weathering and erosion. Water, wind, ice, and even plants and animals all act to wear down rocks. Over time

FIGURE 2.5
This mica schist is a metamorphic rock. It was changed from a sedimentary rock like shale.

they can break larger rocks into smaller pieces called sediments. Moving water, wind, and glaciers then carry these pieces from one place to another. The sediments are eventually dropped, or **deposited**, somewhere. The sediments may then be compacted and cemented together. This forms a sedimentary rock. This whole process can take hundreds or thousands of years.

- Metamorphism. This long word means "to change form." A rock undergoes metamorphism if it is exposed to extreme heat and pressure within the crust. With metamorphism, the rock does not melt all the way. The rock changes due to heat and pressure. A metamorphic rock may have a new mineral composition and/or texture.

An interactive rock cycle diagram can be found here: http://www.classzone.com/books/earth_science/terc/content/investigations/es0602/es0602page02.cfm?chapter_no=investigation

The rock cycle really has no beginning or end. It just continues. The processes involved in the rock cycle take place over hundreds, thousands, or even millions of years. Even though for us rocks are solid and unchanging, they slowly change all the time.

Lesson Summary

- There are three main types of rocks: igneous, sedimentary, and metamorphic.
- Melting and later cooling, erosion and sedimentation, and metamorphism transform one type of rock into another type of rock or change sediments into rock.
- The rock cycle describes the transformations of one type of rock to another.

Lesson Review Questions

Recall

1. What is the difference between magma and lava?

2. What are igneous rocks? How do igneous rocks form?

3. What are metamorphic rocks? How do metamorphic rocks form?

4. What are sedimentary rocks? How do sedimentary rocks form?

Apply Concepts

5. How do minerals combine to form an igneous rock?

6. How do minerals combine to form a metamorphic rock?

7. How do minerals combine to form a sedimentary rock?

Think Critically

8. What clues do the minerals in an igneous rock give about how the rock formed? A metamorphic rock? A sedimentary rock?

9. Describe how an igneous rock can change to a metamorphic rock.

10. If Earth's interior was cool, how would this change the types of rocks formed on Earth?

Points to Consider

- What processes on Earth are involved in forming rocks?
- What rocks are important to modern humans and for what purposes?

2.2 Igneous Rocks

Lesson Objectives

- Describe how igneous rocks are formed.
- Describe the properties of some common types of igneous rocks.
- Relate some common uses of igneous rocks.

Vocabulary

- extrusive
- intrusive

Introduction

Most of the Earth is made of igneous rock. The entire mantle is igneous rock, as are some areas of the crust. One of the most common igneous rocks is granite (**Figure** 2.6). Many mountain ranges are made of granite. People use granite for countertops, buildings, monuments and statues. Pumice is also an igneous rock. Perhaps you have used a pumice stone to smooth your skin. Pumice stones are put into giant washing machines with new jeans and tumbled around. The result is stone-washed jeans!

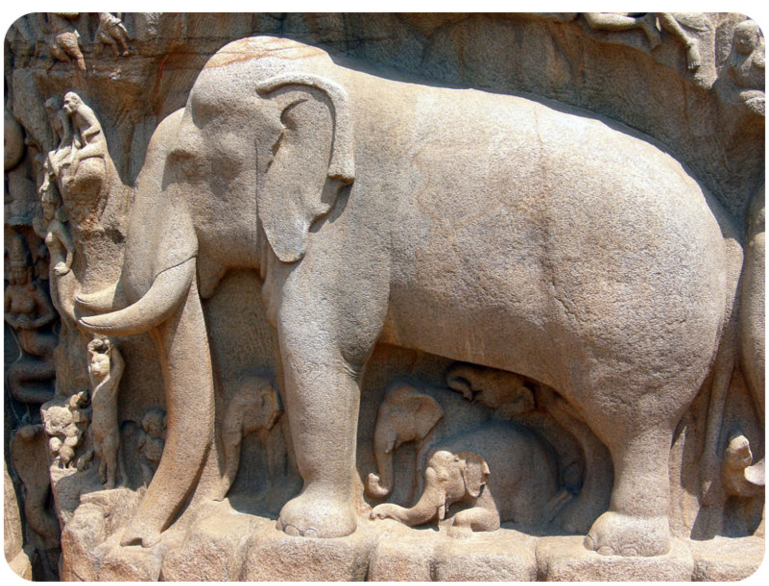


FIGURE 2.6
This life-size elephant is carved from granite.

Forming Crystals

Igneous rocks form when magma cools and forms crystals. These rocks can form at Earth's surface or deep underground. **Figure** 2.7 shows a landscape in California's Sierra Nevada that consists entirely of granite.

FIGURE 2.7
The Sierra Nevada of California are composed mainly of granite. These rocks are beautifully exposed in the Yosemite Valley.

Intrusive igneous rocks cool and form into crystals beneath the surface. Deep in the Earth, magma cools slowly. Slow cooling gives large crystals a chance to form. Intrusive igneous rocks have relatively large crystals that are easy to see. Granite is the most common intrusive igneous rock. **Figure** 2.8 shows four types of intrusive rocks.

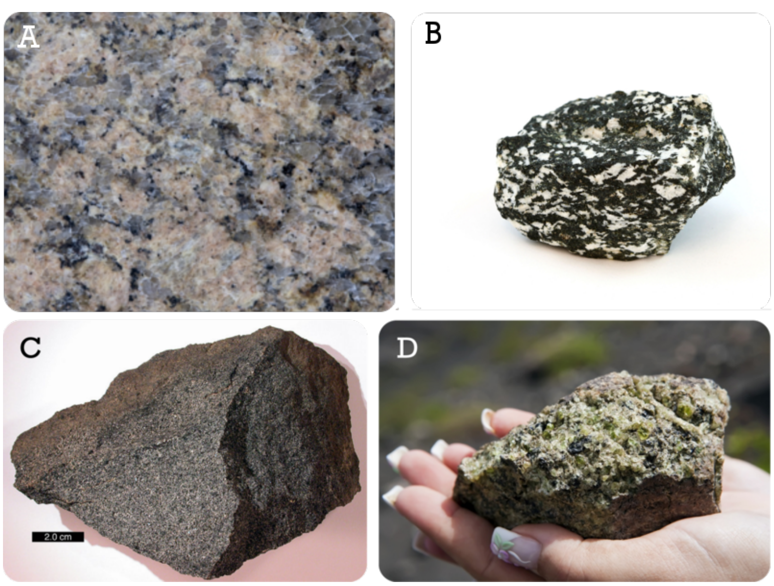


FIGURE 2.8
(A) This granite has more plagioclase feldspar than many granites. (B) Diorite has more dark-colored minerals than granite. (C) Gabbro. (D) Peridotite is an intrusive igneous rock with olivine and other mafic minerals.

Extrusive igneous rocks form above the surface. The lava cools quickly as it pours out onto the surface (**Figure** 2.9). Extrusive igneous rocks cool much more rapidly than intrusive rocks. They have smaller crystals, since the

rapid cooling time does not allow time for large crystals to form. Some extrusive igneous rocks cool so rapidly that crystals do not develop at all. These form a glass, such as obsidian. Others, such as pumice, contain holes where gas bubbles were trapped in the lava. The holes make pumice so light that it actually floats in water. The most common extrusive igneous rock is basalt. It is the rock that makes up the ocean floor. **Figure** 2.10 shows four types of extrusive igneous rocks.

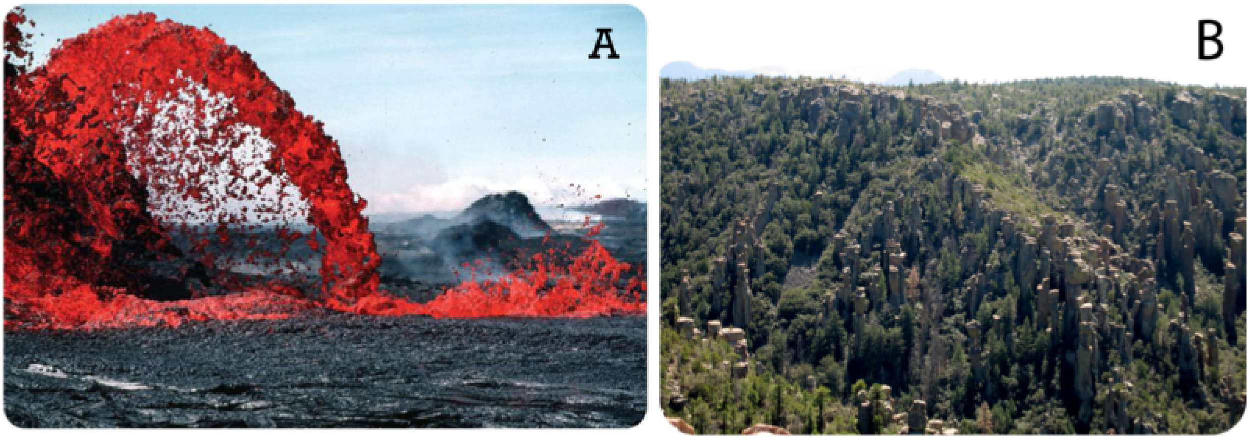


FIGURE 2.9

(A) Lava cools to form extrusive igneous rock. The rocks here are basalts. (B) The strange rock formations of Chiricahua National Monument in Arizona are formed of the extrusive igneous rock rhyolite.

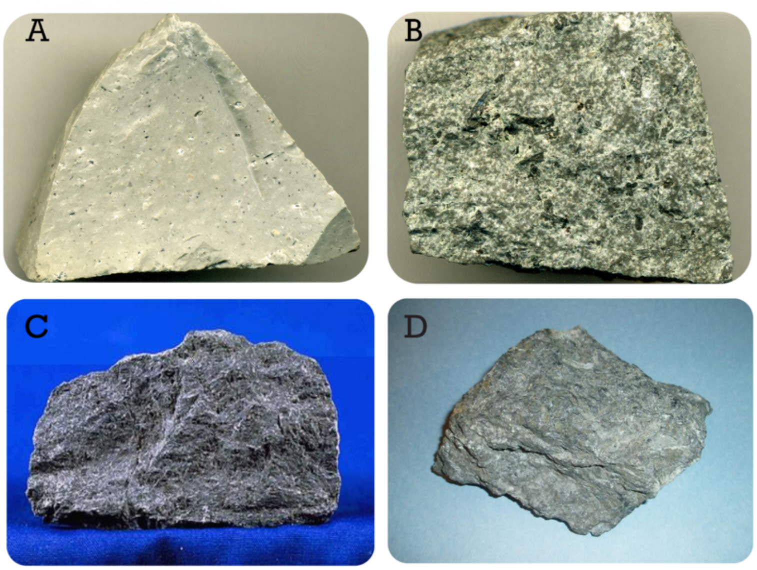


FIGURE 2.10

(A) This rhyolite is light colored. Few minerals are visible to the naked eye. (B) Andesite is darker than rhyolite. (C) Since basalt crystals are too small to see, the rock looks dark all over. (D) Komatiite is a very rare ultramafic rock. This rock is derived from the mantle.

Composition

Igneous rocks are grouped by the size of their crystals and the minerals they contain. The minerals in igneous rocks are grouped into families. Some contain mostly lighter colored minerals, some have a combination of light and dark minerals, and some have mostly darker minerals. The combination of minerals is determined by the composition of the magma. Magmas that produce lighter colored minerals are higher in silica. These create rocks such as granite and rhyolite. Darker colored minerals are found in rocks such as gabbro and basalt.

There are actually more than 700 different types of igneous rocks. Diorite is extremely hard and is commonly used for art. It was used extensively by ancient civilizations for vases and other decorative art work (**Figure** 2.11).

FIGURE 2.11
This sarcophagus is housed at the Vatican Museum. The rock is the igneous extrusive rock porphyry. Porphyry has large crystals because the magma began to cool slowly, then erupted.

Lesson Summary

- Igneous rocks form either when they cool very slowly deep within the Earth or when magma cools rapidly at the Earth's surface.
- Composition of the magma will determine the minerals that will crystallize forming different types of igneous rocks.

Lesson Review Questions

Recall

1. What is the difference between an intrusive and an extrusive igneous rock?

2. List three common uses of igneous rocks.

Apply Concepts

3. Why do extrusive igneous rocks usually have smaller crystals than intrusive igneous rocks?

4. How are igneous rocks classified?

Think Critically

5. Occasionally, igneous rocks will contain both large crystals and tiny mineral crystals. Propose a way that both these sizes of crystals might have formed in the rock.

6. Why is the ocean floor more likely to have extrusive rocks than intrusive rocks?

Points to Consider

- Do you think igneous rocks could form where you live?
- Would all igneous rocks with the same composition have the same name? Explain why they might not.
- Could an igneous rock cool at two different rates? What would the crystals in such a rock look like?

2.3 Sedimentary Rocks

Lesson Objectives

- Describe how sedimentary rocks are formed.
- Describe the properties of some common sedimentary rocks.
- Relate some common uses of sedimentary rocks.

Vocabulary

- cemented
- compacted
- fossils

Introduction

FIGURE 2.12
Layers of sand turned to rock are seen in the Navajo sandstone. The geologic feature is a slot canyon called Antelope Canyon.

Did you know that the White House, the official home and workplace of the President of the United States of America, is made out of the same material as the rock faces in **Figure** 2.12? This material is a sedimentary rock called sandstone. Sandstone is very porous. Water can easily move through it. So the sandstone of the White House could have been water damaged. But during construction workers covered the sandstone in a mixture of salt, rice, and glue. This mixture protects the sandstone and is what gives the White House its distinct white color.

Sediments

Most sedimentary rocks form from sediments. Sediments are small pieces of other rocks, like pebbles, sand, silt, and clay. Sedimentary rocks may include fossils. **Fossils** are materials left behind by once-living organisms. Fossils can be pieces of the organism, like bones. They can also be traces of the organism, like footprints.

Most often, sediments settle out of water (**Figure** 2.13). For example, rivers carry lots of sediment. Where the water slows, it dumps these sediments along its banks, into lakes and the ocean. When sediments settle out of water, they form horizontal layers. A layer of sediment is deposited. Then the next layer is deposited on top of that layer. So each layer in a sedimentary rock is younger than the layer under it. It is older than the layer over it.

FIGURE 2.13
Cobbles, pebbles, and sands are the sediments that are seen on this beach.

Sediments are deposited in many different types of environments. Beaches and deserts collect large deposits of sand. Sediments also continuously wind up at the bottom of the ocean and in lakes, ponds, rivers, marshes, and swamps. Avalanches produce large piles of sediment. The environment where the sediments are deposited determines the type of sedimentary rock that can form.

Sedimentary Rock Formation

Sedimentary rocks form in two ways. Particles may be cemented together. Chemicals may precipitate.

Clastic Rocks

Over time, deposited sediments may harden into rock. First, the sediments are **compacted**. That is, they are squeezed together by the weight of sediments on top of them. Next, the sediments are **cemented** together. Minerals fill in the spaces between the loose sediment particles. These cementing minerals come from the water that moves through the sediments. These types of sedimentary rocks are called “clastic rocks.“ Clastic rocks are rock fragments that are compacted and cemented together.

Clastic sedimentary rocks are grouped by the size of the sediment they contain. Conglomerate and breccia are made of individual stones that have been cemented together. In conglomerate, the stones are rounded. In breccia, the stones are angular. Sandstone is made of sand-sized particles. Siltstone is made of smaller particles. Silt is smaller than sand but larger than clay. Shale has the smallest grain size. Shale is made mostly of clay-sized particles and hardened mud.

Chemical Sedimentary Rocks

Chemical sedimentary rocks form when crystals precipitate out from a liquid. The mineral halite, also called rock salt, forms this way. You can make halite! Leave a shallow dish of salt water out in the Sun. As the water evaporates,

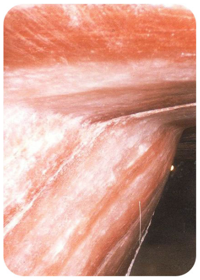
salt crystals form in the dish. There are other chemical sedimentary rocks, like gypsum.

Table 2.1 shows some common types of sedimentary rocks and the types of sediments that make them up.

TABLE 2.1: Common Sedimentary Rocks

Picture	Rock Name	Type of Sedimentary Rock
	Conglomerate	Clastic
	Breccia	Clastic
	Sandstone	Clastic
	Siltstone	Clastic
	Limestone	Bioclastic
	Coal	Organic

TABLE 2.1: (continued)

Picture	Rock Name	Type of Sedimentary Rock
	Rock Salt	Chemical precipitate

Lesson Summary

- Most sedimentary rocks form from sediments. These sediments are deposited, forming layers.
- The youngest layers are found on top, with older layers below.
- Sediments must be compacted and cemented to make sedimentary rock.
- Chemical sedimentary rocks are made of precipitated minerals.

Lesson Review Questions

Recall

1. What are three things that sedimentary rocks may be made of?

2. Describe the two processes necessary for sediments to harden into rock.

Apply Concepts

3. If you see a sedimentary rock outcrop and red layers of sand are on top of pale yellow layers of sand, what do you know for sure about the ages of the two layers?

Think Critically

4. What type of sedimentary rock is coal?

5. Why do you think sandstone allows water to move through it easily?

Points to Consider

- If you were interested in learning about Earth's history, which type of rocks would give you the most information?

- Could a younger layer of sedimentary rock ever be found under an older layer? How do you think this could happen?
- Could a sedimentary rock form only by compaction from intense pressure?

2.4 Metamorphic Rocks

Lesson Objectives

- Describe how metamorphic rocks are formed.
- Describe the properties of some common metamorphic rocks.
- Relate some common uses of metamorphic rocks.

Vocabulary

- contact metamorphism
- foliation
- regional metamorphism
- stable

Introduction

Metamorphism changes rocks by heat and pressure. These agents create an entirely new type of rock. Metamorphism changes rocks physically and/or chemically.

Metamorphism

Metamorphic rocks start off as some kind of rock. The starting rock can be igneous, sedimentary or even another metamorphic rock. Heat and/or pressure then change the rock's physical or chemical makeup.

During metamorphism a rock may change chemically. Ions move and new minerals form. The new minerals are more stable in the new environment. Extreme pressure may lead to physical changes like **foliation**. Foliation forms as the rocks are squeezed. If pressure is exerted from one direction, the rock forms layers. This is foliation. If pressure is exerted from all directions, the rock usually does not show foliation.

There are two main types of metamorphism:

1. **Contact metamorphism** results when magma contacts a rock, changing it by extreme heat (**Figure** 2.14).

2. **Regional metamorphism** occurs over a wide area. Great masses of rock are exposed to pressure from rock and sediment layers on top of it. The rock may also be compressed by other geological processes.

Metamorphism does not cause a rock to melt completely. It only causes the minerals to change by heat or pressure.

Hornfels is a rock with alternating bands of dark and light crystals. Hornfels is a good example of how minerals rearrange themselves during metamorphism (**Figure** 2.14). The minerals in hornfels separate by density. The result

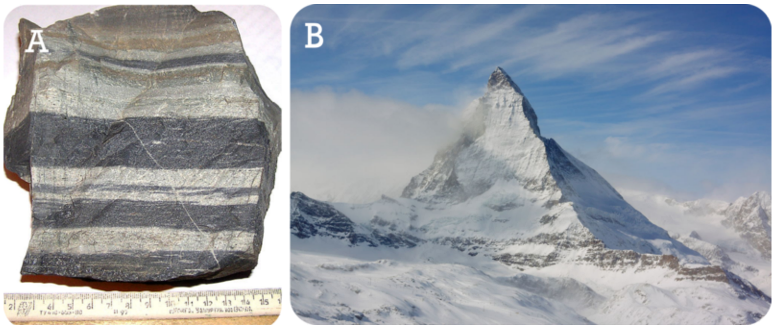


FIGURE 2.14

(A) Hornfels is a rock that is created by contact metamorphism. (B) Hornfels is so hard that it can create peaks like the Matterhorn.

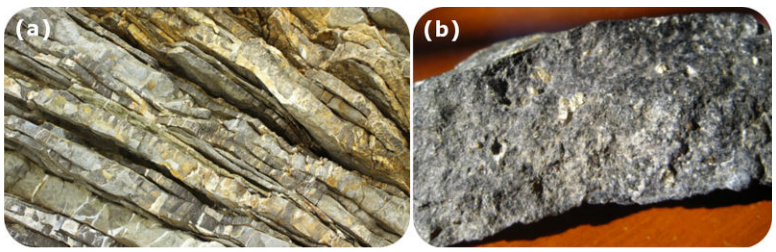


FIGURE 2.15

(A) Regional metamorphic rocks often display layering called foliation. (B) Regional metamorphism with high pressures and low temperatures can result in blue schist.

is that the rock becomes banded. Gneiss forms by regional metamorphism from extremely high temperature and pressure.

Uses of Metamorphic Rocks

Quartzite and marble are the most commonly used metamorphic rocks. They are frequently chosen for building materials and artwork. Marble is used for statues and decorative items like vases (**Figure** 2.16). Quartzite is very hard and is often crushed and used in building railroad tracks. Schist and slate are sometimes used as building and landscape materials.

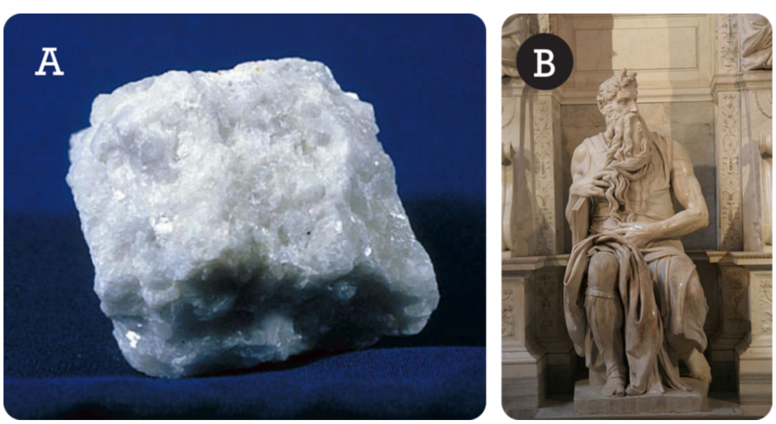


FIGURE 2.16

(A) Marble is a beautiful rock that is commonly used for buildings. (B) Many of the great statues of the Renaissance were carved from marble. Michelangelo created this Moses between 1513 and 1515.

Lesson Summary

- Metamorphic rocks form when heat and pressure transform an existing rock into a new rock.
- Contact metamorphism occurs when hot magma transforms rock that it contacts.
- Regional metamorphism transforms large areas of existing rocks under the tremendous heat and pressure created by tectonic forces.

Lesson Review Questions

Recall

1. Why do the minerals in a rock sometimes rearrange themselves when exposed to heat or pressure?
2. List and describe the two main types of metamorphism.

Apply Concepts

3. How does layering form in metamorphic rocks?
4. What clues in metamorphic rocks tell you how they were formed?

Think Critically

5. Suppose a phyllite sample was exposed to even more heat and pressure. What metamorphic rock would form?

Points to Consider

- What type of plate boundary would produce the most intense metamorphism of rock?
- Do you think new minerals could form when an existing rock is metamorphosed?

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2.5 References

1. User:Woudloper/Woodwalker; modified by CK-12 Foundation. The Rock Cycle . Public Domain
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CHAPTER 3 MS Plate Tectonics

Chapter Outline

Earth is a restless planet. Heat in the Earth's interior causes giant plates of crust to move around on the surface. The crashing and smashing of these plates leads to nearly all of the geological activity we see. Plate collisions bring us volcanoes and earthquakes, mountain ranges, and many resources. Seafloor forms as plates move apart. Some of Earth's most beautiful landscapes come from plate tectonics. The Grand Tetons in Wyoming rose up as the Farallon Plate sunk beneath the North American Plate during the Laramide orogeny.

Miles Orchinik. CK–12 Foundation. CC BY–NC 3.0.

3.1 Inside Earth

Lesson Objectives

- Compare and describe each of Earth's layers.
- Compare some of the ways geologists learn about Earth's interior.
- Define oceanic and continental crust and the lithosphere.
- Describe how heat moves, particularly how convection takes place in the mantle.
- Compare the two parts of the core and describe why they are different from each other.

Vocabulary

- asthenosphere
- convection cell
- continental crust
- core
- crust
- lithosphere
- mantle
- meteorite
- oceanic crust
- plate tectonics
- seismic waves

Introduction

From outside to inside, Earth is divided into crust, mantle, and core. Each has a different chemical makeup. Earth can also be divided into layers with different properties. The two most important are lithosphere and asthenosphere.

How Do We Know About Earth's Interior?

If someone told you to figure out what is inside Earth, what would you do? How could you figure out what is inside our planet? How do scientists figure it out?

Seismic Waves

Geologists study earthquake waves to "see" Earth's interior. Waves of energy radiate out from an earthquake's focus. These are called **seismic waves** (**Figure** 3.1). Seismic waves change speed as they move through different

materials. This causes them to bend. Some seismic waves do not travel through liquids or gases. Scientists use all of this information to understand what makes up the Earth's interior.

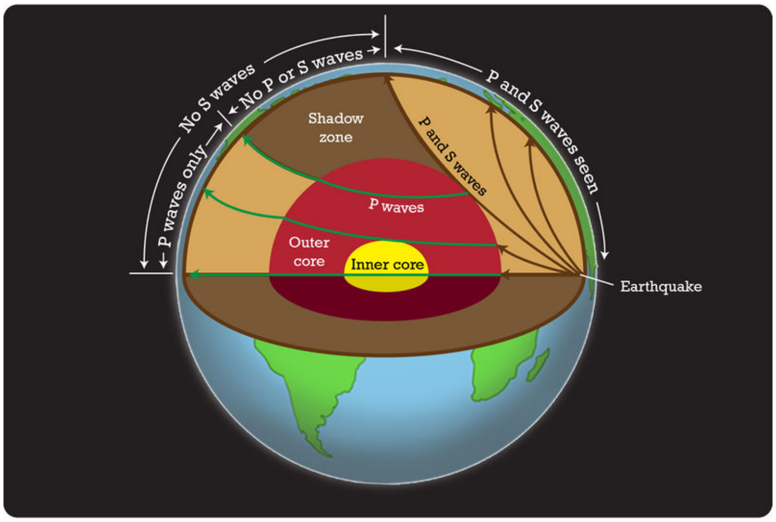

FIGURE 3.1
The properties of seismic waves allow scientists to understand the composition of Earth's interior.

Meteorites

Scientists study **meteorites** to learn about Earth's interior. Meteorites formed in the early solar system. These objects represent early solar system materials. Some meteorites are made of iron and nickel. They are thought to be very similar to Earth's core (**Figure** 3.2). An iron meteorite is the closest thing to a sample of the core that scientists can hold in their hands!

FIGURE 3.2
The Willamette Meteorite is a metallic meteorite that was found in Oregon.

Crust

Crust, mantle, and core differ from each other in chemical composition. It's understandable that scientists know the most about the crust, and less about deeper layers (**Figure** 3.3). Earth's **crust** is a thin, brittle outer shell. The crust is made of rock. This layer is thinner under the oceans and much thicker in mountain ranges.

Oceanic Crust

There are two kinds of crust. **Oceanic crust** is made of basalt lavas that flow onto the seafloor. It is relatively thin, between 5 to 12 kilometers thick (3 - 8 miles). The rocks of the oceanic crust are denser (3.0 g/cm^3) than the rocks that make up the continents. Thick layers of mud cover much of the ocean floor.

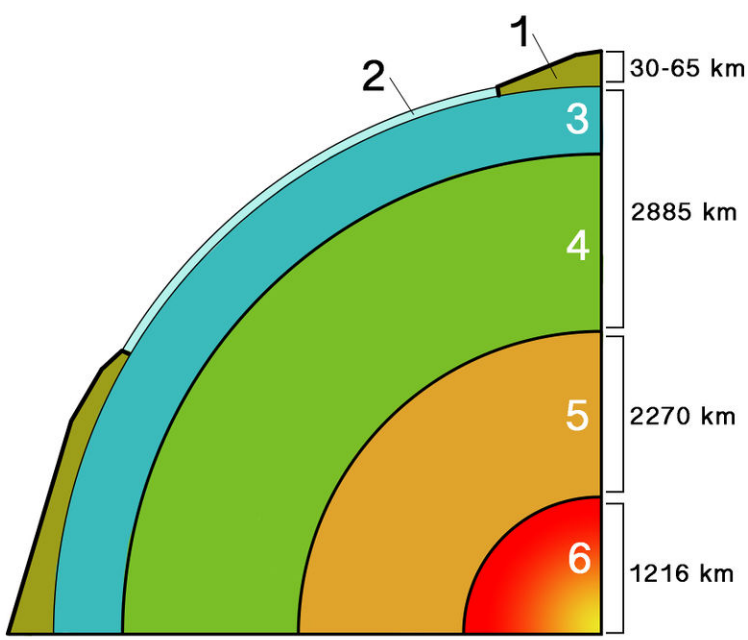

FIGURE 3.3
A cross-section of Earth showing the following layers: (1) continental crust, (2) oceanic crust, (3) upper mantle, (4) lower mantle, (5) outer core, (6) inner core.

Continental Crust

Continental crust is much thicker than oceanic crust. It is 35 kilometers (22 miles) thick on average, but it varies a lot. Continental crust is made up of many different rocks. All three major rock types —igneous, metamorphic, and sedimentary —are found in the crust. On average, continental crust is much less dense (2.7 g/cm3) than oceanic crust. Since it is less dense, it rises higher above the mantle than oceanic crust.

Mantle

Beneath the crust is the **mantle**. The mantle is made of hot, solid rock. Through the process of conduction, heat flows from warmer objects to cooler objects (**Figure** 3.4). The lower mantle is heated directly by conduction from the core.

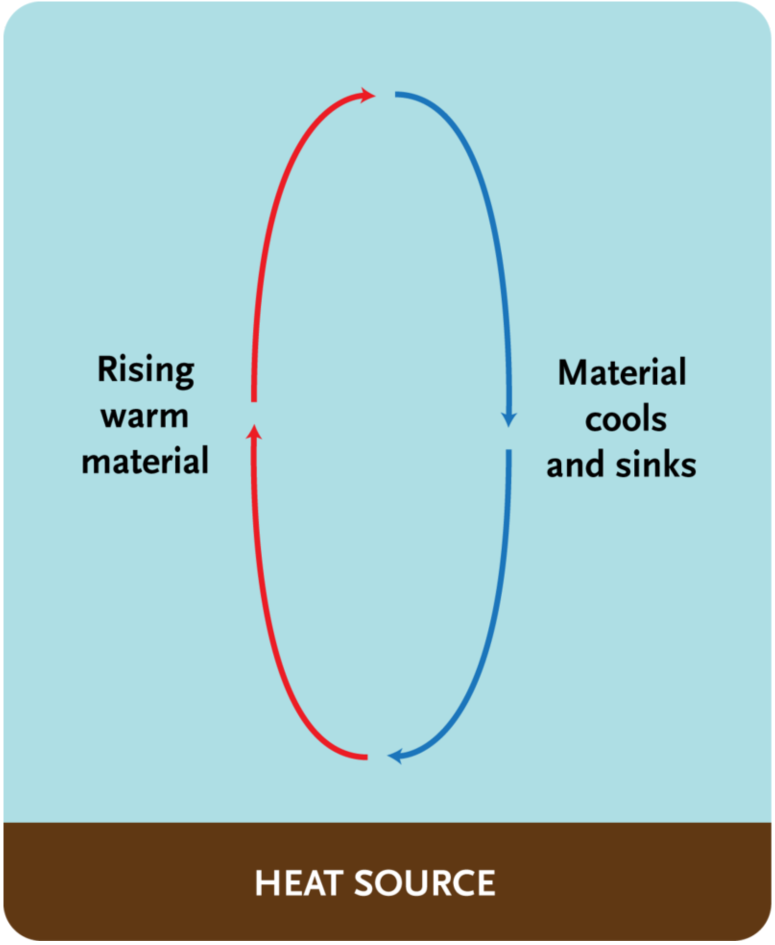

FIGURE 3.4
In the process of conduction, heat flows from warmer objects to cooler objects.

Hot lower mantle material rises upwards (**Figure** 3.5). As it rises, it cools. At the top of the mantle it moves horizontally. Over time it becomes cool and dense enough that it sinks. Back at the bottom of the mantle, it travels horizontally. Eventually the material gets to the location where warm mantle material is rising. The rising and sinking of warm and cooler material is convection. The motion described creates a convection cell.

Core

The dense, iron **core** forms the center of the Earth. Scientists know that the core is metal from studying metallic meteorites and the Earth's density. Seismic waves show that the outer core is liquid, while the inner core is solid. Movement within Earth's outer liquid iron core creates Earth's magnetic field. These convection currents form in the outer core because the base of the outer core is heated by the even hotter inner core.

Lithosphere and Asthenosphere

Lithosphere and asthenosphere are layers based on physical properties. The outermost layer is the **lithosphere**. The lithosphere is the crust and the uppermost mantle. In terms of physical properties, this layer is rigid, solid, and brittle. It is easily cracked or broken.

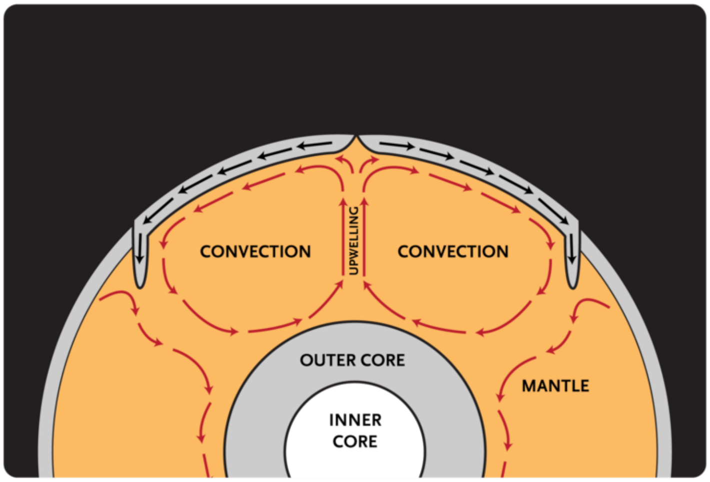

FIGURE 3.5
The rising and sinking of mantle material of different temperatures and densities creates a convection cell.

Below the lithosphere is the **asthenosphere**. The asthenosphere is also in the upper mantle. This layer is solid, but it can flow and bend. A solid that can flow is like silly putty.

Lesson Summary

- The Earth is made of three layers with different composition: the crust, mantle, and core.
- The lithosphere is made of the rigid, brittle, solid crust and uppermost mantle.
- Beneath the lithosphere, the asthenosphere is solid rock that can flow.
- The hot core warms the base of the mantle, which creates convection currents in the mantle.

Lesson Review Questions

Recall

1. List two ways that scientists learn about what makes up the Earth's interior.

2. What type of rock makes up the oceanic crust?

3. What types of rock make up the continental crust?

Apply Concepts

4. Describe the properties of the lithosphere and asthenosphere. What parts of the Earth do these layers include?

5. When you put your hand near a pan above a pan filled with boiling water, does your hand warm up because of convection or conduction? If you touch the pan, does your hand warm up because of convection or conduction?

Think Critically

6. List two reasons that scientists know that the outer core is liquid.

7. Suppose that Earth's interior contains a large amount of lead. Lead is very dense: 11.34 g/cm^3. Would the lead be more likely to be found in the crust, mantle, or core?

Points to Consider

- The oceanic crust is thinner and denser than continental crust. All crust sits atop the mantle. What might our planet be like if this were not true.
- If sediments fall onto the seafloor over time, what can sediment thickness tell scientists about the age of the seafloor in different regions?
- How might convection cells in the mantle affect the movement of plates of lithosphere on the planet's surface?

3.2 Continental Drift

Lesson Objectives

- Be able to explain the continental drift hypothesis.
- Describe the evidence Wegener used to support his continental drift idea.
- Describe how the north magnetic pole appeared to move, and how that is evidence for continental drift.

Vocabulary

- continental drift
- magnetic field

Introduction

To develop plate tectonics, first scientists had to accept that continents could move. Today they do. But it took a long time for scientists to accept that this could happen (**Figure** 3.6). This idea is called continental drift.

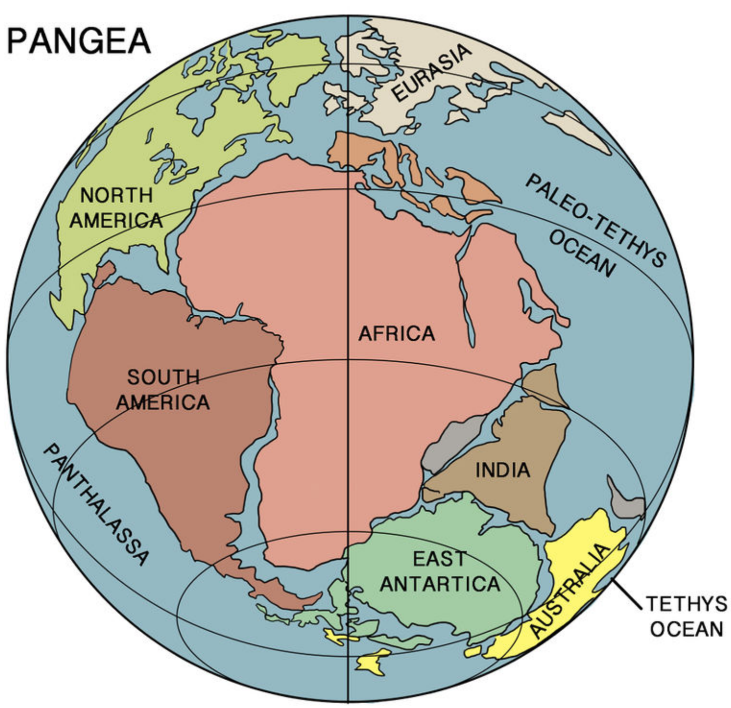

FIGURE 3.6
The supercontinent Pangaea contained all of the modern day continents.

The Continental Drift Idea

Alfred Wegener was an early 20th century German meteorologist. Wegener believed that the continents were once all joined together. He named the supercontinent Pangaea, meaning "all earth." Wegener suggested that Pangaea broke up long ago. Since then, the continents have been moving to their current positions. He called his hypothesis **continental drift**.

Evidence for Continental Drift

Wegener and his supporters collected a great deal of evidence for the continental drift hypothesis. Wegener found that this evidence was best explained if the continents had at one time been joined together.

Rocks and Geologic Structures

Wegener found rocks of the same type and age on both sides of the Atlantic Ocean. He thought that the rocks formed side by side. These rocks then drifted apart on separate continents.

Wegener also matched up mountain ranges across the Atlantic Ocean. The Appalachian Mountains were just like mountain ranges in eastern Greenland, Ireland, Great Britain, and Norway. Wegener concluded that they formed as a single mountain range. This mountain range broke apart as the continents split up. The mountain range separated as the continents drifted.

Fossil Plants and Animals

Wegener also found evidence for continental drift from fossils (**Figure** 3.7). The same type of plant and animal fossils are found on continents that are now widely separated. These organisms would not have been able to travel across the oceans.

Fossils of the seed fern Glossopteris are found across all of the southern continents. These seeds are too heavy to be carried across the ocean by wind. Mesosaurus fossils are found in South America and South Africa. Mesosaurus could swim, but only in fresh water. Cynognathus and Lystrosaurus were reptiles that lived on land. Both of these animals were unable to swim at all. Their fossils have been found across South America, Africa, India and Antarctica.

Wegener thought that all of these organisms lived side by side. The lands later moved apart so that the fossils are separated.

Glaciation

Wegener also looked at evidence from ancient glaciers. Glaciers are found in very cold climates near the poles. The evidence left by some ancient glaciers is very close to the equator. Wegener knew that this was impossible! However, if the continents had moved, the glaciers would have been centered close to the South Pole.

Climate

Coral reefs are found only in warm water. Coal swamps are also found in tropical and subtropical environments. Wegener discovered ancient coal seams and coral reef fossils in areas that are much too cold today. Wegener thought that the continents have moved since the time of Pangaea.

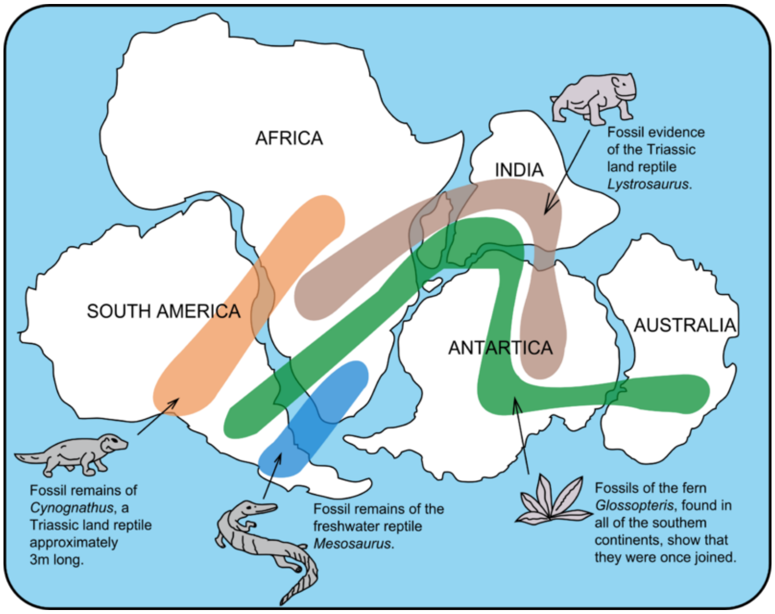

FIGURE 3.7
Wegener used fossil evidence to support his continental drift hypothesis. The fossils of these organisms are found on lands that are now far apart. Wegener suggested that when the organisms were alive, the lands were joined and the organisms were living side-by-side.

Magnetic Evidence

Some important evidence for continental drift came after Wegener's death. This is the magnetic evidence. Earth's magnetic field surrounds the planet from pole to pole. If you have ever been hiking or camping, you may have used a compass to help you find your way. A compass points to the magnetic North Pole. The compass needle aligns with Earth's **magnetic field** (**Figure** 3.8).

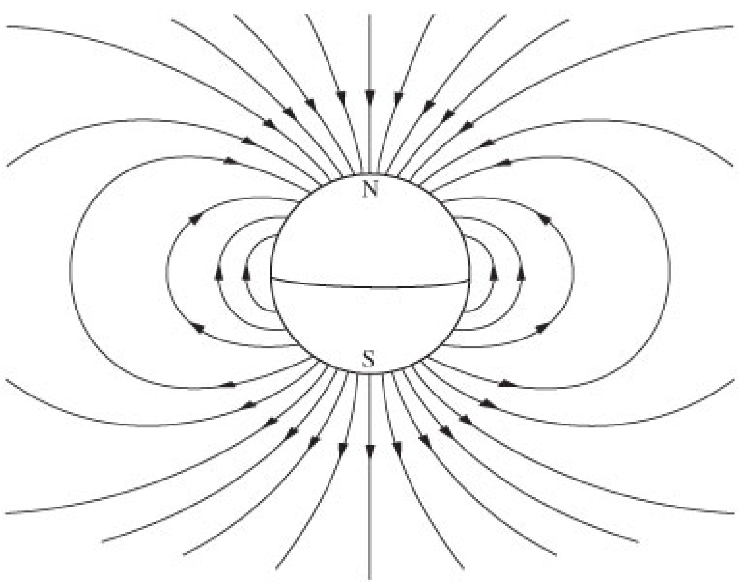

FIGURE 3.8
Earth's magnetic field is like a magnet with its north pole near the geographic north pole and the south pole near the geographic south pole.

Some rocks contain little compasses too! As lava cools, tiny iron-rich crystals line up with Earth's magnetic field.

Anywhere lavas have cooled, these magnetite crystals point to the magnetic poles. The little magnets point to where the north pole was when the lava cooled. Scientists can use this to figure out where the continents were at that time. This evidence clearly shows that the continents have moved.

During Wegener's life, scientists did not know how the continents could move. Wegener's idea was nearly forgotten. But as more evidence mounted, new ideas came about.

Lesson Summary

- Alfred Wegener gathered evidence that the continents had moved around on Earth's surface.
- The evidence for continental drift included the fit of the continents; the distribution of ancient fossils, rocks, and mountain ranges; and the locations of ancient climate zones.
- Although the evidence was extremely strong, scientists did not yet know how continents could move, so most rejected the idea.

Lesson Review Questions

Recall

1. How do the continents resemble puzzle pieces?

2. List the evidence Wegener had for continental drift.

Apply Concepts

3. What other regions fit together besides South America and Africa?

Think Critically

4. Make a case before a scientific jury to convince them that continental drift is real. Line up all your evidence. Does the lack of a mechanism for continents to move destroy your case?

5. What ideas can you come up with for what could drive continental motions?

Points to Consider

- Why is continental drift referred to as a hypothesis and not a theory?
- Why is Wegener's continental drift idea accepted today?
- Explain how each of these phenomena can be used as evidence for continental drift:
- The fit of the continents
- The distribution of fossils
- The distribution of similar rock types
- Rocks from ancient climate zones

3.3 Seafloor Spreading

Lesson Objectives

- List the main features of the seafloor: mid-ocean ridges, deep sea trenches, and abyssal plains.
- Describe what seafloor magnetism tells scientists about the seafloor.
- Describe the process of seafloor spreading.

Vocabulary

- echo sounder
- seafloor spreading
- trenches

Introduction

Ocean research during World War II gave scientists the tools to find out how the continents move. The evidence all pointed to seafloor spreading.

Seafloor Bathymetry

Before World War II, people thought the seafloor was completely flat and featureless. There was no reason to think otherwise.

Echo Sounders

But during the war, battleships and submarines carried echo sounders. Their goal was to locate enemy submarines (**Figure** 3.9). **Echo sounders** produce sound waves that travel outward in all directions. The sound waves bounce off the nearest object, and then return to the ship. Scientists know the speed of sound in seawater. They then can calculate the distance to the object that the sound wave hit. Most of these sound waves did not hit submarines. They instead were used to map the ocean floor.

Features of the Seafloor

Scientists were surprised to find huge mountains and deep trenches when they mapped the seafloor. The mid-ocean ridges form majestic mountain ranges through the deep oceans (**Figure** 3.10).

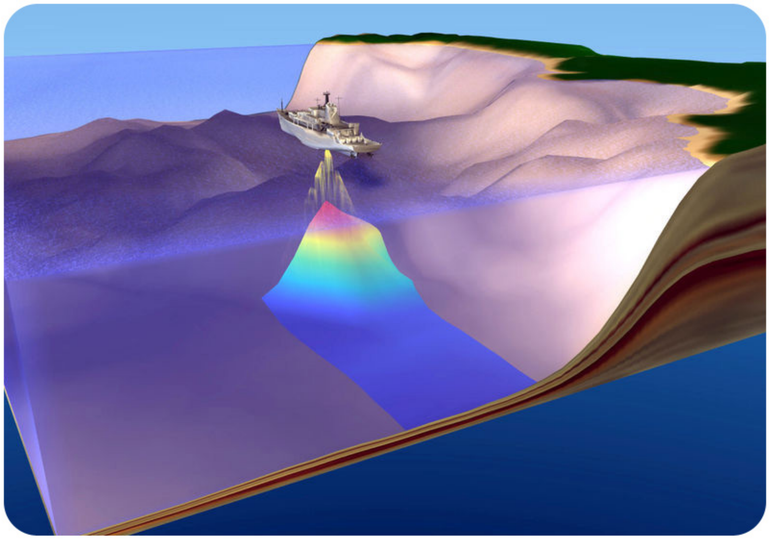

FIGURE 3.9
A ship sends out sound waves to create a picture of the seafloor below it. The echo sounder pictured has many beams and as a result it creates a three dimensional map of the seafloor beneath the ship. Early echo sounders had only a single beam and created a line of depth measurements.

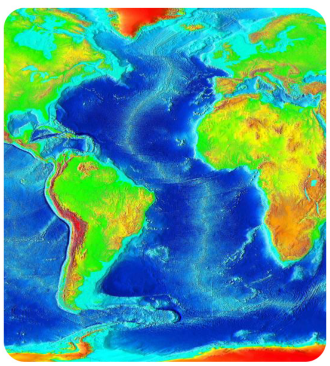

FIGURE 3.10
A modern map of the eastern Pacific and Atlantic Oceans. Darker blue indicates deeper seas. A mid-ocean ridge can be seen running through the center of the Atlantic Ocean. Deep sea trenches are found along the west coast of Central and South America and in the mid-Atlantic, east of the southern tip of South America. Isolated mountains and flat, featureless regions can also be spotted.

Deep sea trenches are found near chains of active volcanoes. These volcanoes can be at the edges of continents or in the oceans. **Trenches** are the deepest places on Earth. The deepest trench is the Mariana Trench in the southwestern Pacific Ocean. This trench plunges about 11 kilometers (35,840 feet) beneath sea level. The ocean floor does have lots of flat areas. These abyssal plains are like the scientists had predicted.

Seafloor Magnetism

Warships also carried magnetometers. They were also used to search for submarines. The magnetometers also revealed a lot about the magnetic properties of the seafloor.

Polar Reversals

Indeed, scientists discovered something astonishing. Many times in Earth's history, the magnetic poles have switched positions. North becomes south and south becomes north! When the north and south poles are aligned as they are now, geologists say it is normal polarity. When they are in the opposite position, they say that it is reversed polarity.

Magnetic Stripes

Scientists were also surprised to discover a pattern of stripes of normal and reversed polarity. These stripes surround the mid-ocean ridges. There is one long stripe with normal magnetism at the top of the ridge. Next to that stripe are two long stripes with reversed magnetism. One is on either side of the normal stripe. Next come two normal stripes and then two reversed stripes, and so on across the ocean floor. The magnetic stripes end abruptly at the edges of continents. Sometimes the stripes end at a deep sea trench (**Figure** 3.11).

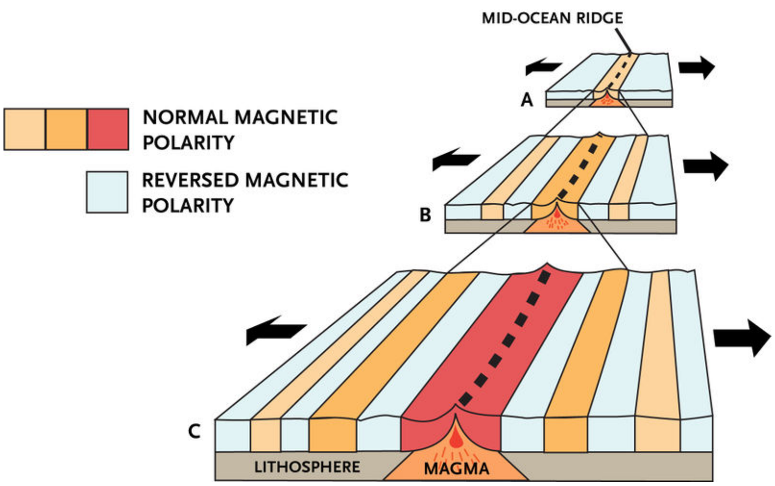

FIGURE 3.11

Scientists found that magnetic polarity in the seafloor was normal at mid-ocean ridges but reversed in symmetrical patterns away from the ridge center. This normal and reversed pattern continues across the seafloor.

Seafloor Ages

The scientists used geologic dating techniques on seafloor rocks. They found that the youngest rocks on the seafloor were at the mid-ocean ridges. The rocks get older with distance from the ridge crest. The scientists were surprised to find that the oldest seafloor is less than 180 million years old. This may seem old, but the oldest continental crust is around 4 billion years old.

Scientists also discovered that the mid-ocean ridge crest is nearly sediment free. The crust is also very thin there. With distance from the ridge crest, the sediments and crust get thicker. This also supports the idea that the youngest rocks are on the ridge axis and that the rocks get older with distance away from the ridge (**Figure** 3.12). Something causes the seafloor to be created at the ridge crest. The seafloor is also destroyed in a relatively short time.

The Seafloor Spreading Hypothesis

The **seafloor spreading** hypothesis brought all of these observations together in the early 1960s. Hot mantle material rises up at mid-ocean ridges. The hot magma erupts as lava. The lava cools to form new seafloor. Later, more lava erupts at the ridge. The new lava pushes the seafloor that is at the ridge horizontally away from ridge axis. The seafloor moves!

In some places, the oceanic crust comes up to a continent. The moving crust pushes that continent away from the ridge axis as well. If the moving oceanic crust reaches a deep sea trench, the crust sinks into the mantle. The creation and destruction of oceanic crust is the reason that continents move. Seafloor spreading is the mechanism that Wegener was looking for!

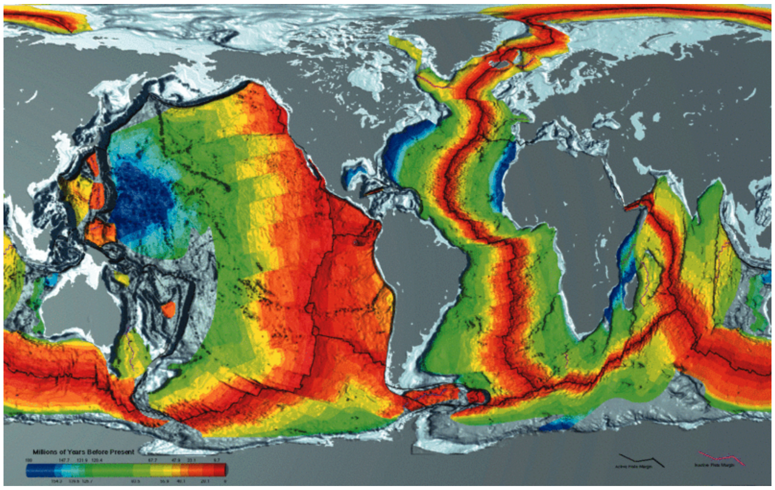

FIGURE 3.12
Seafloor is youngest near the mid-ocean ridges and gets progressively older with distance from the ridge. Orange areas show the youngest seafloor. The oldest seafloor is near the edges of continents or deep sea trenches.

Lesson Summary

- Using technologies developed during World War II, scientists were able to gather data that allowed them to recognize that seafloor spreading is the mechanism for Wegener's drifting continents.
- Maps of the ocean floor showed high mountain ranges and deep trenches.
- Changes in Earth's magnetic field give clues as to how seafloor forms and the importance of mid-ocean ridges in the creation of oceanic crust.
- Seafloor spreading processes create new oceanic crust at mid-ocean ridges and destroy older crust at deep sea trenches.

Lesson Review Questions

Recall

1. Describe a mid-ocean ridge. What geological processes are happening there?

2. Describe deep sea trenches and abyssal plains and their relative ages.

Apply Concepts

3. Using what you've learned about echo sounders, how do bats and dolphins use sound waves to create pictures of their worlds?

Think Critically

4. Why is the oceanic crust so young? Why is the continental crust so old?

5. Describe how continents move across the ocean basins.

6. Where would plate tectonics theory be if World War II hasn't happened?

Points to Consider

- How were the technologies that were developed during World War II used by scientists for the development of the seafloor spreading hypothesis?
- In what two ways did magnetic data lead scientists to understand more about plate tectonics?
- How does seafloor spreading provide a mechanism for continental drift?
- Describe the features of the North Pacific Ocean basin described in terms of seafloor spreading.

3.4 Theory of Plate Tectonics

Lesson Objectives

- Describe what a plate is and how scientists can recognize its edges.
- Explain how the plates move by convection in the mantle.
- Describe the three types of plate boundaries and the features of each type of boundary.
- Describe how plate tectonics processes lead to changes in Earth's surface features.

Vocabulary

- continental rifting
- convergent plate boundary
- divergent plate boundary
- intraplate activity
- island arc
- plate
- plate boundary
- subduction
- subduction zone
- transform fault
- transform plate boundary

Introduction

The theory of plate tectonics explains most of the features of Earth's surface. Plate tectonics helps us to understand where and why mountains form. Using the theory, we know where new ocean floor will be created and where it will be destroyed. We know why earthquakes and volcanic eruptions happen where they do. We even can search for mineral resources using information about past plate motions. Plate tectonics is the key that unlocks many of the mysteries of our amazing planet.

Earth's Tectonic Plates

The Cold War helped scientists to learn more about our planet. They set up seismograph networks during the 1950s and early 1960s. The purpose was to see if other nations were testing atomic bombs. Of course, at the same time, the seismographs were recording earthquakes.

Earthquake Locations

The scientists realized that the earthquakes were most common in certain areas. In the oceans, they were found along mid-ocean ridges and deep sea trenches. Earthquakes and volcanoes were common all around the Pacific Ocean. They named this region the Pacific Ring of Fire (**Figure** 3.13). Earthquakes are also common in the world's highest mountains, the Himalaya Mountains of Asia. The Mediterranean Sea also has many earthquakes.

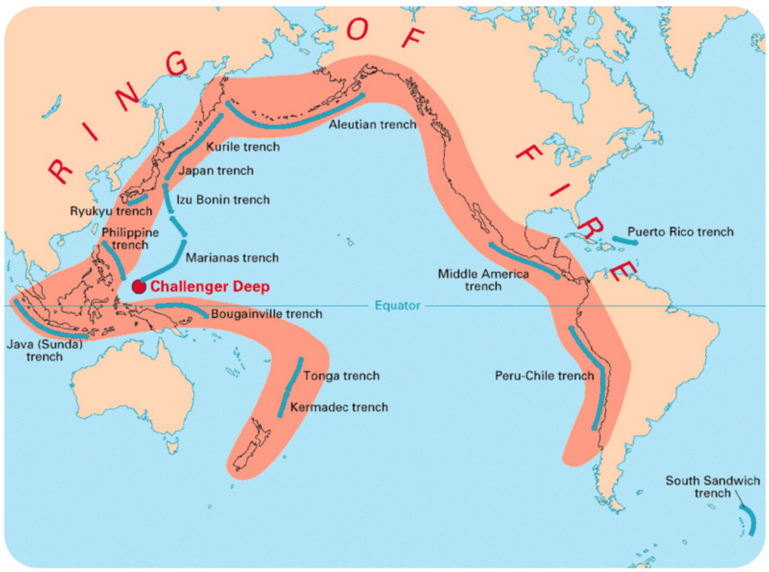

FIGURE 3.13
The Ring of Fire that circles the Pacific Ocean is where the most earthquakes and volcanic eruptions take place.

Earthquakes and Plate Boundaries

Earthquakes are used to identify plate boundaries (**Figure** 3.14). When earthquake locations are put on a map, they outline the **plates**. The movements of the plates are called plate tectonics.

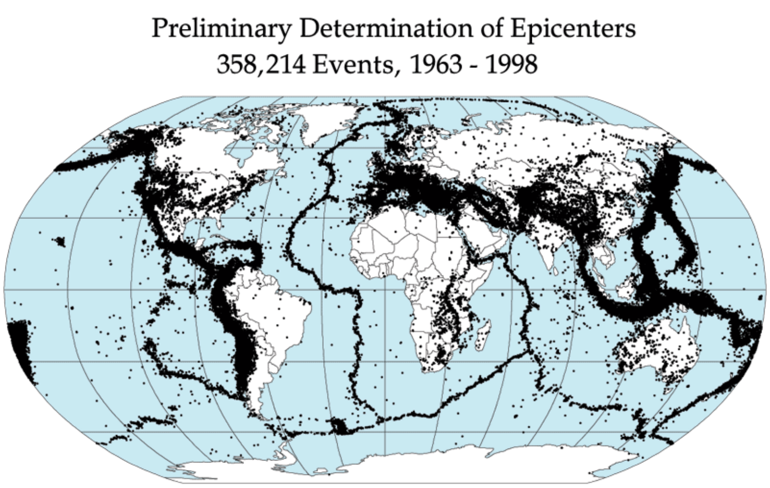

FIGURE 3.14
A map of earthquake epicenters shows that earthquakes are found primarily in lines that run up the edges of some continents, through the centers of some oceans, and in patches in some land areas.

The lithosphere is divided into a dozen major and several minor plates. Each plate is named for the continent or ocean basin it contains. Some plates are made of all oceanic lithosphere. A few are all continental lithosphere. But

most plates are made of a combination of both.

Scientists have determined the direction that each plate is moving (**Figure** 3.15). Plates move around the Earth's surface at a rate of a few centimeters a year. This is about the same rate fingernails grow.

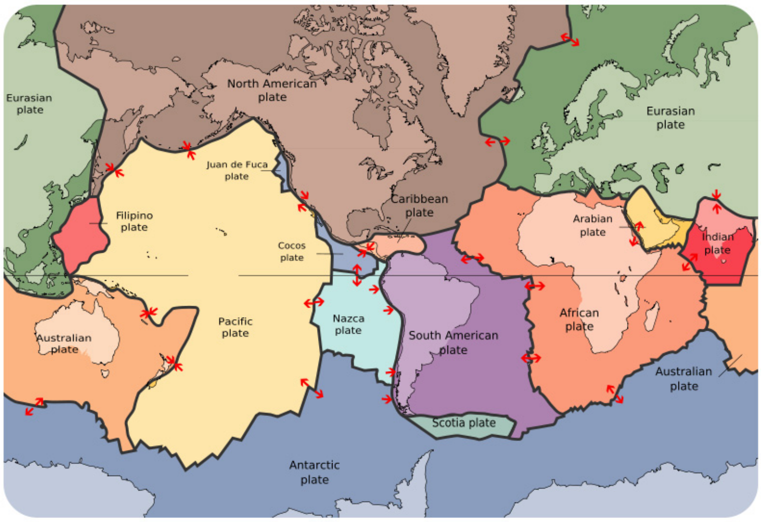

FIGURE 3.15
Earth's plates are shown in different colors. Arrows show the direction the plate is moving.

How Plates Move

Convection within the Earth's mantle causes the plates to move. Mantle material is heated above the core. The hot mantle rises up towards the surface (**Figure** 3.16). As the mantle rises it cools. At the surface the material moves horizontally away from a mid-ocean ridge crest. The material continues to cool. It sinks back down into the mantle at a deep sea trench. The material sinks back down to the core. It moves horizontally again, completing a convection cell.

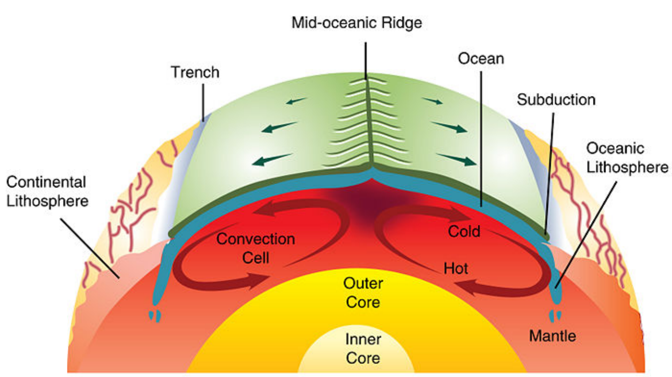

FIGURE 3.16
Plates move for two reasons. Upwelling mantle at the mid-ocean ridge pushes plates outward. Cold lithosphere sinking into the mantle at a subduction zone pulls the rest of the plate down with it.

Plate Boundaries

Plate boundaries are where two plates meet. Most geologic activity takes place at plate boundaries. This activity includes volcanoes, earthquakes, and mountain building. The activity occurs as plates interact. How can plates interact? Plates can move away from each other. They can move toward each other. Finally, they can slide past each other.

These are the three types of plate boundaries:

- **Divergent plate boundaries**: the two plates move away from each other.
- **Convergent plate boundaries**: the two plates move towards each other.
- **Transform plate boundaries**: the two plates slip past each other.

The features that form at a plate boundary are determined by the direction of plate motion and by the type of crust at the boundary.

Divergent Plate Boundaries

Plates move apart at divergent plate boundaries. This can occur in the oceans or on land.

Mid-ocean Ridges

Plates move apart at mid-ocean ridges. Lava rises upward, erupts, and cools. Later, more lava erupts and pushes the original seafloor outward. This is seafloor spreading. Seafloor spreading forms new oceanic crust. The rising magma causes earthquakes. Most mid-ocean ridges are located deep below the sea. The island of Iceland sits right on the Mid-Atlantic ridge (**Figure** 3.17).

FIGURE 3.17
The rift valley in Iceland that is part of the Mid-Atlantic Ridge is seen in this photo.

Continental Rifting

A divergent plate boundary can also occur within a continent. This is called **continental rifting** (**Figure** 3.18). Magma rises beneath the continent. The crust thins, breaks, and then splits apart. This first produces a rift valley. The East African Rift is a rift valley. Eastern Africa is splitting away from the African continent. Eventually, as the continental crust breaks apart, oceanic crust will form. This is how the Atlantic Ocean formed when Pangaea broke up.

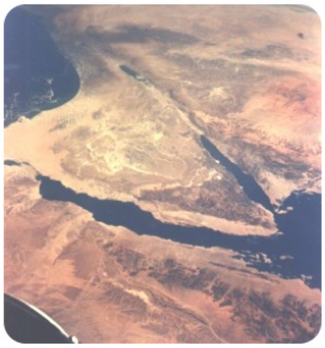

FIGURE 3.18

The Arabian, Indian, and African plates are rifting apart, forming the Great Rift Valley in Africa. The Dead Sea fills the rift with seawater.

Convergent Plate Boundaries

A convergent plate boundary forms where two plates collide. That collision can happen between a continent and oceanic crust, between two oceanic plates, or between two continents. Oceanic crust is always destroyed in these collisions.

Ocean-Continent Convergence

Oceanic crust may collide with a continent. The oceanic plate is denser, so it undergoes **subduction**. This means that the oceanic plate sinks beneath the continent. This occurs at an ocean trench (**Figure** 3.19). **Subduction zones** are where subduction takes place.

As you would expect, where plates collide there are lots of intense earthquakes and volcanic eruptions. The subducting oceanic plate melts as it reenters the mantle. The magma rises and erupts. This creates a volcanic mountain range near the coast of the continent. This range is called a **volcanic arc**. The Andes Mountains, along the western edge of South America, are a volcanic arc (**Figure** 3.20).

Ocean-Ocean Convergence

Two oceanic plates may collide. In this case, the older plate is denser. This plate subducts beneath the younger plate. As the subducting plate is pushed deeper into the mantle, it melts. The magma this creates rises and erupts. This forms a line of volcanoes, known as an **island arc** (**Figure** 3.21). Japan, Indonesia, the Philippine Islands, and the Aleutian Islands of Alaska are examples of island arcs (**Figure** 3.22).

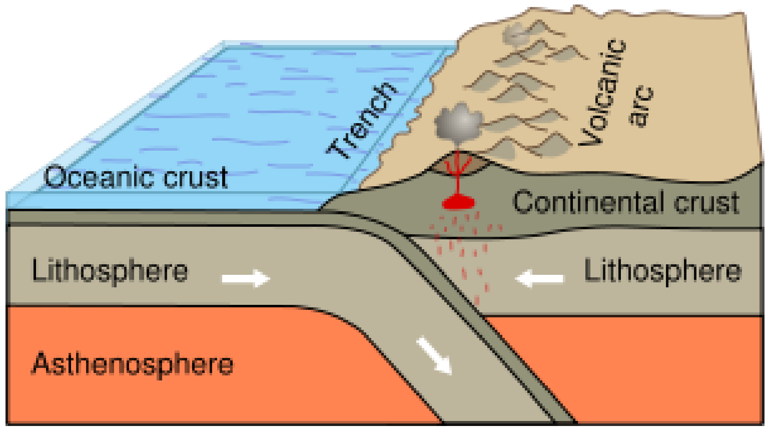

FIGURE 3.19
Subduction of an oceanic plate beneath a continental plate forms a line of volcanoes known as a continental arc and causes earthquakes.

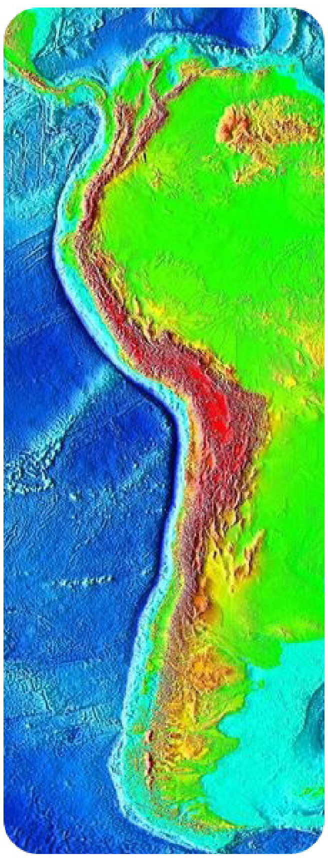

FIGURE 3.20
A relief map of South America shows the trench west of the continent. The Andes Mountains line the western edge of South America.

Continent-Continent Convergence

Continental lithosphere is low in density and very thick. Continental lithosphere cannot subduct. So when two continental plates collide, they just smash together, just like if you put your hands on two sides of a sheet of paper and bring your hands together. The material has nowhere to go but up (**Figure** 3.23)! Earthquakes and metamorphic rocks result from the tremendous forces of the collision. But the crust is too thick for magma to get through, so there are no volcanoes.

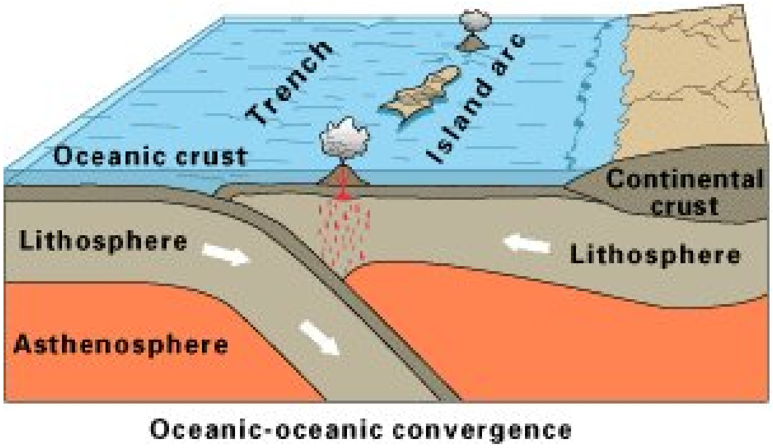

FIGURE 3.21
A convergent plate boundary subduction zone between two plates of oceanic lithosphere. Melting of the subducting plate causes volcanic activity and earthquakes.

FIGURE 3.22
The Aleutian Islands that border southern Alaska are an island arc. In this winter image from space, the volcanoes are covered with snow.

Mountain Building

Continent-continent convergence creates some of the world's largest mountains ranges. The Himalayas (**Figure** 3.24) are the world's tallest mountains. They are forming as two continents collide. The Appalachian Mountains are the remnants of a larger mountain range. This range formed from continent-continent collisions in the time of Pangaea.

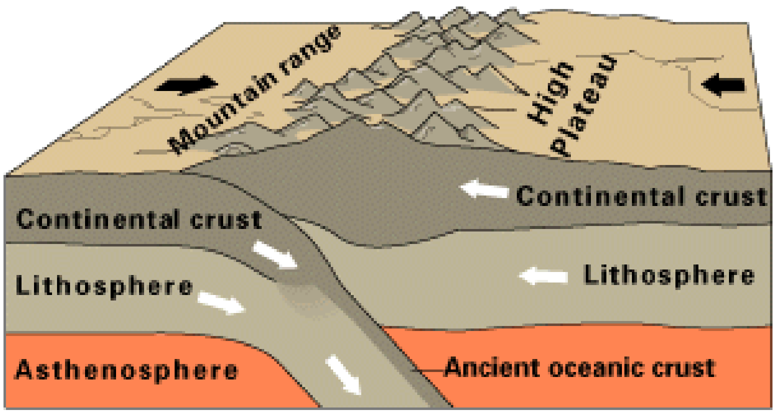

FIGURE 3.23
When two plates of continental crust collide, the material pushes upward, forming a high mountain range. The remnants of subducted oceanic crust remain beneath the continental convergence zone.

FIGURE 3.24
The Karakoram Range is part of the Himalaya Mountains. K2, pictured here, is the second highest mountain the world at over 28,000 feet. The number and height of mountains is impressive.

Transform Plate Boundaries

Two plates may slide past each other in opposite directions. This is called a transform plate boundary. These plate boundaries experience massive earthquakes. The world's best known transform fault is the San Andreas Fault in California (**Figure** 3.25). At this fault, the Pacific and North American plates grind past each other. Transform plate boundaries are most common as offsets along mid-ocean ridges.

Transform plate boundaries are different from the other two types. At divergent plate boundaries, new oceanic crust is formed. At convergent boundaries, old oceanic crust is destroyed. But at transform plate boundaries, crust is not created or destroyed.

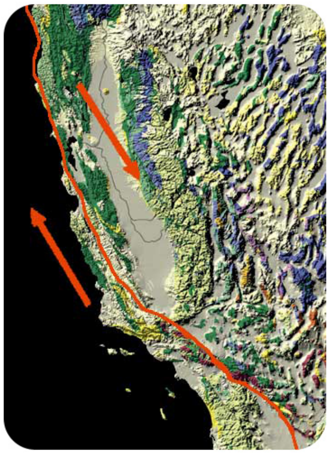

FIGURE 3.25
The red line is the San Andreas Fault. On the left is the Pacific Plate, which is moving northeast. On the right is the North American Plate, which is moving southwest. The movement of the plates is relative to each other.

Earth's Changing Surface

Knowing where plate boundaries are helps explain the locations of landforms and types of geologic activity. The activity can be current or old.

Active Plate Margins

Western North America has volcanoes and earthquakes. Mountains line the region. California, with its volcanoes and earthquakes, is an important part of the Pacific Ring of Fire. This is the boundary between the North American and Pacific Plates.

Passive Plate Margins

Mountain ranges also line the eastern edge of North America. But there are no active volcanoes or earthquakes. Where did those mountains come from? These mountains formed at a convergent plate boundary when Pangaea came together. About 200 million years ago these mountains were similar to the Himalayas today (**Figure** 3.26)! There were also earthquakes.

The Supercontinent Cycle

Scientists think that Pangaea was not the first supercontinent. There were others before it. The continents are now moving together. This is because of subduction around the Pacific Ocean. Eventually, the Pacific will disappear and a new supercontinent will form. This won't be for hundreds of millions of years. The creation and breakup of a supercontinent takes place about every 500 million years.

Intraplate Activity

Most geological activity takes place at plate boundaries. But some activity does not. Much of this **intraplate activity** is found at hot spots. Hotspot volcanoes form as plumes of hot magma rise from deep in the mantle.

FIGURE 3.26
The White Mountains in New Hampshire are part of the Appalachian province. The mountains are only around 6,000 feet high.

Hotspots in the Oceans

A chain of volcanoes forms as an oceanic plate moves over a hot spot. This is how it happens. A volcano forms over the hotspot. Since the plate is moving, the volcano moves off of the hotspot. When the hotspot erupts again, a new volcano forms over it. This volcano is in line with the first. Over time, there is a line of volcanoes. The youngest is directly above the hot spot. The oldest is the furthest away (**Figure** 3.27).

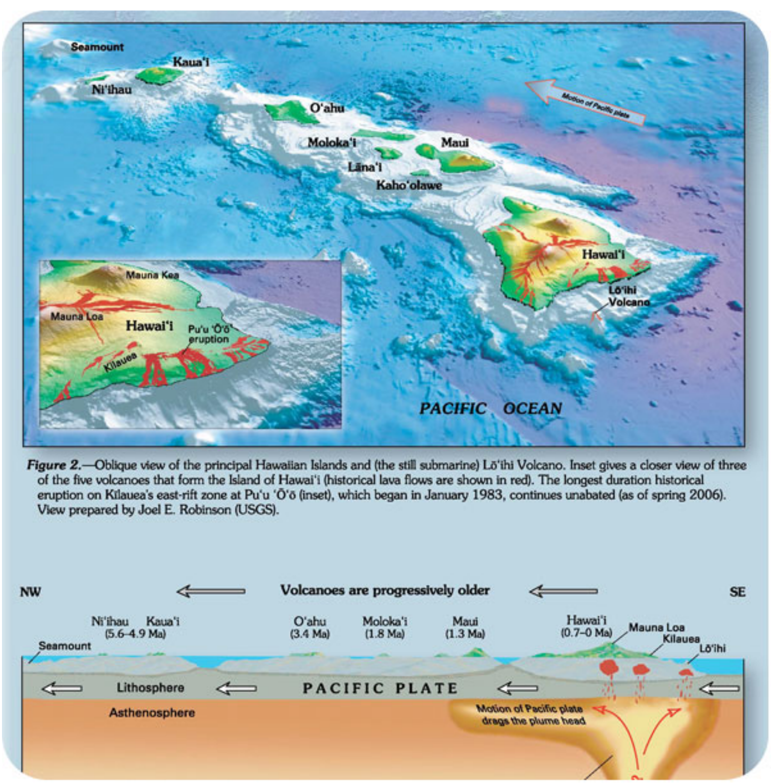

FIGURE 3.27
This view of the Hawaiian islands shows the youngest islands in the southeast and the oldest in the northwest. Kilauea volcano, which makes up the southeastern side of the Big Island of Hawaii, is located above the Hawaiian hotspot.

The Hawaii-Emperor chain of volcanoes formed over the Hawaiian Hotspot. The Hawaiian Islands formed most

recently. Kilauea volcano is currently erupting. It is over the hotspot. The Emperor Seamounts are so old they no longer reach above sea level. The oldest of the Emperor Seamounts is about to subduct into the Aleutian trench off of Alaska. Geologists use hotspot chains to tell the direction and the speed a plate is moving.

Hotspots Beneath Continents

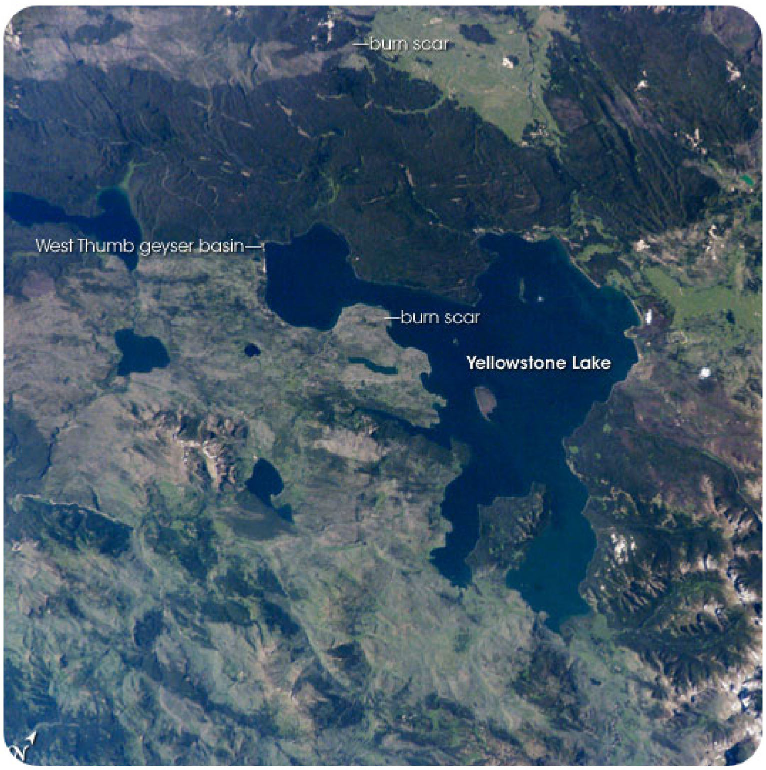

FIGURE 3.28
Yellowstone Lake lies at the center of a giant caldera. This hole in the ground was created by enormous eruptions at the Yellowstone hotspot. The hotspot lies beneath Yellowstone National Park.

Hot spots are also found under the continental crust. Since it is more difficult for magma to make it through the thick crust, they are much less common. One exception is the Yellowstone hotspot (**Figure** 3.28). This hotspot is very active. In the past, the hotspot produced enormous volcanic eruptions. Now its activity is best seen in the region's famous geysers.

Lesson Summary

- Convection in the mantle drives the movement of the plates of lithosphere over the Earth's surface. New oceanic crust forms at the ridge and pushes the older seafloor away from the ridge horizontally.
- Plates interact at three different types of plate boundaries: divergent, convergent and transform fault boundaries, where most of the Earth's geologic activity takes place.
- These processes acting over long periods of time are responsible for the geographic features we see.

Lesson Review Questions

Recall

1. Name the three types of plate boundaries? Which has volcanoes? Which has earthquakes? Which has mountain building?

Apply Concepts

2. Describe convection. How does this work to create plate boundaries?

Think Critically

3. Make some generalizations about which types of plate boundaries have volcanoes and which have earthquakes. Could you look at a plate boundary and determine what geological activity there would be?

4. Why is continental crust thicker than oceanic crust? Why is oceanic crust relatively thin?

Points to Consider

- On the map in **Figure** 3.15, the arrows show the directions that the plates are going. The Atlantic has a mid-ocean ridge, where seafloor spreading is taking place. The Pacific Ocean has many deep sea trenches, where subduction is taking place. What is the future of the Atlantic plate? What is the future of the Pacific plate?
- Using your hands and words, explain to someone how plate tectonics works. Be sure you describe how continents drift and how seafloor spreading provides a mechanism for continental movement.
- Now that you know about plate tectonics, where do you think would be a safe place to live if you wanted to avoid volcanic eruptions and earthquakes?

3.5 References

1. Christopher Auyeung and Laura Guerin. CK-12 Foundation . CC BY-NC 3.0
2. Flickr:herval. http://commons.wikimedia.org/wiki/File:Willamette_meteorite_AMNH.jpg . CC BY 2.0
3. Laura Guerin. CK-12 Foundation . CC BY-NC 3.0
4. Christopher Auyeung. CK-12 Foundation . CC BY-NC 3.0
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CHAPTER 4 MS Earthquakes

Chapter Outline

After the 1906 San Francisco earthquake, much of the city was destroyed. Besides the loss of buildings to ground shaking, a massive fire after the quake burned down much of what was left. The experiences people gain from earthquakes like these allow engineers and city planners to create safer buildings. Earthquakes will always happen. The damage that is done to property and lives can be changed.

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4.1 Stress in Earth's Crust

Lesson Objectives

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

Vocabulary

- anticline
- basin
- compression
- confining stress
- deform
- dip-slip fault
- dome
- fault zone
- fold
- footwall
- fracture
- hanging wall
- joint
- monocline
- normal fault
- reverse fault
- shear
- slip
- stress
- strike-slip fault
- syncline
- tension
- thrust fault

Introduction

When plates collide, move apart, and slide past each other, lots of things happen. Nearly all earthquakes, volcanic eruptions, and mountain building happens at plate boundaries.

When plates are pushed or pulled, the rock is subjected to stress. Stress can cause a rock to change shape or to

break. When a rock bends without breaking, it folds. When the rock breaks, it fractures. Mountain building and earthquakes are some of the responses rocks have to stress.

Causes and Types of Stress

Stress is the force applied to a rock. There are four types of stresses:

- **Confining stress** happens as weight of all the overlying rock pushes down on a deeply buried rock. The rock is being pushed in from all sides, which compresses it. The rock will not deform because there is no place for it to move.
- **Compression** stress squeezes rocks together. Compression causes rocks to fold or fracture (**Figure** 4.1). When two cars collide, compression causes them to crumple. Compression is the most common stress at convergent plate boundaries.

FIGURE 4.1
Stress caused these rocks to fracture.

- **Tension** stress pulls rocks apart. Tension causes rocks to lengthen or break apart. Tension is the major type of stress found at divergent plate boundaries.
- **Shear** stress happens when forces slide past each other in opposite directions (**Figure** 4.2). This is the most common stress found at transform plate boundaries.

The amount of stress on a rock may be greater than the rock's strength. In that case, the rock will change and **deform** (**Figure** 4.3). Deep within the Earth, the pressure is very great. A rock behaves like a stretched rubber band. When the stress stops, the rock goes back to its original shape. If more stress is applied to the rock, it bends and flows. It does not return to its original shape. Near the surface, if the stress continues, the rock will **fracture** and break.

Geologic Structures

Sedimentary rocks are formed in horizontal layers. This is magnificently displayed around the southwestern United States. The arid climate allows rock layers to be well exposed (**Figure** 4.4). The lowest layers are the oldest and the higher layers are younger.

Folds, joints and faults are caused by stresses. **Figure** 4.5 shows joints in a granite hillside.

If a sedimentary rock is tilted or folded, we know that stresses have changed the rock (**Figure** 4.6).

FIGURE 4.2
This rock has undergone shearing. The pencil is pointing to a line. Stresses forced rock on either side of that line to go in opposite directions.

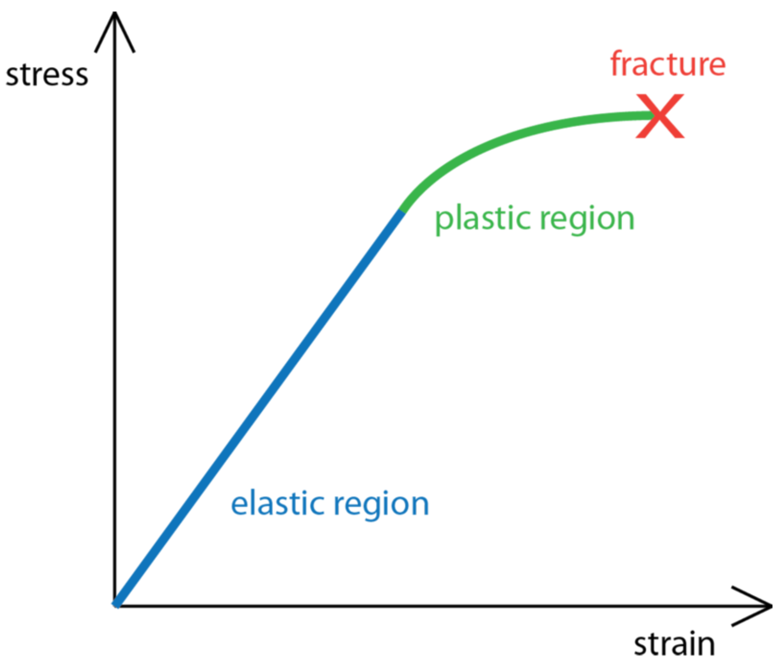

FIGURE 4.3
With increasing stress, the rock deforms and may eventually fracture.

Folds

Deep within the Earth, as plates collide, rocks crumple into **folds**. You can model these folds by placing your hands on opposite edges of a piece of cloth and pushing your hands together. In sedimentary rocks, you can easily trace the folding of the layers. In the **Figure** 4.6, the rock layers are no longer horizontal. They tilt downhill from right to left in a monocline. Once rocks are folded, they do not return to their original shape.

There are three types of folds: monoclines, anticlines, and synclines. A **monocline** is a simple "one step" bend in the rock layers (**Figure** 4.7). In a monocline, the oldest rocks are still at the bottom and the youngest are at the top.

An **anticline** is a fold that arches upward. The rocks dip away from the center of the fold (**Figure** 4.8). The oldest

FIGURE 4.4
Layers of different types of rocks are exposed in this photo from Grand Staircase-Escalante National Monument. White layers of limestone are hard and form cliffs. Red layers of shale are flakier and form slopes.

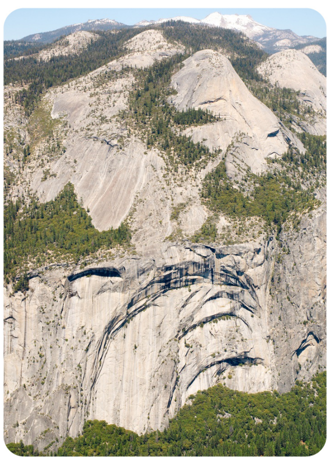

FIGURE 4.5
Joints in this granite created a zone of weakness. The rock below the joints fell, leaving scars in this hillside.

rocks are found at the center of an anticline. The youngest rocks are draped over them at the top of the structure. When upward folding rocks form a circular structure, that structure is called a **dome**. If the top of the dome is eroded off, the oldest rocks are exposed at the center.

A **syncline** is a fold that bends downward (**Figure** 4.9). In a syncline, the youngest rocks are at the center. The oldest rocks are at the outside edges. When rocks bend downward in a circular structure, it is called a **basin**. If the rocks are eroded, the youngest rocks are at the center. Basins can be enormous, like the Michigan Basin.

Faults

With enough stress, a rock will fracture, or break. The fracture is called a **joint** if the rock breaks but doesn't move, as shown in **Figure** 4.10.

If the rocks on one or both sides of a fracture move, the fracture is called a **fault** (**Figure** 4.11). Faults can occur alone or in clusters, creating a **fault zone**. Earthquakes happen when rocks break and move suddenly. The energy released causes an earthquake.

Slip is the distance rocks move along a fault, as one block of rock moves past the other. The angle of a fault is called

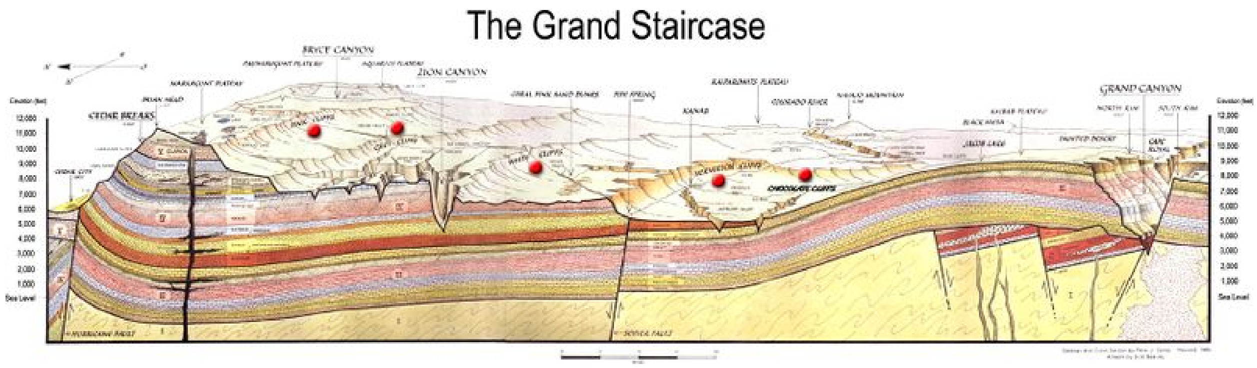

FIGURE 4.6

This is a geologic cross section of the Grand Staircase in Utah. A small fold, called an syncline, is revealed at the left of the diagram.

FIGURE 4.7

The rock layers in the center right are tilted in one direction, forming a monocline.

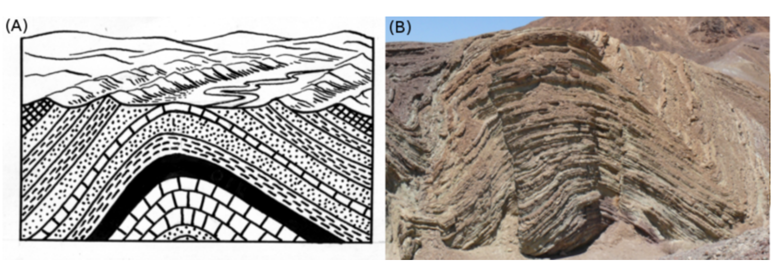

FIGURE 4.8

An anticline is a convex upward fold, as shown in (A). An anticline is well displayed in (B), which was taken at Calico Ghost Town, California.

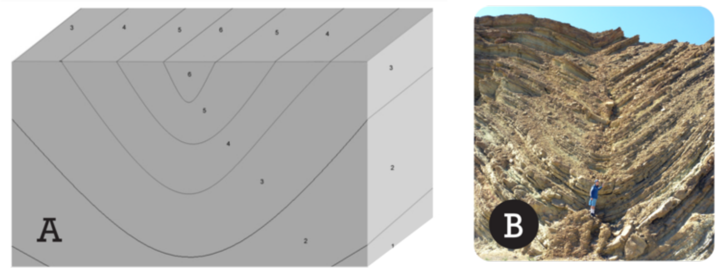

FIGURE 4.9
(A) A syncline is a concave downward fold. (B) This syncline is seen at Calico Ghost Town near Barstow, California.

FIGURE 4.10
Joints in boulders in the Arizona desert. The rock on either side of the joints has not moved.

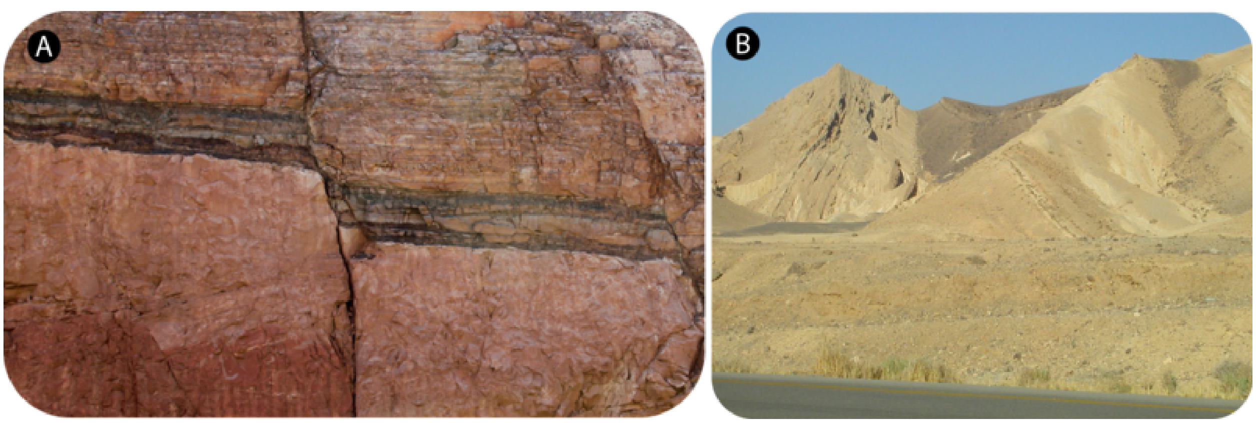

FIGURE 4.11
(A) This image shows a small fault. The black rock layer is not a line because a fault has broken it. Rock on each side of the fault has moved. (B) A large fault runs between the lighter colored rock on the left and the darker colored rock on the right. There has been so much movement along the fault that the darker rock doesn't resemble anything around it.

the fault's "dip." If the fault dips at an angle, the fault is a **dip-slip fault**.

Imagine you are standing on a road looking at the fault. The **hanging wall** is the rock that overlies the fault, while the **footwall** is beneath the fault. If you are walking along a fault, the hanging wall is above you and the footwall is where your feet would be. Miners often extract mineral resources along faults. They used to hang their lanterns above their heads. That is why these layers were called the hanging wall.

In **normal faults**, the hanging wall drops down relative to the footwall. Normal faults are caused by tension that pulls the crust apart, causing the hanging wall to slide down. Normal faults can build huge mountain ranges in regions experiencing tension (**Figure** 4.12).

FIGURE 4.12

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

When compression squeezes the crust into a smaller space, the hanging wall pushes up relative to the footwall. This creates a **reverse fault**. A **thrust fault** is a type of reverse fault where the angle is nearly horizontal. Rocks can slip many miles along thrust faults (**Figure** 4.13).

Strike-Slip

A **strike-slip fault** is a dip-slip fault where the dip of the fault plane is vertical. Strike-slip faults result from shear stresses. If you stand with one foot on each side of a strike-slip fault, one side will be moving toward you while the other side moves away from you. If your right foot moves toward you, the fault is known as a right-lateral strike-slip fault. If your left foot moves toward you, the fault is a left-lateral strike-slip fault (**Figure** 4.14).

San Andreas Fault

The San Andreas Fault in California is a right-lateral strike-slip fault (**Figure** 4.15). It is also a transform fault because the San Andreas is a plate boundary. As you can see, California will not fall into the ocean someday. The land west of the San Andreas Fault is moving northeastward, while the North American plate moves southwest. Someday, millions of years from now, Los Angeles will be a suburb of San Francisco!

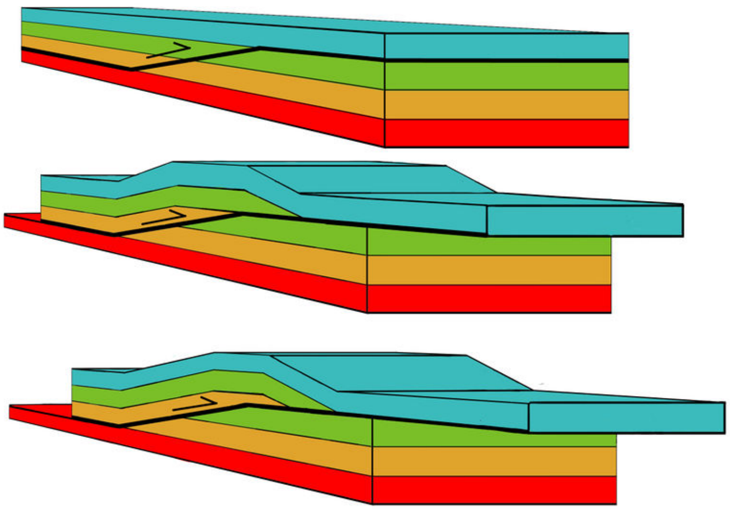

FIGURE 4.13
In this thrust fault, the rock on the left is thrust over the rock on the right.

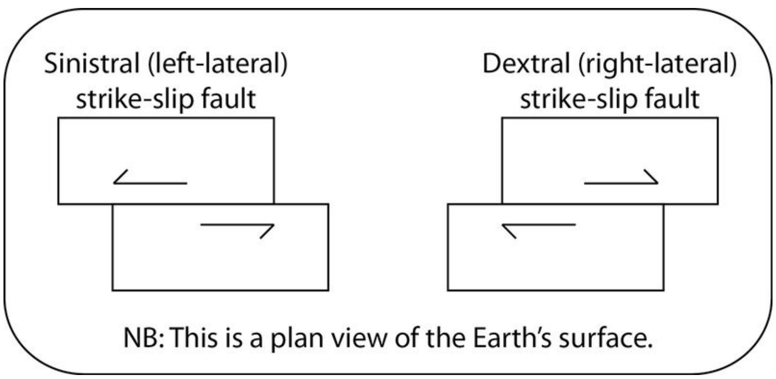

FIGURE 4.14
Diagram of strike-slip faults.

FIGURE 4.15
The San Andreas Fault is visible from the air in some locations. This transform fault separates the Pacific plate on the west and the North American plate on the east.

Stress and Mountain Building

Many processes create mountains. Most mountains form along plate boundaries. A few mountains may form in the middle of a plate. For example, huge volcanoes are mountains formed at hotspots within the Pacific Plate.

Continent-Continent Convergence

Most of the world's largest mountains form as plates collide at convergent plate boundaries. Continents are too buoyant to get pushed down into the mantle. So when the plates smash together, the crust crumples upwards. This creates mountains. Folding and faulting in these collision zones makes the crust thicker.

The world's highest mountain range, the Himalayas, is growing as India collides with Eurasia. About 80 million years ago, India was separated from Eurasia by an ocean (**Figure** 4.16). As the plates collided, pieces of the old seafloor were forced over the Asian continent. This old seafloor is now found high in the Himalayas (**Figure** 4.17).

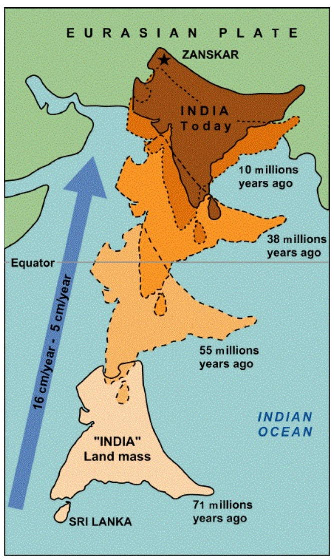

FIGURE 4.16
As India rams into Eurasia, the Himalaya Mountains rise.

Oceanic Plate Subduction

Volcanic mountain ranges form when oceanic crust is pushed down into the mantle at convergent plate boundaries. The Andes Mountains are a chain of coastal volcanic mountains. They are forming as the Nazca plate subducts beneath the South American plate (**Figure** 4.18).

Rifting

Mid-ocean ridges form at divergent plate boundaries. As the ocean floor separates an enormous line of volcanoes is created.

When continental crust is pulled apart, it breaks into blocks. These blocks of crust are separated by normal faults. The blocks slide up or down. The result is alternating mountain ranges and valleys. This topography is known as basin-and-range (**Figure** 4.19). The area near Death Valley, California is the center of a classic basin-and-range province (**Figure** 4.20).

FIGURE 4.17
The Himalayas.

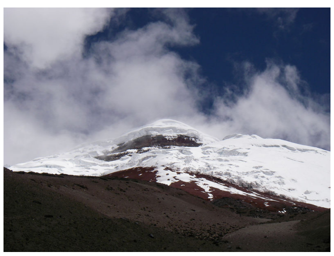

FIGURE 4.18
Cotopaxi is in the Andes Mountains of Ecuador. The 19,300 foot tall mountain is the highest active volcano in the world.

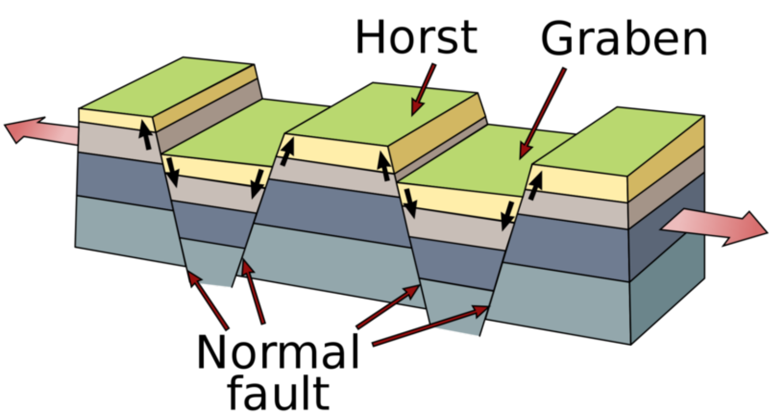

FIGURE 4.19
This diagram shows how a basin-and-range forms.

Lesson Summary

- Stress is the force applied to a rock, which can cause the rock to change. The three main types of stress go along with the three types of plate boundaries. Compression is common at convergent boundaries, tension at divergent boundaries, and shear at transform boundaries.
- Rocks can bend and fold. Rocks can also fracture and break. Movement along a fracture produces a fault. The two main types of faults are dip-slip and strike-slip.

FIGURE 4.20
This photograph was taken from a basin with a range in the distance near Death Valley, California.

- In dip-slip faults, the angle of the fault plane is at an angle. In strike-slip faults, the fault plane is vertical.
- The world's largest mountains grow at convergent plate boundaries, primarily by thrust faulting and folding.

Lesson Review Questions

Recall

1. What causes confining stress? What type of deformation is caused by confining stress?

2. What causes compression stress? What type of deformation is caused by compression stress?

3. What causes tension stress? What type of deformation is caused by tension stress?

4. What causes shear stress? What type of deformation is caused by shear stress?

Apply Concepts

5. What happens when a rock deforms plastically? For how long does this happen? What factors should be considered when answering that last question?

6. Why is California know for having so many large earthquakes?

7. Imagine that you find a sequence of rock layers with the older rocks at the top and the younger rocks at the bottom. How could this have happened?

Think Critically

8. Identify all of the structures that you can find in the image below.

9. In the image above, where are the oldest rocks in each structure? Where are the youngest rocks?

Points to Consider

- Think about stresses in the ocean basins. Where in the ocean basins are plates pulling apart? Where do plates come together?
- Earthquakes are primarily the result of plate tectonic motions. What type of stress would cause earthquakes at each of the three types of plate boundaries?
- Which type of plate boundary do you think has the most dangerous earthquakes? How do earthquakes cause the greatest damage?

4.2 Nature of Earthquakes

Lesson Objectives

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

Vocabulary

- amplitude
- body waves
- crest
- earthquake
- elastic rebound theory
- epicenter
- focus
- Love waves
- primary waves (P-waves)
- Rayleigh waves
- secondary waves (S-waves)
- surface waves
- trough
- tsunami
- wavelength

Introduction

An **earthquake** is sudden ground movement. This movement is caused by the sudden release of the energy stored in rocks. An earthquake happens when so much stress builds up in the rocks that the rocks break. An earthquake's energy is transmitted by seismic waves. Each year, there are more than 150,000 earthquakes strong enough to be felt by people. An amazing 900,000 are recorded by seismometers.

Causes of Earthquakes

Almost all earthquakes occur at plate boundaries. All types of plate boundaries have earthquakes. Convection within the Earth causes the plates to move. As the plates move, stresses build. When the stresses build too much,

the rocks break. The break releases the energy that was stored in the rocks. The sudden release of energy creates an earthquake. During an earthquake the rocks usually move several centimeters or rarely as much as a few meters. **Elastic rebound theory** describes how earthquakes occur (**Figure** 4.21).

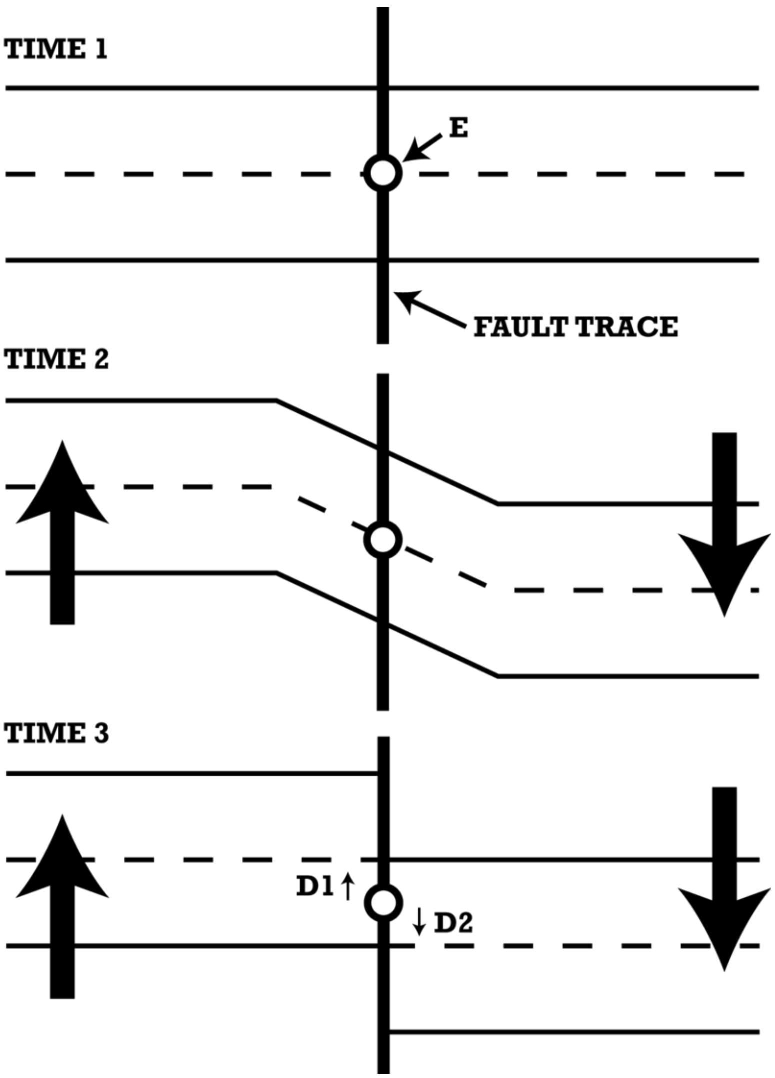

FIGURE 4.21

Elastic rebound theory. Stresses build on both sides of a fault. The rocks deform plastically as seen in Time 2. When the stresses become too great, the rocks return to their original shape. To do this, the rocks move, as seen in Time 3. This movement releases energy, creating an earthquake.

Earthquake Focus and Epicenter

Where an earthquake takes place is described by its focus and epicenter.

Focus

The point where the rock ruptures is the earthquake's **focus**. The focus is below the Earth's surface. A shallow earthquake has a focus less than 70 kilometers (45 miles). An intermediate-focus earthquake has a focus between 70 and 300 kilometers (45 to 200 miles). A deep-focus earthquake is greater than 300 kilometers (200 miles). About 75% of earthquakes have a focus in the top 10 to 15 kilometers (6 to 9 miles) of the crust. Shallow earthquakes cause the most damage. This is because the focus is near the Earth's surface, where people live.

Epicenter

The area just above the focus, on the land surface, is the earthquake's **epicenter** (**Figure** 4.22). The towns or cities near the epicenter will be strongly affected by the earthquake.

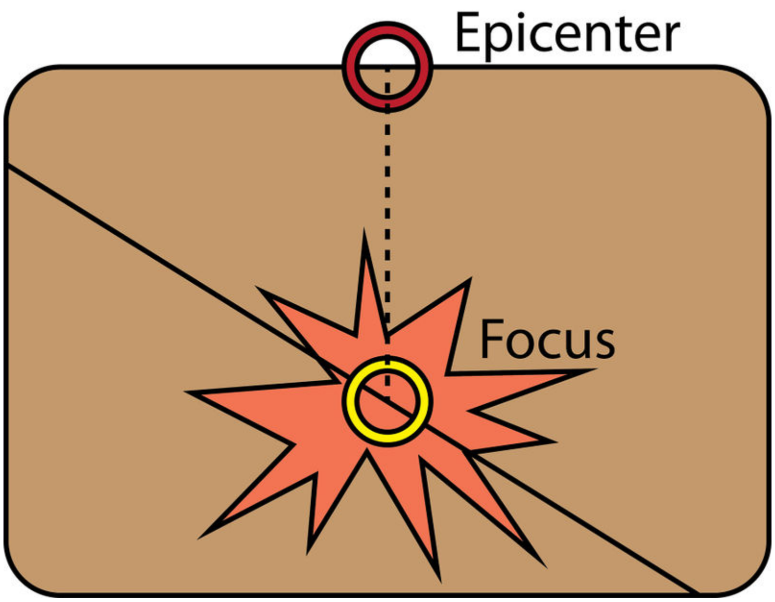

FIGURE 4.22
The focus of an earthquake is in the ground where the ground breaks. The epicenter is the point at the surface just above the focus.

Earthquake Zones

Nearly 95% of all earthquakes take place along one of the three types of plate boundaries. As you learned in the *Plate Tectonics* chapter, scientists use the location of earthquakes to draw plate boundaries.

The region around the Pacific Ocean is called the Pacific Ring of Fire. This is due to the volcanoes that line the region. The area also has the most earthquakes. About 80% of all earthquakes strike this area. The Pacific Ring of Fire is caused by the convergent and transform plate boundaries that line the Pacific Ocean basin.

About 15% of all earthquakes take place in the Mediterranean-Asiatic belt. The convergent plate boundaries in the region are shrinking the Mediterranean Sea. The convergence is also causing the Himalayas to grow. The remaining 5% of earthquakes are scattered around the other plate boundaries. A few earthquakes take place in the middle of a plate, away from plate boundaries.

Transform Plate Boundaries

Transform plate boundaries produce enormous and deadly earthquakes. These quakes at transform faults have shallow focus. This is because the plates slide past each other without moving up or down. The largest earthquake on the San Andreas Fault occurred in 1906 in San Francisco. Other significant earthquakes in California include the 1989 Loma Prieta earthquake near Santa Cruz (**Figure** 4.23) and the 1994 Northridge earthquake near Los Angeles.

There are many other faults spreading off the San Andreas, which produce around 10,000 earthquakes a year (**Figure** 4.24). While most of those earthquakes cannot even be felt by people nearby, occasionally one is very strong.

FIGURE 4.23

Three people died in this mall in Santa Cruz during the 1989 Loma Prieta earthquake.

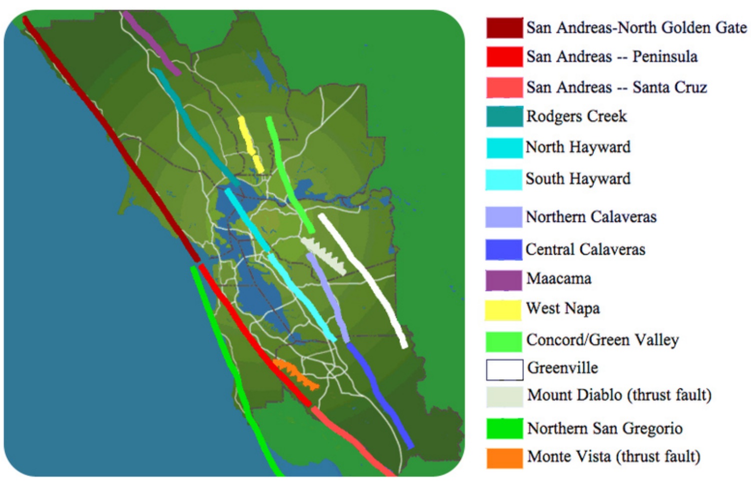

FIGURE 4.24

The San Andreas Fault runs through the San Francisco Bay Area. Other related faults cross the region. Lines indicate strike slip faults. Lines with hatches are thrust faults.

Subduction Zones

Convergent plate boundaries also produce strong, deadly earthquakes. Earthquakes mark the motions of colliding plates and the locations where plates plunge into the mantle. These earthquakes can be shallow, intermediate or deep focus.

The Philippine plate and the Pacific plate subduct beneath Japan, creating as many as 1,500 earthquakes every year. In March 2011, the 9.0 magnitude Tōhoku earthquake struck off of northeastern Japan. Damage from the quake was severe. More severe was the damage from the tsunami generated by the quake (**Figure** 4.25). In all, 25,000 people were known dead or missing.

The Cascades Volcanoes line the Pacific Northwest of the United States. Here, the Juan de Fuca plate subducts beneath the North American plate. The Cascades volcanoes are active and include Mount Saint Helens. Major earthquakes occur here approximately every 300 to 600 years. The last was in 1700. Its magnitude was between 8.7 and 9.2. It has now been more than 300 years since that earthquake. The next massive earthquake could strike the Pacific Northwest at any time.

FIGURE 4.25
The damage in Minato, Japan after a 9.0 magnitude earthquake and the massive tsunami it generated struck in March, 2011.

Continent-Continent Collisions

The collision of two continents also creates massive earthquakes. Many earthquakes happen in the region in and around the Himalayan Mountains. The 2001 Gujarat, India earthquake is responsible for about 20,000 deaths, with many more people injured or made homeless.

Divergent Plate Boundaries

Earthquakes also occur at divergent plate boundaries. At mid-ocean ridges, these earthquakes tend to be small and shallow focus because the plates are thin, young, and hot. Earthquakes in the oceans are usually far from land, so they have little effect on peoples' lives. On land, where continents are rifting apart, earthquakes are larger and stronger.

Intraplate Earthquakes

About 5% of earthquakes take place within a plate, away from plate boundaries. These intraplate earthquakes are caused by stresses within a plate. The plate moves over a spherical surface, creating zones of weakness. Intraplate earthquakes happen along these zones of weakness.

A large intraplate earthquake occurred in 1812. A magnitude 7.5 earthquake struck near New Madrid, Missouri. This is a region not usually known for earthquakes. Because very few people lived here at the time, only 20 people died. The New Madrid Seismic Zone continues to be active (**Figure** 4.26). Many more people live here today.

Seismic Waves

Seismic waves are the energy from earthquakes. Seismic waves move outward in all directions away from their source. Each type of seismic wave travels at different speeds in different materials. All seismic waves travel through rock, but not all travel through liquid or gas. Geologists study seismic waves to learn about earthquakes and the Earth's interior.

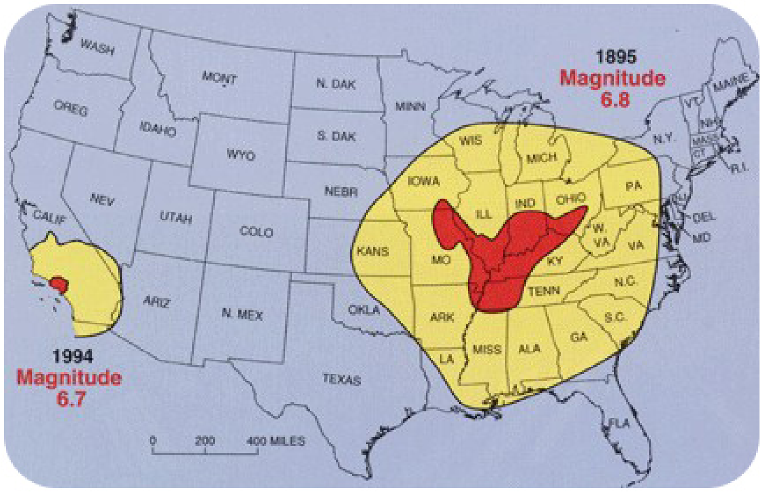

FIGURE 4.26
The range of damage in the 1895 New Madrid earthquake and the 1994 Los Angeles earthquake. New Madrid activity affected a much larger area.

Wave Structure

Seismic waves are just one type of wave. Sound and light also travel in waves. Every wave has a high point called a **crest** and a low point called a **trough**. The height of a wave from the center line to its crest is its **amplitude**. The horizontal distance between waves from crest to crest (or trough to trough) is its **wavelength** (**Figure** 4.27).

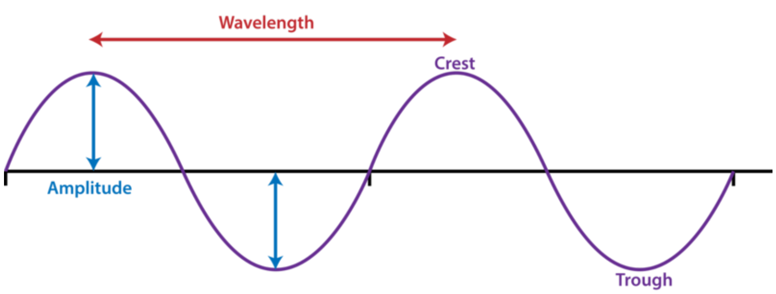

FIGURE 4.27
The energy from earthquakes travels in waves, such as the one shown in this diagram.

Types of Seismic Waves

There are two major types of seismic waves. **Body waves** travel through the Earth's interior. **Surface waves** travel along the ground surface. In an earthquake, body waves are responsible for sharp jolts. Surface waves are responsible for rolling motions that do most of the damage in an earthquake.

Body Waves

Primary waves (P-waves) and **secondary waves (S-waves)** are the two types of body waves (**Figure** 4.28). Body waves move at different speeds through different materials.

P-waves are faster. They travel at about 6 to 7 kilometers (about 4 miles) per second. Primary waves are so named because they are the first waves to reach a seismometer. P-waves squeeze and release rocks as they travel. The material returns to its original size and shape after the P-wave goes by. For this reason, P-waves are not the most damaging earthquake waves. P-waves travel through solids, liquids and gases.

S-waves are slower than P-waves. They are the second waves to reach a seismometer. S-waves move up and down. They change the rock's shape as they travel. S-waves are about half as fast as P-waves, at about 3.5 km (2 miles) per second. S-waves can only move through solids. This is because liquids and gases don't resist changing shape.

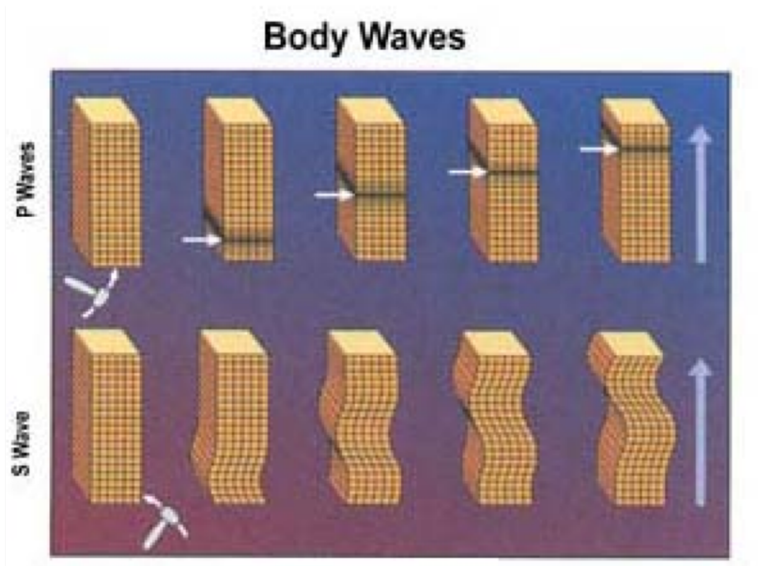

FIGURE 4.28
P-waves and S-waves are the two types of body waves.

Surface Waves

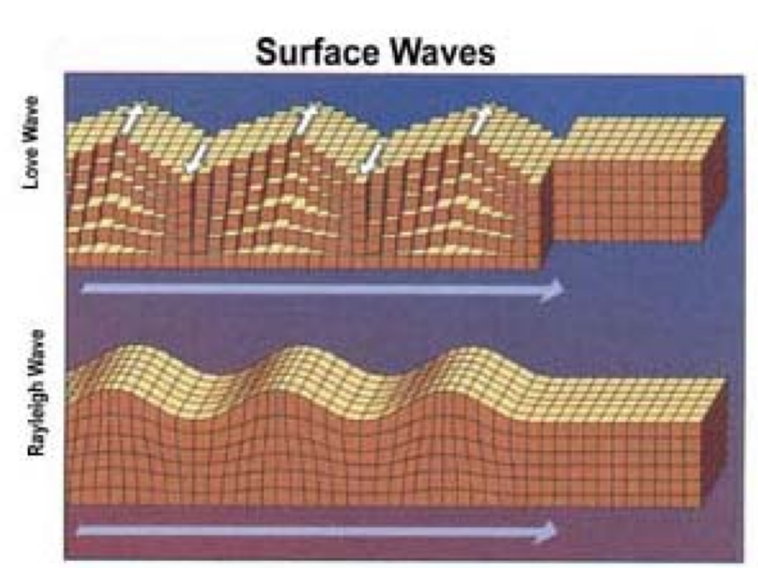

FIGURE 4.29
Love waves and Rayleigh waves are the two types of surface waves.

Surface waves travel along the ground outward from an earthquake's epicenter. Surface waves are the slowest of all seismic waves. They travel at 2.5 km (1.5 miles) per second. There are two types of surface waves. **Love waves** move side-to-side, much like a snake. **Rayleigh waves** produce a rolling motion as they move up and backwards (**Figure** 4.29). Surface waves cause objects to fall and rise, while they are also swaying back and forth. These

motions cause damage to rigid structures during an earthquake.

Tsunami

Earthquakes can cause **tsunami**. These deadly ocean waves may result from any shock to ocean water. A shock could be a meteorite impact, landslide, or a nuclear explosion.

An underwater earthquake creates a tsunami this way: The movement of the crust displaces water. The displacement forms a set of waves. The waves travel at jet speed through the ocean. Since the waves have low amplitudes and long wavelengths, they are unnoticed in deep water. As the waves reach shore they compress. They are also pushed upward by the shore. For these reasons, tsunami can grow to enormous wave heights. Tsunami waves can cause tremendous destruction and loss of life. Fortunately, few undersea earthquakes generate tsunami.

The Boxing Day Tsunami, 2004

The Boxing Day Tsunami struck on December 26, 2004. This tsunami was by far the deadliest of all time (**Figure** 4.30). The tsunami was caused by the second largest earthquake ever recorded. The Indian Ocean Earthquake registered magnitude 9.1. The quake struck near Sumatra, Indonesia, where the Indian plate is subducting beneath the Burma plate. It released about 550 million times the energy of the atomic bomb dropped on Hiroshima.

FIGURE 4.30
This dramatic image shows the Boxing Day Tsunami of 2004 coming ashore.

Several tsunami waves were created. The tsunami struck eight countries around the Indian Ocean (**Figure** 4.31).

About 230,000 people died. More than 1.2 million people lost their homes. Many more lost their way of making a living. Fishermen lost their boats, and businesspeople lost their restaurants and shops. Many marine animals washed onshore, including dolphins, turtles, and sharks.

Tilly Smith, Hero

Like other waves, a tsunami wave has a crest and a trough. When the wave hits the beach, the crest or the trough may come ashore first. When the trough comes in first, water is sucked out to sea. The seafloor just offshore from

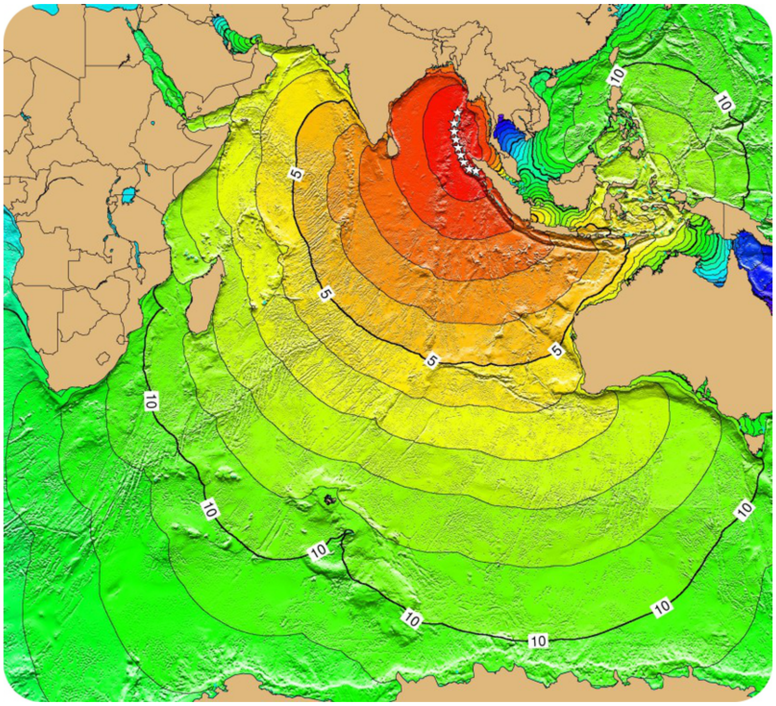

FIGURE 4.31

Travel time map for the Boxing Day Tsunami (in hours). Countries near red, orange, and yellow areas were affected the most.

the beach is exposed. Curious people often walk out onto the beach to see the unusual sight. They drown when the wave crest hits.

One amazing story from the Indian Ocean tsunami is that of Tilly Smith. Tilly was a 10-year-old British girl who was visiting Maikhao Beach in Thailand with her parents. Tilly had learned about tsunami in school two weeks before the earthquake. She knew that the receding water and the frothy bubbles at the sea surface meant a tsunami was coming. Tilly told her parents, who told other tourists and the staff at their hotel. The beach was evacuated and no one on Maikhao Beach died. Tilly is credited with saving nearly 100 people!

Tsunami Warning Systems

Most of the Indian Ocean tragedy could have been avoided if a warning system had been in place(**Figure** 4.32). As of June 2006, the Indian Ocean now has a warning system. Since tsunami are much more common in the Pacific, communities around the Pacific have had a tsunami warning system since 1948.

Warning systems aren't always helpful. People in communities very close to the earthquake do not have enough time to move inland or uphill. Farther away from the quake, evacuation of low-lying areas saves lives.

Lesson Summary

- During an earthquake, the ground shakes as stored up energy is released from rocks.
- Nearly all earthquakes occur at plate boundaries, and all types of plate boundaries have earthquakes.
- The Pacific Ocean basin and the Mediterranean-Asiatic belt are the two geographic regions most likely to experience quakes.
- Body waves travel through the Earth and arrive at seismograms before surface waves.
- The surface seismic waves do the most damage because they only travel along the surface of the ground.

FIGURE 4.32
This sign is part of the tsunami warning system used in communities around the Pacific Ocean since 1948.

- Tsunami are deadly ocean waves that can be caused by undersea earthquakes.

Lesson Review Questions

Recall

1. What is an earthquake's focus? What is its epicenter?

2. Other than a transform fault boundary, what type of plate boundary produces large earthquakes and where are these earthquakes likely to occur?

3. What are the two types of body waves? What are the characteristics of each?

4. What materials can P-waves travel through and how fast are they? Describe a P-wave's motion.

5. What materials can S-waves travel through and how fast are they? Describe an S-wave's motion.

6. How are surface waves different from body waves? In general, which type of wave is more damaging in an earthquake?

Apply Concepts

7. Where do most earthquakes take place? Why?

8. What causes an earthquake?

9. An earthquake just took place at Kilauea in Hawaii (an intraplate volcano). What caused it?

10. What happens when two continents collide? Draw a diagram of the fault.

11. What did Tilly Smith notice on the beach in Thailand that prompted the evacuation of the beach before the enormous tsunami hit in 2004? How were these signs evidence of a tsunami?

Think Critically

12. Try to picture in your mind the Pacific plate moving. It is being created at the East Pacific Rise. It is being destroyed at subduction zones in most locations. Now picture where the earthquakes are taking place.

13. Do the largest earthquakes cause the most deaths and the most damage to property?

14. What type of plate motion formed the Cascades Mountains of the Pacific Northwest? What is likely to occur in the future? Include earthquakes and tsunami.

Points to Consider

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

4.3 Measuring and Predicting Earthquakes

Lesson Objectives

- Describe how seismologists can use seismic waves to learn about earthquakes and the Earth's interior.
- Describe how to find an earthquake's epicenter.
- Describe the different earthquake magnitude scales and what the numbers for moment magnitude mean.
- Describe how earthquakes are predicted and why the field of earthquake prediction has had little success.

Vocabulary

- Mercalli Intensity Scale
- moment magnitude scale
- Richter magnitude scale
- seismogram
- seismograph
- seismometer

Introduction

Seismograms record earthquake strength. Scientists can use them to determine the distance to an earthquake. Using at least three seismograms, they can locate the earthquake's epicenter. Scientists measure earthquake intensity in several ways. So far no one has found a way to predict earthquakes.

Measuring Seismic Waves

Seismic waves are measured on a seismograph. Seismographs contain a lot of information, and not just about earthquakes.

Seismographs

A **seismograph** is a machine that records seismic waves. In the past, seismographs produced a **seismogram**. A seismogram is a paper record of the seismic waves the seismograph received. Seismographs have a weighted pen suspended from a stationary frame. A drum of paper is attached to the ground. As the ground shakes in an earthquake, the pen remains stationary but the drum moves beneath it. This creates the squiggly lines that make up a seismogram (**Figure** 4.33).

Modern seismographs record ground motions using electronic motion detectors. The data are recorded digitally on a computer.

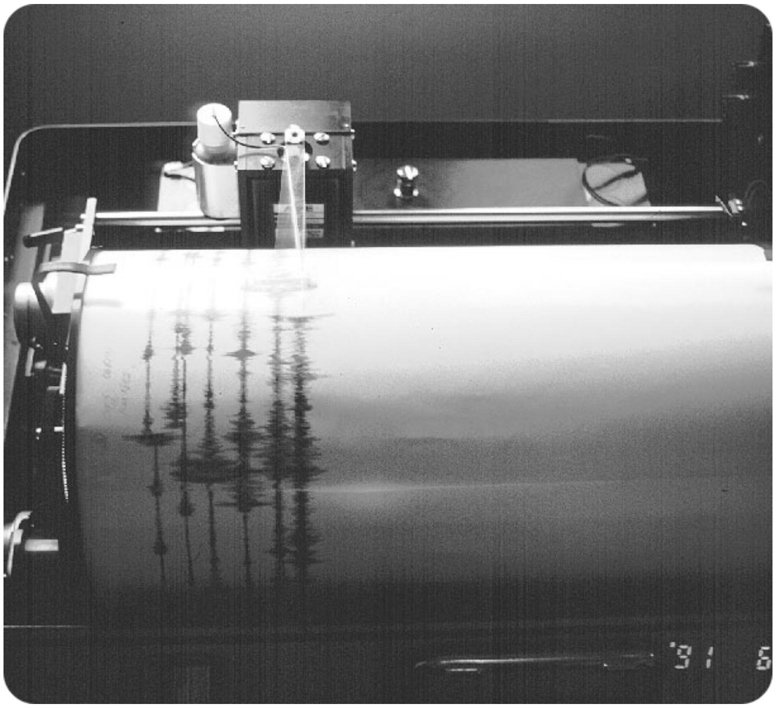

FIGURE 4.33
This seismograph records seismic waves.

What We Learn from Seismograms

Seismograms contain a lot of information about an earthquake: its strength, length and distance. Wave height used to determine the magnitude of the earthquake. The seismogram shows the different arrival times of the seismic waves (**Figure** 4.34). The first waves are P-waves since they are the fastest. S-waves come in next and are usually larger than P-waves. The surface waves arrive just after the S-waves. If the earthquake has a shallow focus, the surface waves are the largest ones recorded.

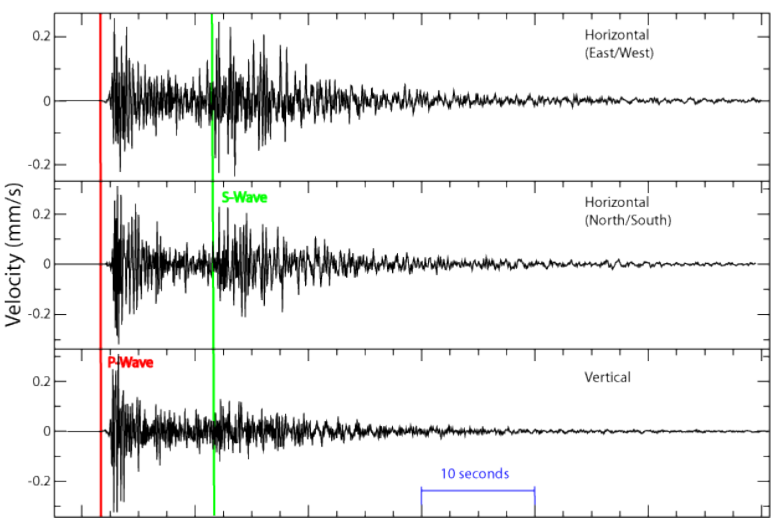

FIGURE 4.34
These seismograms show the arrival of P-waves and S-waves.

A seismogram may record P-waves and surface waves, but not S-waves. This means that it was located more than halfway around the Earth from the earthquake. The reason is that Earth's outer core is liquid. S-waves cannot travel

through liquid. So the liquid outer core creates an S-wave shadow zone on the opposite side of the Earth from the quake.

Finding the Epicenter

One seismogram indicates the distance to the epicenter. This is determined by the P-and S-wave arrival times. If a quake is near the seismograph, the S-waves arrive shortly after the P-waves. If a quake is far from the seismograph, the P-waves arrive long before the S-waves. The longer the time is between the P-and S-wave arrivals, the further away the earthquake was from the seismograph. First, seismologists calculate the arrival time difference. Then they know the distance to the epicenter from that seismograph.

Next, the seismologists try to determine the location of the earthquake epicenter. To do this they need the distances to the epicenter from at least three seismographs. Let's say that they know that an earthquake's epicenter is 50 kilometers from Kansas City. They draw a circle with a 50 km radius around that seismic station. They do this twice more around two different seismic stations. The three circles intersect at a single point. This is the earthquake's epicenter (**Figure** 4.35).

FIGURE 4.35
Seismographs in Portland, Los Angeles, and Salt Lake City are used to find an earthquake epicenter.

Earthquake Intensity

The ways seismologists measure an earthquake have changed over the decades. Initially, they could only measure what people felt and saw, the intensity. Now they can measure the energy released during the quake, the magnitude.

Earthquake Intensity

Early in the 20th century, earthquakes were described in terms of what people felt and the damage that was done to buildings. The **Mercalli Intensity Scale** describes earthquake intensity.

There are many problems with the Mercalli scale. The damage from an earthquake is affected by many things. Different people experience an earthquake differently. Using this scale, comparisons between earthquakes were

difficult to make. A new scale was needed.

The Richter Magnitude Scale

Charles Richter developed the **Richter magnitude scale** in 1935. The Richter scale measures the magnitude of an earthquake's largest jolt of energy. This is determined by using the height of the waves recorded on a seismograph.

Richter scale magnitudes jump from one level to the next. The height of the largest wave increases 10 times with each level. So the height of the largest seismic wave of a magnitude 5 quake is 10 times that of a magnitude 4 quake. A magnitude 5 is 100 times that of a magnitude 3 quake. With each level, thirty times more energy is released. A difference of two levels on the Richter scale equals 900 times more released energy.

The Richter scale has limitations. A single sharp jolt measures higher on the Richter scale than a very long intense earthquake. Yet this is misleading because the longer quake releases more energy. Earthquakes that release more energy are likely to do more damage. As a result, another scale was needed.

The Moment Magnitude Scale

The **moment magnitude scale** is the favored method of measuring earthquake magnitudes. It measures the total energy released by an earthquake. Moment magnitude is calculated by two things. One is the length of the fault break. The other is the distance the ground moves along the fault.

Earthquake Magnitudes

Each year, more than 900,000 earthquakes are recorded. 150,000 of them are strong enough to be felt by people. About 18 each year are major, with a Richter magnitude of 7.0 to 7.9. Usually there is one earthquake with a magnitude of 8 to 8.9 each year.

Earthquakes with a magnitude in the 9 range are rare. The United States Geological Survey lists five such earthquakes on the moment magnitude scale since 1900 (see **Figure** 4.36). All but one, the Great Indian Ocean Earthquake of 2004, occurred somewhere around the Pacific Ring of Fire.

Earthquake Prediction

Scientists are not able to predict earthquakes. Since nearly all earthquakes take place at plate boundaries, scientists can predict where an earthquake will occur (**Figure** 4.37). This information helps communities to prepare for an earthquake. For example, they can require that structures are built to be earthquake safe.

Predicting when an earthquake will occur is much more difficult. Scientists can look at how often earthquakes have struck in the past. This does not allow an accurate prediction for the future. Small tremors, called foreshocks, often happen a short time before a major quake. The ground may also tilt as stress builds up in the rocks. Water levels in wells also change as groundwater moves through rock fractures. These do not usually allow accurate predictions.

Folklore tells of animals behaving strangely just before an earthquake. Most people tell stories of these behaviors after the earthquake. Chinese scientists actively study the behavior of animals before earthquakes to see if there is a connection. So far nothing concrete has come of these studies.

Once an earthquake has started, many actions must take place. Seismometers can detect P-waves a few seconds before more damaging S-waves and surface waves arrive. Although a few seconds is not much, computers can shut down gas mains and electrical transmission lines. They can initiate protective measures in chemical plants, nuclear power plants, mass transit systems, airports, and roadways.

FIGURE 4.36
Earthquake and tsunami damage in Japan, 2011. The Tōhoku earthquake had a magnitude of 9.0.

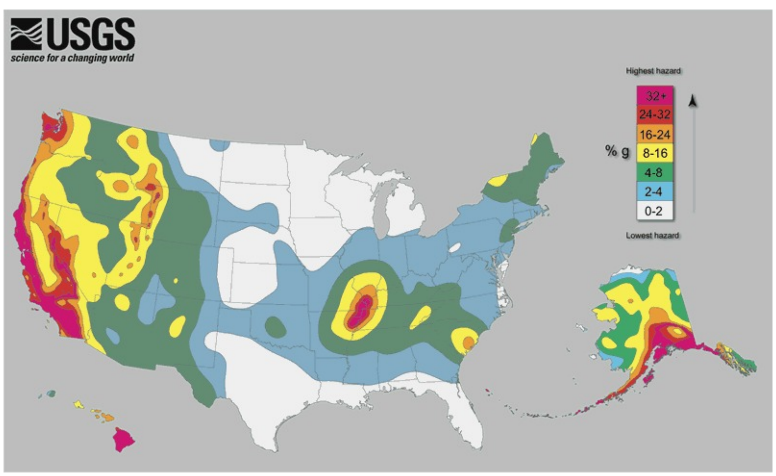

FIGURE 4.37
This map shows earthquake probability regions in the United States.

Lesson Summary

- Seismologists use seismograms to determine how strong an earthquake is, how far away it is, and how long it lasts.
- Epicenters can be calculated using the difference in the arrival times of P-and S-waves from three seismograms.
- The intensity of an earthquake can be determined in many ways. The Mercalli Scale identifies the damage done and what people feel, the Richter Scale measures the height of the largest seismic wave, and the moment

magnitude scale measures the total energy released by an earthquake.
- Despite some successes, seismologists cannot yet accurately predict earthquakes.

Lesson Review Questions

Recall

1. How does a seismograph work?

2. In what order do waves arrive at a seismograph?

3. What information is needed for seismologists to calculate the distance that a seismic station is from an earthquake's epicenter?

4. Describe how to locate an earthquake epicenter.

Apply Concepts

5. Draw a picture to show the S-wave shadow zone. How does this indicate a liquid outer core?

6. While the Mercalli scale is still used for measuring earthquake magnitude, why is it not the only scale used? Where does it fall short relative to the Richter and moment magnitude scales?

Think Critically

7. Like the Richter scale, the moment magnitude scale is logarithmic. The 2011 Tōhoku earthquake in Japan was 9.0 and did tremendous damage. A few months earlier, an 8.8 struck Chile and did much less damage. Why?

8. What are the characteristics of a good earthquake prediction? Why are these features needed?

Points to Consider

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

4.4 Staying Safe in Earthquakes

Lesson Objectives

- Describe different types of earthquake damage.
- Describe the features that make a structure more earthquake safe.
- Describe the ways that a person and a household can protect themselves in earthquake country.

Vocabulary

- liquefy

Introduction

Only hurricanes cause more damage than earthquakes. Only one source of earthquake damage is ground shaking. More damage may be done from the tsunami, fires, and landslides that can happen afterwards. Communities along faults can prepare for earthquakes. One way is to use earthquake-safe construction methods and to make older buildings stronger. If you live in earthquake country, it is important to secure heavy objects and put together an emergency kit.

Damage from Earthquakes

Earthquake magnitude affects how much damage is done in an earthquake. A larger earthquake damages more buildings and kills more people than a smaller earthquake. But that's not the only factor that determines earthquake damage. The location of an earthquake relative to a large city is important. More damage is done if the ground shakes for a long time.

The amount of damage also depends on the geology of the region. Strong, solid bedrock shakes less than soft or wet soils. Wet soils **liquefy** during an earthquake and become like quicksand. Soil on a hillside that is shaken loose can become a landslide.

Hazard maps help city planners choose the best locations for buildings (**Figure** 4.38). For example, when faced with two possible locations for a new hospital, planners must build on bedrock rather than silt and clay.

Mexico City, 1985

The 1985 Mexico City earthquake measured magnitude 8.1. The earthquake killed at least 9,000 people, injured 30,000 more, and left 100,000 people homeless. It destroyed 416 buildings, and seriously damaged 3,000 other buildings.

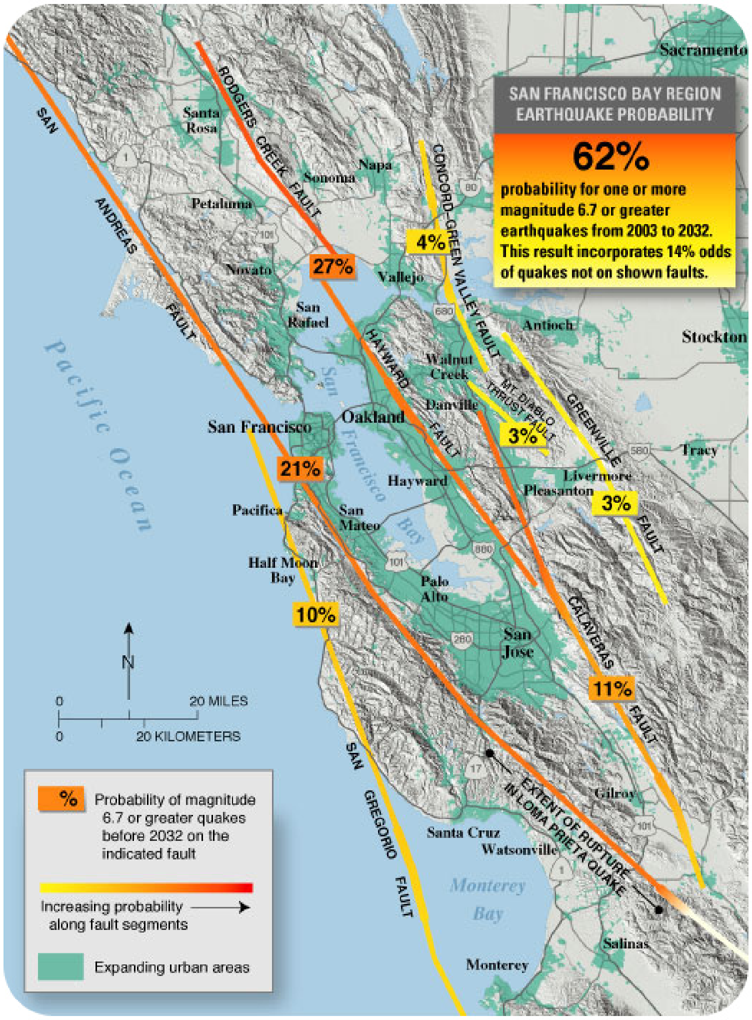

FIGURE 4.38
This hazard map predicts the likelihood of strong earthquakes in the area around San Francisco, California.

The intense destruction was due to the soft ground the city is built on. Silt and clay fill a basin made of solid rock. In an earthquake, seismic waves bounce back-and-forth off the sides and bottom of the rock basin. This amplifies the shaking. The wet clay converts to quicksand (**Figure** 4.39).

Many buildings were not anchored to bedrock. They settled into the muck. This caused enormous damage. Water, sewer, and electrical systems were destroyed, resulting in fires. Acapulco was much closer to the epicenter, but since the city is built on bedrock it suffered little damage.

Anchorage, Alaska, 1964

The amount of damage depends on the amount of development in the region. The 1964 Great Alaska Earthquake, near Anchorage, was the largest earthquake ever recorded in North America. The gigantic quake had a magnitude of 9.2. The earthquake lasted for several minutes and the ground slipped up to 11.5 meters (38 feet). An area of 100,000 square miles (250,000 square km) was affected. The ground liquefied, causing landslides (**Figure** 4.40). The earthquake occurred at a subduction zone, and large tsunami up to 70 meters (20 feet) high were created.

Despite the intensity of the earthquake, only 131 people died. Most deaths were due to the tsunami. Property damage was just over $300 million ($1.8 billion in 2007 U.S. dollars). The reason there was such a small amount of damage is that very few people lived in the area (Alaska had only been a state for five years!). A similar earthquake today

FIGURE 4.39
Mexico City suffers tremendously in earthquakes because it is built on an old lake bed. In 1985 many buildings collapsed.

FIGURE 4.40
A landslide in a neighborhood in Anchorage Alaska after the 1964 Great Alaska earthquake.

would affect many more people.

Earthquake-Safe Structures

Buildings must be specially built to withstand earthquakes. Skyscrapers and other large structures built on soft ground must be anchored to bedrock. Sometimes that bedrock is hundreds of meters below the ground surface!

Buildings

Building materials need to be both strong and flexible. Small structures, like houses, should bend and sway. Wood and steel bend. Brick, stone, and adobe are brittle and will break. Larger buildings must sway, but not so much that

they touch nearby buildings. Counterweights and diagonal steel beams can hold down sway. Buildings need strong, flexible connections where the walls meet the foundation. Earthquake-safe buildings are well connected (**Figure** 4.41).

FIGURE 4.41
The Transamerica Pyramid in San Francisco is more stable in an earthquake or in high winds than a rectangular skyscraper.

Steel or wood can be added to older buildings to reinforce a building's structure and its connections (**Figure** 4.42). Elevated freeways and bridges can also be reinforced so that they do not collapse. Important structures must be designed to survive intact.

Avoiding Fire

One of the biggest problems caused by earthquakes is fire. Fires start because earthquakes rupture gas and electrical lines. Water mains may break. This makes it difficult to fight the fires. The shapes of pipes can make a big difference. Straight pipes will break in a quake. Zigzag pipes bend and flex when the ground shakes. In San Francisco, water and gas pipelines are separated by valves. Areas can be isolated if one segment breaks.

Making Choices

Strong, sturdy structures are expensive to build. Communities must decide how safe to make their buildings. They must weigh how great the hazard is, what different building strategies will cost, and how much risk they are willing to take.

FIGURE 4.42
Buildings can be retrofit to be made more earthquake safe.

Protecting Yourself in an Earthquake

If you live in an earthquake zone, there are many things you can do to protect yourself. You must protect your home. Your household must be ready to live independently for a few days. It may take emergency services that long to get to everyone.

Before an Earthquake:

- Make sure the floor, walls, roof, and foundation are all well attached to each other. Have an engineer evaluate your house for structural integrity.
- Bracket or brace brick chimneys to the roof.
- Be sure that heavy objects are not stored in high places. Move them to low places so that they do not fall.
- Secure water heaters all around and at the top and bottom.
- Bolt heavy furniture onto walls with bolts, screws, or strap hinges.
- Replace halogen and incandescent light bulbs with fluorescent bulbs to lessen fire risk.
- Check to see that gas lines are made of flexible material so they do not rupture. Any equipment that uses gas should be well secured.
- Everyone in the household should know how to shut off the gas line. A wrench should be placed nearby for

doing so.
- Prepare an earthquake kit with at least three days' supply of water and food. Include a radio and batteries.
- Place flashlights all over the house so there is always one available. Place one in the glove box of your car.
- Keep several fire extinguishers around the house to fight any small fires that break out.
- Be sure to have a first aid kit. Everyone in the household who is capable should know basic first aid and CPR.
- Plan in advance how you will evacuate your property and where you will go. Do not plan on driving, as roadways will likely be damaged.

During the Earthquake:

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

After the Earthquake:

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

Lesson Summary

- A person standing in an open field in an earthquake will almost certainly be safe. Nearly all earthquake danger is from buildings falling, roadways collapsing, or from the fires and tsunami that come after the shaking stops.
- Communities can prepare for earthquakes by requiring that buildings be earthquake safe and by educating citizens on how to prepare for an earthquake.
- Individuals and households can prepare in two ways: by protecting your home and by being ready to live independently for a few days.

Lesson Review Questions

Recall

1. What usually kills or injures people in an earthquake?

2. In two earthquakes of the same size, what could cause greater damage for one community?

Apply Concepts

3. What types of building design make a skyscraper earthquake safe?

4. If you live in earthquake country, what can you do to minimize your dangers?

Think Critically

5. Pretend that you live in an old home in an earthquake-prone region. No work has ever been done to prepare your home for an earthquake. What should you do to minimize the harm that will come to yourself and your home?

6. Will a building better withstand an earthquake if it is built absolutely solid, or if it is able to sway? Why?

Points to Consider

- Many people think that in a large earthquake California will fall into the ocean and that Arizona and Nevada will be beachfront property. Why is this not true?
- If you were the mayor of a small city in an earthquake-prone area, what would you like to know before choosing the building site of a new hospital?
- How are decisions made for determining how much money to spend preparing people and structures for earthquakes?

4.5 References

1. Ryan Dickey (Flickr:Wallula Junction). http://www.flickr.com/photos/meesterdickey/2075201884/ . CC BY 2.0
2. Roland Gotthard. http://commons.wikimedia.org/wiki/File:Asymmetric_shear.jpg . Public Domain
3. Jodi So. CK-12 Foundation . CC BY-NC 3.0
4. Wolfgang Staudt. http://commons.wikimedia.org/wiki/File:Grand_Staircase-Escalante_National_Monument_-%282279640905%29.jpg . CC BY 2.0
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6. Courtesy of National Park Service. http://commons.wikimedia.org/wiki/File:Grand_Staircase-big.jpg . Public Domain
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9. (A) User:Jonathan3784/Wikipedia; (B) Mark A. Wilson (Department of Geology, The College of Wooster). (A) http://commons.wikimedia.org/wiki/File:Syncline.gif; (B) http://commons.wikimedia.org/wiki/File:SynclineCalico.JPG . Public Domain
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11. (A) Roy Luck; (B) Mark A. Wilson (Department of Geology, The College of Wooster). (A) http://www.flickr.com/photos/royluck/6206254956/; (B) http://commons.wikimedia.org/wiki/File:RamonFault1.JPG . (A) CC BY 2.0; (B) Public Domain
12. John Sullivan, PD Photo. http://commons.wikimedia.org/wiki/File:Barns_grand_tetons.jpg . Public Domain
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14. Jodi So. CK-12 Foundation . CC BY-NC 3.0
15. Courtesy of Robert E. Wallace, USGS. http://pubs.usgs.gov/gip/dynamic/San_Andreas.html . Public Domain
16. Pierre Dèzes 1999, "Tectonic and metamorphic Evolution of the Central Himalayan Domain in Southeast Zanskar (Kashmir, India)". http://commons.wikimedia.org/wiki/File:India_71-0_Ma.gif . Author allows use for any purpose, provide reference is made to http://comp1.geol.unibas.ch/zanskar/
17. Flickr:ilkerender. http://www.flickr.com/photos/ilker/2493909927/ . CC BY 2.0
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23. Courtesy of C.E. Meyer, United States Geological Survey. http://commons.wikimedia.org/wiki/File:LomaPrieta-PacificGardenMall.jpeg . Public Domain
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29. Courtesy of US Geological Survey. http://commons.wikimedia.org/wiki/File:Pswaves.jpg . Public Domain
30. David Rydevik. http://commons.wikimedia.org/wiki/File:2004-tsunami.jpg . Public Domain
31. Courtesy of NOAA, NGDC. http://www.ngdc.noaa.gov/hazard/tsu_travel_time_events.shtml . Public Domain
32. Flickr:youngthousands. http://www.flickr.com/photos/theyoungthousands/2609041263/ . CC BY 2.0
33. Courtesy of R. P. Hoblitt, US Geological Survey. http://commons.wikimedia.org/wiki/File:Seismograph_Pinatubo.jpg . Public Domain
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37. Courtesy of the US Geological Survey. http://earthquake.usgs.gov/hazards/about/basics.php . Public Domain
38. Courtesy of US Geological Survey. http://commons.wikimedia.org/wiki/File:Eq-prob.jpg . Public Domain
39. Courtesy of the US Geological Survey. http://libraryphoto.cr.usgs.gov/cgi-bin/show_picture.cgi?ID=ID.%20Celebi,%20M.%2040ct&SIZE=medium . Public Domain
40. Courtesy of the National Oceanic and Atmospheric Administration. http://commons.wikimedia.org/wiki/File:Good_Friday_Earthquake_at_Turnagain_Arm.jpg . Public Domain
41. User:Leonard G./Wikimedia Commons. http://commons.wikimedia.org/wiki/File:TransamericaPyramidFromTI.jpg . Public Domain
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CHAPTER 5 MS Volcanoes

Chapter Outline

A fissure eruption on a volcano in Iceland. The lava flows downhill and turns snow into steam. Iceland is made of a set of volcanoes that are the result of a hotspot that lies on a mid-ocean ridge. The island is the only location where the mid-ocean ridge can be seen above sea level. Icelandic volcanoes have made the news lately since some have shut down air traffic in parts of Europe.

5.1 Volcanic Activity

Lesson Objectives

- Explain how volcanoes form.
- Describe places where volcanoes occur.
- Describe what volcanic hot spots are and where they occur.

Vocabulary

- fissure
- hot spot
- mantle plume

Introduction

Volcanoes are fantastic displays of the power of the Earth. What is a volcano? How and where are they formed? Why do some places have lots of volcanoes?

Where Volcanoes Are Found

Volcanoes rise where magma forms underground. Volcanoes are found at convergent plate boundaries and at hotspots. Volcanic activity is found at divergent plate boundaries. The map in **Figure** 5.1 shows where volcanoes are located.

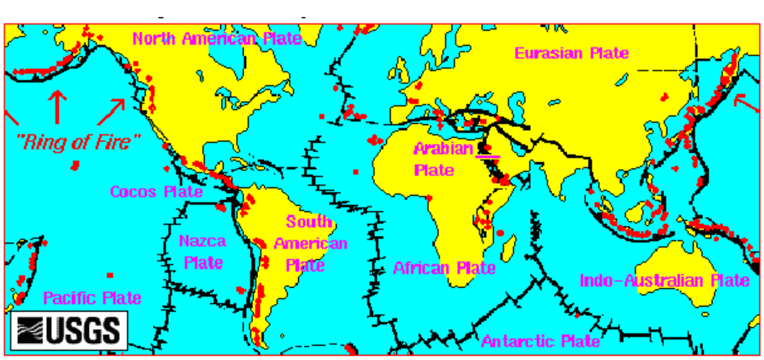

FIGURE 5.1
This map shows where volcanoes are located.

Divergent Plate Boundaries

There is a lot of volcanic activity at divergent plate boundaries in the oceans. As the plates pull away from each other, they create deep fissures. Molten lava erupts through these cracks. The East Pacific Rise is a divergent plate boundary in the Pacific Ocean (**Figure** 5.2). The Mid-Atlantic Ridge is a divergent plate boundary in the Atlantic Ocean.

Continents can also rift apart. When mantle gets close enough to the surface, volcanoes form. Eventually, a rift valley will create a new mid-ocean ridge.

Convergent Plate Boundaries

Lots of volcanoes form along subduction plate boundaries. The edges of the Pacific Plate are a long subduction boundary. Lines of volcanoes can form at subduction zones on oceanic or continental crust. Japan is an example of a volcanic arc on oceanic crust. The Cascade Range and Andes Mountains are volcanic arcs on continental crust.

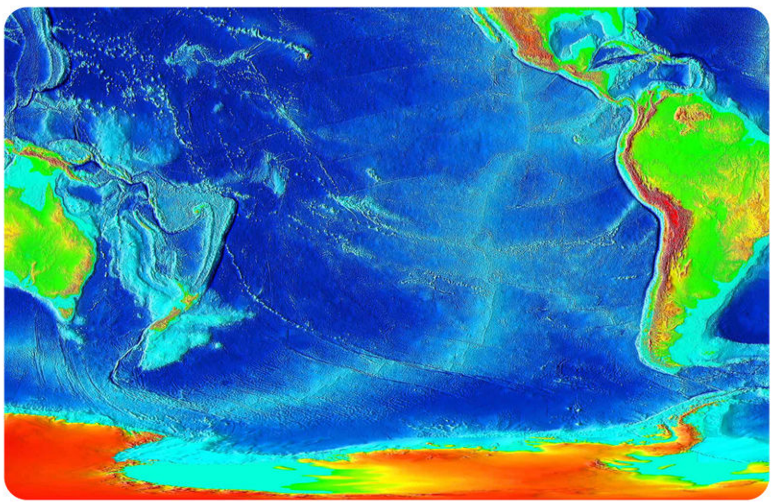

FIGURE 5.2
The Pacific Ocean basin is a good place to look for volcanoes. The light blue wavy line that goes up the right-center of the diagram is the East Pacific Rise. Trenches due to subduction are on the west and east sides of the plate. Hawaii trends southeast-northwest near the center-top of the image.

Volcanic Hot Spots

Some volcanoes form over active **hot spots**. Scientists count about 50 hot spots on the Earth. Hot spots may be in the middle of a tectonic plate. Hot spots lie directly above a column of hot rock called a **mantle plume**. Mantle plumes continuously bring magma up from the mantle towards the crust (**Figure** 5.3).

As the tectonic plates move above a hot spot, they form a chain of volcanoes. The islands of Hawaii formed over a hot spot in the middle of the Pacific plate. The Hawaii hot spot has been active for tens of millions of years. The volcanoes of the Hawaiian Islands formed at this hot spot. Older volcanoes that formed at the hot spot have eroded below sea level. These are called the Emperor Seamounts.

Loihi seamount is currently active beneath the water southeast of the Big Island of Hawaii. One day the volcano will rise above sea level and join the volcanoes of the island or create a new island (**Figure** 5.4).

Hot spots may also be active at plate boundaries. This is especially common at mid-ocean ridges. Iceland is formed by a hot spot along the Mid-Atlantic Ridge.

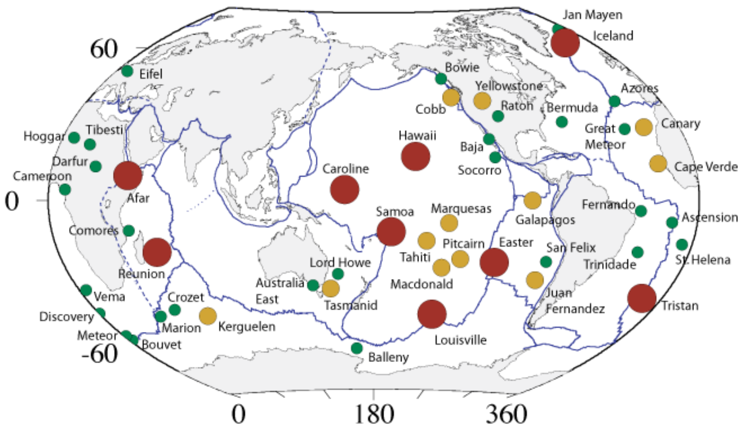

FIGURE 5.3

Mantle plumes are found all over the world, especially in the ocean basins. The size of the eruptions is different at different plumes.

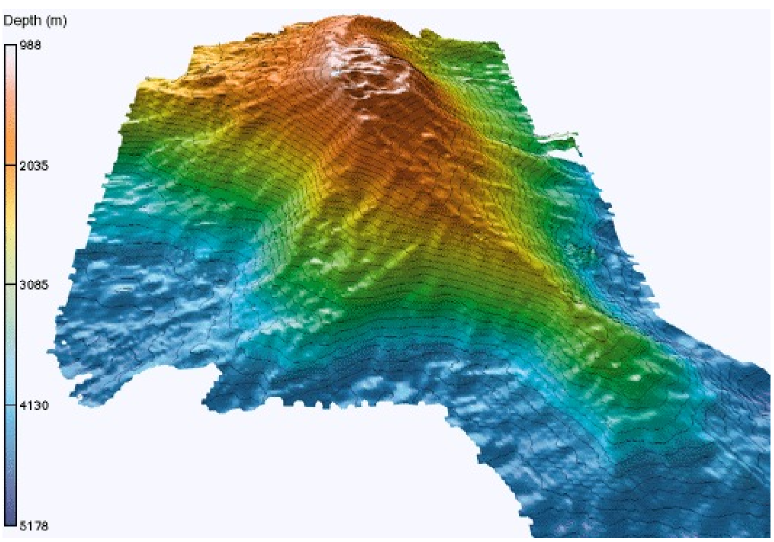

FIGURE 5.4

A bathymetric map of Loihi seamount. Loihi will be the next shield volcano in the Hawaiian-Emperor chain.

Hot spots are found within continents, but not as commonly as within oceans. The Yellowstone hot spot is a famous example of a continental hot spot.

Lesson Summary

- Volcanoes form when magma reaches the Earth's surface.
- Volcanoes occur most often along plate boundaries.
- Convergent plate boundaries, where oceanic crust is forced down into the mantle, form many of the volcanoes found on Earth.
- Divergent plate boundaries produce huge mountain ranges under water in every ocean basin.
- Volcanoes like those that make up the islands of Hawaii form over areas called hot spots.

Lesson Review Questions

Recall

1. What is a hot spot?
2. How is a hot spot related to a mantle plume?
3. Why do hot spot volcanoes form in lines?

Apply Concepts

4. What plate tectonic setting produces the most volcanoes?
5. What are the ages of hotspot volcanoes relative to each other?
6. What are the ages of volcanic arc volcanoes relative to each other?

Think Critically

7. Volcanoes have been found on Venus, Mars, and even Jupiter's moon Io. What do you think this indicates to planetary geologists?

Points to Consider

- When you look at the map of tectonic plates (**Figure** 5.1), what areas besides the Pacific Ring of Fire would you expect to have volcanic activity?
- Why do you think some volcanoes are no longer active and probably never will be again?
- Why do you think it's hard to study hot spots?

5.2 Volcanic Eruptions

Lesson Objectives

- Explain how volcanoes erupt.
- Describe and compare the types of volcanic eruptions.
- Distinguish between different types of lava and understand the difference between magma and lava.
- Describe a method for predicting volcanic eruptions.

Vocabulary

- active volcano
- dormant volcano
- eruption
- explosive eruption
- extinct volcano
- magma chamber
- pyroclast

Introduction

In 1980, Mount St. Helens, located between Portland, Oregon and Seattle, Washington, erupted explosively. The eruption killed 57 people, destroyed 250 homes, and swept away 47 bridges. The volcano blew off its top so that it lost over 400 meters (1,300 feet) of height. Mt. St. Helens is still active (**Figure** 5.5). Within the crater, a new lava dome formed. How did this eruption occur? Why aren't all volcanoes explosive, like Mt. St. Helens? Why did so many people die if we knew that it was going to erupt?

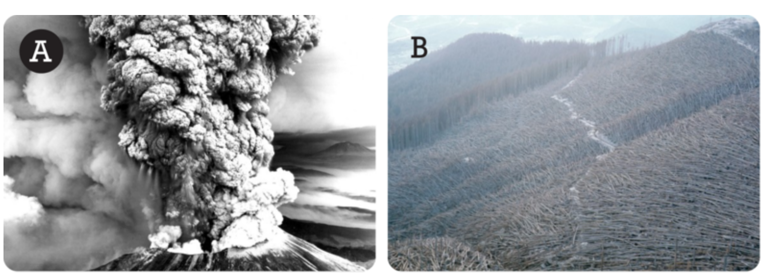

FIGURE 5.5
(A) Mount St. Helens eruption on May 18, 1980. Mt. Adams is in the background on the right. (B) The eruption of Mt. St. Helens blew down acres of trees like they were toothpicks.

How Volcanoes Erupt

All volcanoes share the same basic features. First, mantle rock melts. The molten rock collects in magma chambers that can be 160 kilometers (100 miles) beneath the surface. As the rock heats, it expands. The hot rock is less dense than the surrounding rock. The magma rises toward the surface through cracks in the crust. A volcanic **eruption** occurs when the magma reaches the surface. Lava can reach the surface gently or explosively.

Types of Eruptions

Eruptions can be explosive or non-explosive. Only rarely do gentle and explosive eruptions happen in the same volcano.

Explosive Eruptions

An **explosive eruption** produces huge clouds of volcanic ash. Chunks of the volcano fly high into the atmosphere. Explosive eruptions can be 10,000 times as powerful as an atomic bomb (**Figure** 5.6). Hot magma beneath the surface mixes with water. This forms gases. The gas pressure grows until it must be released. The volcano erupts in an enormous explosion.

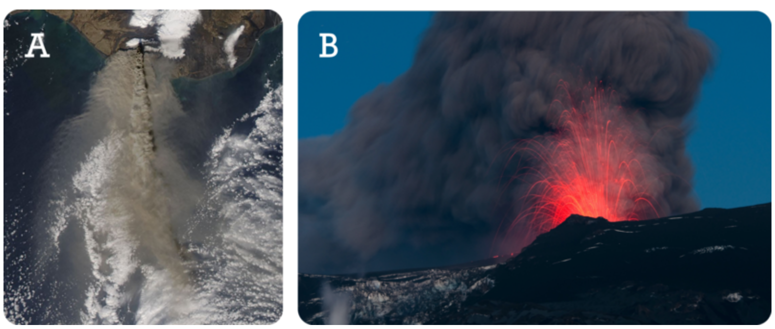

FIGURE 5.6

(A) Eyjafjallajökull volcano in Iceland spewed ash into the atmosphere in 2010. This was a fairly small eruption, but it disrupted air travel across Europe for six days. (B) The eruption seen from nearby.

Ash and particles shoot many kilometers into the sky. The material may form a mushroom cloud, just like a nuclear explosion. Hot fragments of rock, called **pyroclasts**, fly up into the air at very high speeds. The pyroclasts cool in the atmosphere. Some ash may stay in the atmosphere for years. The ash may block out sunlight. This changes weather patterns and affects the temperature of the Earth. For a year or two after a large eruption, sunsets may be especially beautiful worldwide.

Volcanic gases can form poisonous, invisible clouds. The poisonous gases may be toxic close to the eruption. The gases may cause environmental problems like acid rain and ozone destruction.

Mt St. Helens was not a very large eruption for the Cascades. Mt. Mazama blew itself apart in an eruption about 42 times more powerful than Mount St. Helens in 1980. Today all that remains of that huge stratovolcano is Crater Lake (**Figure** 5.18).

Non-explosive Eruptions

Some volcanic eruptions are non-explosive (**Figure** 5.7). This happens when there is little or no gas. The lava is thin, fluid and runny. It flows over the ground like a river. People generally have a lot of warning before a lava flow

like this reaches them, so non-explosive eruptions are much less deadly. They may still be destructive to property, though. Even when we know that a lava flow is approaching, there are few ways of stopping it!

FIGURE 5.7
A lava flow in Iceland in 1984.

Magma and Lava

Great volcanic explosions and glowing red rivers of lava are fascinating. All igneous rock comes from magma or lava. Remember that magma is molten rock that is below Earth's surface. Lava is molten rock at Earth's surface.

Magma

Magma forms deep beneath the Earth's surface. Rock melts below the surface under tremendous pressure and high temperatures. Molten rock flows like taffy or hot wax. Most magmas are formed at temperatures between 600^{o}C and 1300^{o}C (**Figure** 5.8).

Magma collects in **magma chambers** beneath Earth's surface. Magma chambers are located where the heat and pressure are great enough to melt rock. These locations are at divergent or convergent plate boundaries or at hotpots.

The chemistry of a magma determines the type of igneous rock it forms. The chemistry also determines how the magma moves. Thicker magmas tend to stay below the surface or erupt explosively. When magma is fluid and runny, it often reaches the surface by flowing out in rivers of lava.

Lava

The way lava flows depends on what it is made of. Thick lava doesn't flow easily. It may block the vent of a volcano. If the lava traps a lot of gas, the pressure builds up. After the pressure becomes greater and greater, the volcano finally explodes. Ash and pyroclasts shoot up into the air. Pumice, with small holes in solid rock, shows where gas bubbles were when the rock was still molten.

Fluid lava flows down mountainsides. The rock that the flow becomes depends on which type of lava it is and where it cools. The three types of flows are a'a, pahoehoe, and pillow lava.

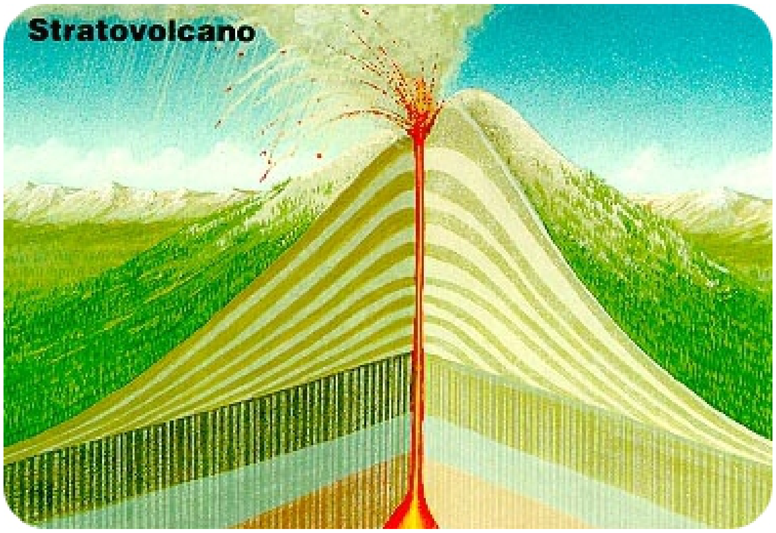

FIGURE 5.8
Magma beneath a volcano erupts onto the volcano's surface. Layer upon layer of lava creates a volcano.

A'a Lava

A'a lava is the thickest of the non-explosive lavas. A'a forms a thick and brittle crust, which is torn into rough, rubbly pieces. The solidified surface is angular, jagged and sharp. A'a can spread over large areas as the lava continues to flow underneath.

Pāhoehoe Lava

Pāhoehoe lava is thinner than a'a, and flows more readily. Its surface looks more wrinkly and smooth. Pāhoehoe lava flows in a series of lobes that form strange twisted shapes and natural rock sculptures (**Figure** 5.9). Pāhoehoe lava can form lava tubes. The outer layer of the lava flow cools and solidifies. The inner part of the flow remains fluid. The fluid lava flows through and leaves behind a tube (**Figure** 5.10).

FIGURE 5.9
Ropy pahoehoe flows are common on Kilauea Volcano in Hawaii.

FIGURE 5.10
A lava tube in a pahoehoe flow.

Pillow Lava

Pillow lava is created from lava that enters the water. The volcanic vent may be underwater. The lava may flow over land and enter the water (**Figure** 5.11). Once in the water, the lava cools very quickly. The lava forms round rocks that resemble pillows. Pillow lava is particularly common along mid-ocean ridges.

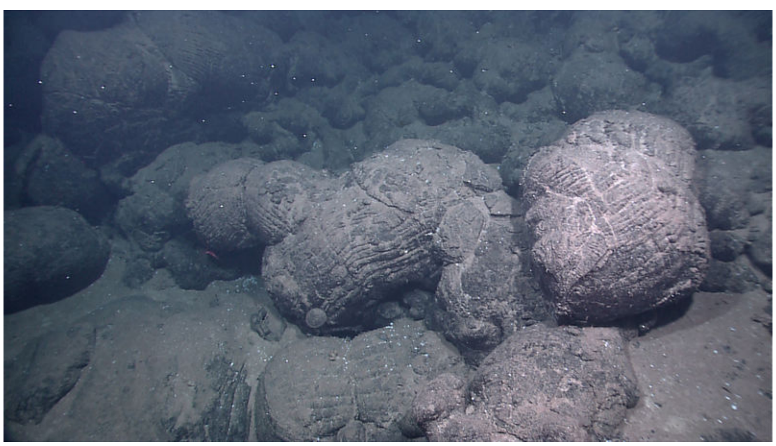

FIGURE 5.11
These underwater rocks in the Galapagos formed from pillow lava.

Predicting Volcanic Eruptions

Volcanic eruptions can be devastating, particularly to the people who live close to volcanoes. Volcanologists study volcanoes to be able to predict when a volcano will erupt. Many changes happen when a volcano is about to erupt.

History of Volcanic Activities

Scientists study a volcano's history to try to predict when it will next erupt. They want to know how long it has been since it last erupted. They also want to know the time span between its previous eruptions.

Volcanoes can be active, dormant, or extinct (**Figure** 5.12). An **active volcano** may be currently erupting. Alternatively, it may be showing signs that it will erupt in the near future. A **dormant volcano** no longer shows signs of activity. But it has erupted in recent history and will probably erupt again. An **extinct volcano** is one that has not erupted in recent history. Scientists think that it will probably not erupt again. Scientists watch both active and dormant volcanoes closely for signs that show they might erupt.

FIGURE 5.12
(A) Mount Etna in Italy is certainly an active volcano. (B) Mount Rainer in Washington State is currently dormant. The volcano could and probably will erupt again. (C) Shiprock in northern New Mexico is the remnant of a long-extinct volcano.

Earthquakes

Earthquakes may take place every day near a volcano. But before an eruption the number and size of earthquakes increases. This is the result of magma pushing upward into the magma chamber. This motion causes stresses on neighboring rock to build up. Eventually the ground shakes. A continuous string of earthquakes may indicate that a volcano is about to erupt. Scientists use seismographs to record the length and strength of each earthquake.

Slope Tilt

All that magma and gas pushing upwards can make the volcano's slope begin to swell. Ground swelling may change the shape of a volcano or cause rock falls and landslides. Most of the time, the ground tilting is not visible. Scientists detect it by using tiltmeters, which are instruments that measure the angle of the slope of a volcano.

Gases

Scientists measure the gases that escape from a volcano to predict eruptions. Gases like sulfur dioxide (SO_2), carbon dioxide (CO_2), hydrochloric acid (HCl), and water vapor can be measured at the site. Gases may also be measured from satellites. The amounts of gases and the ratios of gases are calculated to help predict eruptions.

Remote Monitoring

Satellites can be used to monitor more than just gases (**Figure** 5.13). Satellites can look for high temperature spots or areas where the volcano surface is changing. This allows scientists to detect changes accurately and safely.

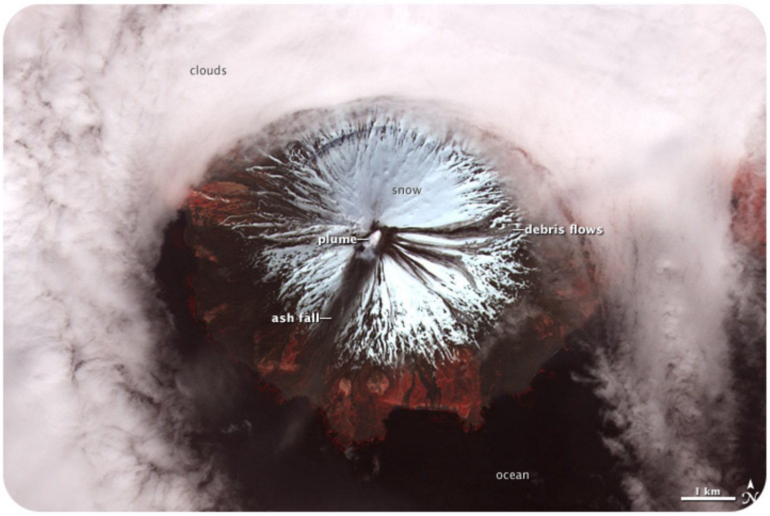

FIGURE 5.13
Mount Cleveland, in Alaska, is monitored by satellite.

Costs and Benefits of Predictions

No scientist or government agency wants to announce an eruption and then be wrong. There is a very real cost and disruption to society during a large-scale evacuation. If the scientists are wrong, people would be less likely to evacuate the next time scientists predicted an eruption. But if scientists predict an eruption that does take place it could save many lives.

Lesson Summary

- Volcanoes are produced when magma rises towards the Earth's surface because it is less dense than the surrounding rock.
- Volcanic eruptions can be non-explosive or explosive depending on the thickness of the magma.
- Explosive eruptions happen with thick magma and produce tremendous amounts of material ejected into the air.
- Non-explosive eruptions mostly produce various types of lava, such as a'a, pahoehoe and pillow lavas.
- Some signs that a volcano may soon erupt include an increase in earthquakes, surface bulging and released gases that can be monitored by scientists.

Lesson Review Questions

Recall

1. Describe what happens during an explosive volcanic eruption.

2. Describe what happens during a non-explosive volcanic eruption.
3. What are pyroclasts?

Apply Concepts

4. What is a magma chamber and what are its characteristics?
5. The boiling point of water is 100^{o}C. Why might water make an eruption more explosive?
6. Why is predicting volcanic eruptions so important?

Think Critically

7. What factors are considered in predicting volcanic eruptions?

Points to Consider

- What types of evidence would scientists use to determine whether an ancient volcanic eruption was explosive or non-explosive?
- Are all volcanoes shaped like tall mountains with a crater on the peak?
- What language do you think gives us the names a'a and pāhoehoe?
- What changes in the pattern of earthquakes might indicate a volcano is about to erupt?

5.3 Types of Volcanoes

Lesson Objectives

- Describe the basic shapes of volcanoes.
- Compare the features of volcanoes.
- Describe the stages in the formation of volcanoes.

Vocabulary

- caldera
- cinder cone
- composite volcano
- shield volcano
- strata
- supervolcano

Introduction

Some volcanoes are tall, cone-shaped mountains. They may be covered by snow or even glaciers. Some volcanoes are huge, gently sloping mountains. Many volcanoes are very small cones. Volcanic eruptions can come through cracks in the ground. Thin, fluid and runny lava forms gentle slopes. Thicker lavas build tall, steep volcanoes. Volcano types are discussed in this section.

Types of Volcanoes

A composite volcano forms the tall cone shape you usually think of when you think of a volcano. Shield volcanoes are huge, gently sloping volcanoes. Cinder cones are small, cone-shaped volcanoes.

Composite Volcanoes

Figure 5.14 shows Mt. Fuji, a classic example of a composite volcano. **Composite volcanoes** have broad bases and steep sides. These volcanoes usually have a large crater at the top. The crater was created during the volcano's last eruption.

Composite volcanoes are also called stratovolcanoes. This is because they are formed by alternating layers (strata) of magma and ash (**Figure** 5.15). The magma that creates composite volcanoes tends to be thick. The steep sides form because the lava cannot flow too far from the vent. The thick magma may also create explosive eruptions. Ash

FIGURE 5.14
Mt. Fuji is a well-known composite volcano.

and pyroclasts erupt into the air. Much of this material falls back down near the vent. This creates the steep sides of stratovolcanoes.

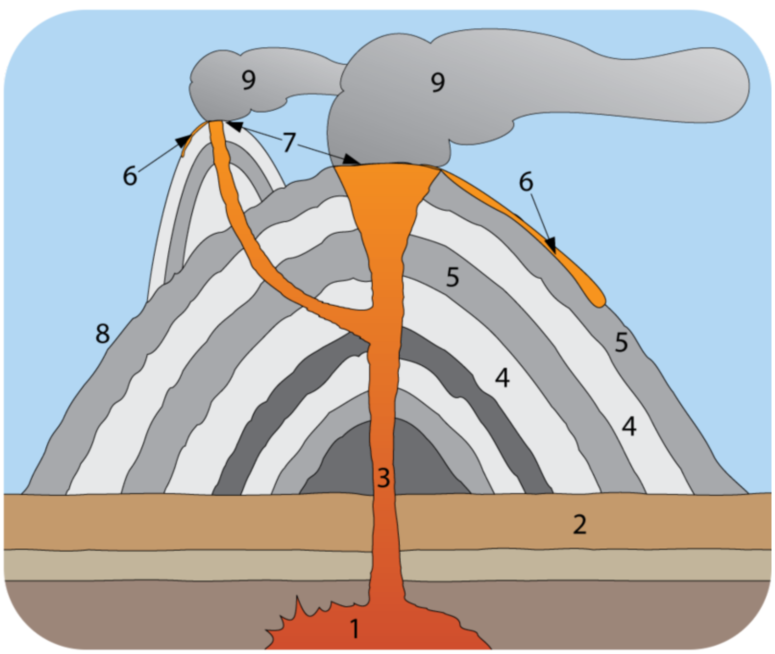

FIGURE 5.15
A cross section of a composite volcano reveals alternating layers of rock and ash: (1) magma chamber, (2) bedrock, (3) pipe, (4) ash layers, (5) lava layers, (6) lava flow, (7) vent, (8) lava, (9) ash cloud. Frequently there is a large crater at the top from the last eruption.

Composite volcanoes are common along convergent plate boundaries. When a tectonic plate subducts, it melts. This creates the thick magma needed for these eruptions. The Pacific Ring of Fire is dotted by composite volcanoes.

Shield Volcanoes

Shield volcanoes look like a huge ancient warrior's shield laid down. **Figure** 5.16 shows the Kilaeua Volcano. A shield volcano has a very wide base. It is much flatter on the top than a composite volcano. The lava that creates shield volcanoes is reltively thin. The thin lava spreads out. This builds a large, flat volcano layer by layer. Shield

FIGURE 5.16
This portion of Kilauea, a shield volcano in Hawaii, erupted between 1969 and 1974.

volcanoes are very large. For example, the Mauna Loa Volcano has a diameter of more than 112 kilometers (70 miles). The volcano forms a significant part of the island of Hawaii. The top of nearby Mauna Kea Volcano is more than ten kilometers (6 miles) from its base on the seafloor.

Shield volcanoes often form along divergent plate boundaries. They also form at hot spots, like Hawaii. Shield volcano eruptions are non-explosive.

Cinder Cones

Cinder cones are the smallest and most common type of volcano. Cinder cones have steep sides like composite volcanoes. But they are much smaller, rarely reaching even 300 meters in height. Cinder cones usually have a crater at the summit. Cinder cones are composed of small fragments of rock, called cinders. The cinders are piled on top of one another. These volcanoes usually do not produce streams of lava. Cinder cones often form near larger volcanoes. Most composite and shield volcanoes have nearby cinder cones.

Cinder cones usually build up very rapidly. They only erupt for a short time. Many only produce one eruption. For this reason, cinder cones do not reach the sizes of stratovolcanoes or shield volcanoes (**Figure** 5.17).

Calderas

During a massive eruption all of the material may be ejected from a magma changer. Without support, the mountain above the empty chamber may collapse. This produces a huge **caldera**. Calderas are generally round, bowl-shaped formations like the picture in **Figure** 5.18.

Supervolcanoes

Supervolcanoes are the most dangerous type of volcano. During an eruption, enormous amounts of ash are thrown into the atmosphere. The ash encircles the globe. This blocks the Sun and lowers the temperature of the entire planet. The result is a volcanic winter.

FIGURE 5.17
A cinder cone volcano in Lassen National Park.

FIGURE 5.18
Crater Lake, Oregon is the remnant of Mount Mazama. After an enormous eruption the mountain collapsed, forming a caldera. Crater Lake should actually be named Caldera Lake. Wizard Island, within the lake, is a cinder cone.

A supervolcano eruption took place at Lake Toba in northern Sumatra about 75,000 years ago (**Figure** 5.19). This was the largest eruption in the past 25 million years. As much as 2,800 cubic kilometers of material was ejected into the atmosphere. The result was a 6- to 10-year volcanic winter. Some scientists think that only 10,000 humans survived worldwide. The numbers of other mammals also plummeted.

The most recent supervolcano eruption was in New Zealand. The eruption was less than 2000 years ago. For a supervolcano eruption it was small, about 100 cubic kilometers of material. A much larger super eruption in Colorado produced over 5,000 cubic kilometers of material. That eruption was 28 million years ago. It was 5000 times larger than the 1980 Mount St. Helens eruption.

The largest potentially active supervolcano in North America is Yellowstone. The caldera has had three super eruptions at 2.1 million, 1.3 million and 640,000 years ago. The floor of the Yellowstone caldera is slowly rising upwards. Another eruption is very likely but no one knows when.

The cause of supervolcano eruptions is being debated. Enormous magma chambers are filled with super hot magma. This enormous eruption leaves a huge hole. The ground collapses and creates a caldera.

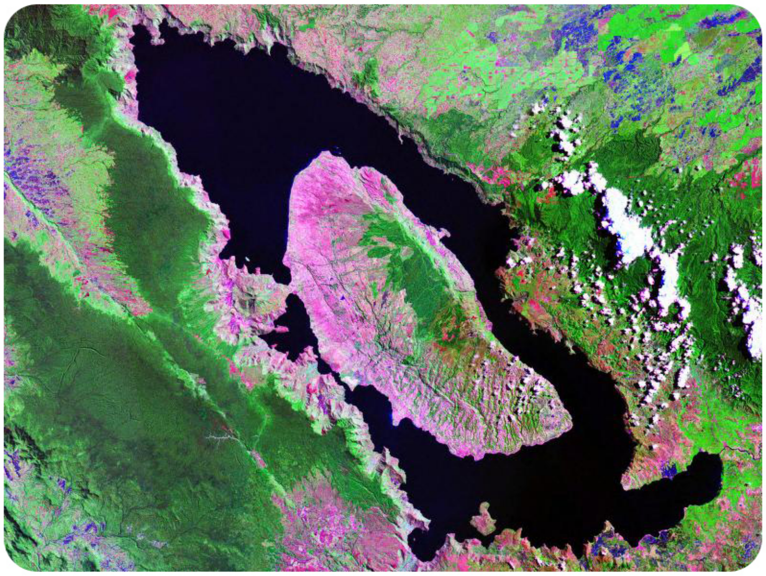

FIGURE 5.19
Lake Toba is now a caldera. It was the site of an enormous super eruption about 25 million years ago.

Lesson Summary

- Composite cones, shield volcanoes, cinder cones and supervolcanoes are some of the types of volcanoes formed.
- Composite cones are steep sided, cone shaped volcanoes that produce explosive eruptions.
- Shield volcanoes form very large, gently sloped volcanoes with a wide base.
- Cinder cones are the smallest volcanic landform. They are formed from accumulation of many small fragments of ejected material.
- A caldera forms when an explosive eruption leaves a large crater when the mountain blows apart.
- Supervolcanoes are tremendously devastating types of volcanoes that could destroy large areas when they erupt.

Lesson Review Questions

Recall

1. Describe a composite volcano and how it forms.

2. Describe a shield volcano and how it forms.

3. Describe a cinder cone and how it forms.

Apply Concepts

4. You have been told to visit an erupting volcano. Since you value your life, which type do you choose to visit and why?

5. How does the composition of magma affect the type of volcano that forms?

Think Critically

6. Scientists have only recently recognized the existence of supervolcanoes. Why were they the last type of volcano discovered?

7. The largest volcano in the solar system is not on Earth. What is needed for there to be an enormous volcano? What does this tell us about planets with enormous volcanoes?

Points to Consider

- Composite volcanoes usually have craters on the top. Why are the craters sometimes "U" or horseshoe-shaped?
- A shield volcano is relatively flat, and a composite volcano is relatively steep because of the type of magma that creates them. What type of lava might create a volcano that is steeper than a shield volcano but not as steep as a composite volcano?
- Some people believe there would be a worldwide catastrophe if a huge asteroid hits the Earth. How might an asteroid impact and a supervolcano eruption be similar?

5.4 Igneous Landforms and Geothermal Activity

Lesson Objectives

- List and describe landforms created by lava.
- Explain how magma creates different landforms.
- Describe the processes that create hot springs and geysers.

Vocabulary

- lava dome
- lava plateau
- intrusion
- hot spring
- geyser

Landforms from Lava

Extrusive igneous rocks cool at the surface. Volcanoes are one type of feature that forms from extrusive rocks. Several other interesting landforms are also extrusive features. Intrusive igneous rocks cool below the surface. These rocks do not always remain hidden. Rocks that formed in the crust are exposed when the rock and sediment that covers them is eroded away.

Lava Domes

When lava is thick, it flows slowly. If thick lava makes it to the surface, it cannot flow far from the vent. It often stays right in the middle of a crater at the top of a volcano. Here the lava creates a large, round **lava dome** (**Figure** 5.20).

Lava Plateaus

A **lava plateau** is made of a large amount of fluid lava. The lava flows over a large area and cools. This creates a large, flat surface of igneous rock. Lava plateaus may be huge. The Columbia Plateau covers over 161,000 square kilometers (63,000 square miles). It makes up parts of the states of Washington, Oregon, and Idaho.

Thin, fluid lava created the rock that makes up the entire ocean floor. This is from multiple eruptions from vents at the mid-ocean ridge. While not exactly a lava plateau, it's interesting to think about so much lava!

FIGURE 5.20
The Mono Craters in California are lava domes.

New Land

New land is created in volcanic eruptions. The Hawaiian Islands are shield volcanoes. These volcanoes formed from fluid lava (**Figure** 5.21). The island grows as lava is added on the coast. New land may also emerge from lava that erupts from beneath the water. This is one way that new land is created.

FIGURE 5.21
Lava erupts into the Pacific Ocean in Hawaii, creating new land.

Landforms from Magma

Magma that cools underground forms **intrusions** (**Figure** 5.22). Intrusions become land formations if they are exposed at the surface by erosion.

FIGURE 5.22
The granite intrusions that form the Sierra Nevada in California are well exposed.

Hot Springs and Geysers

Water works its way through porous rocks or soil. Sometimes this water is heated by nearby magma. If the water makes its way to the surface, it forms a hot spring or a geyser.

Hot Springs

When hot water gently rises to the surface, it creates a **hot spring**. A hot spring forms where a crack in the Earth allows water to reach the surface after being heated underground. Many hot springs are used by people as natural hot tubs. Some people believe that hot springs can cure illnesses. Hot springs are found all over the world, even in Antarctica!

Geysers

Geysers are also created by water that is heated beneath the Earth's surface. The water may become superheated by magma. It becomes trapped in a narrow passageway. The heat and pressure build as more water is added. When the pressure is too much, the superheated water bursts out onto the surface. This is a **geyser**.

There are only a few areas in the world where the conditions are right for the formation of geysers. Only about 1,000 geysers exist worldwide. About half of them are in the United States. The most famous geyser is Old Faithful at Yellowstone National Park (**Figure** 5.23). It is rare for a geyser to erupt so regularly, which is why Old Faithful is famous.

Lesson Summary

- Very thick lava that doesn't travel very far can produce lava domes at or near the Earth's surface or even within a volcano.

FIGURE 5.23
Old Faithful geyser in Yellowstone National Park erupts every 60 to 70 minutes, with a plume of hot water shooting up nearly 60 meters in the air.

- Lava plateaus and the entire ocean floor form from large lava flows that spread out over large areas.
- Many islands are formed from volcanoes.
- Magma can also cool and crystallize below the Earth's surface forming igneous intrusions.
- When magma heats groundwater, it can form hot springs and geysers.

Lesson Review Questions

Recall

1. What types of landforms form from intrusive igneous activity?

2. What types of landforms are created by lava?

Apply Concepts

3. How does new land form? Are the oceans being taken over by land? Why or why not?

Think Critically

4. Millions of people flock to Yellowstone National Park each year. Why are they drawn to the place? Would it be visited as much if the park were full of hot springs that were not geysers?

5. Do you think that Old Faithful will someday stop erupting? Why would it do that?

Points to Consider

- What might the Earth look like if there were no tectonic plates? Can you think of any planets or satellites (moons) that may not have tectonic plates? How is their surface different from that of the Earth?
- What kind of land formations have you seen that may have been created by volcanic activity? Did these rocks cool above or below the Earth's surface?

- Water is not the only material that can be ejected from geysers and hot springs. What other materials might be ejected from geysers and hot springs?

5.5 References

1. Courtesy of the US Geological Survey. http://commons.wikimedia.org/wiki/File:Volcano_Map.png . Public Domain
2. Courtesy of National Oceanographic and Atmospheric Administration. http://commons.wikimedia.org/wiki/File:East_Pacific_Rise.jpg . Public Domain
3. User:Foulger/Wikimedia Commons. http://commons.wikimedia.org/wiki/File:CourtHotspots.png . Public Domain
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6. (A) Courtesy of NASA; (B) David Karnå. (A) http://commons.wikimedia.org/wiki/File:Eruption_of_Eyjafjallaj%C3%B6kull_Volcano,_Iceland_April_17_Detail.jpg; (B) http://commons.wikimedia.org/wiki/File:Eyjafjallaj%C3%B6kull_major_eruption_20100510.jpg . (A) Public Domain; (B) CC BY 1.0
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Chapter 6 MS Evidence About Earth's Past

Chapter Outline

Do you recognize this animal from its skeleton? If you guessed it's *Tyrannosaurus rex*, you're right. Like other dinosaurs, *T. rex* went extinct about 65 million years ago. How do we know what this extinct animal looked like? The answer is right in front of you: from the fossils it left behind. This *T. rex* isn't a true fossil. It's just a copy on display in a museum. But many fossils of *T. rex* have been found.

Fossils not only show us what extinct animals looked like. They also provide evidence about past environments and geological processes. In this chapter, you'll find out how scientists use clues from fossils to understand Earth's history.

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6.1 Fossils

Lesson Objectives

- Explain what fossils are.
- Describe how fossils form.
- State what scientists can learn from fossils.

Vocabulary

- fossilization
- index fossil

Introduction

For thousands of years, people have discovered fossils. They have wondered about the creatures that left them. In ancient times, fossils inspired myths. Stories were told about monsters and other incredible creatures. For example, dinosaur fossils discovered in China two thousand years ago were thought to be dragon bones.

Do you know what fossils are? Do you know how they form? And do you know what they can tell us about the past?

What Are Fossils?

Fossils are preserved remains or traces of organisms that lived in the past. Most preserved remains are hard parts, such as teeth, bones, or shells. Examples of these kinds of fossils are pictured in **Figure** 6.1. Preserved traces can include footprints, burrows, or even wastes. Examples of trace fossils are also shown in **Figure** 6.1.

How Fossils Form

The process by which remains or traces of living things become fossils is called **fossilization**. Most fossils are preserved in sedimentary rocks.

Fossils in Sedimentary Rock

Most fossils form when a dead organism is buried in sediment. Layers of sediment slowly build up. The sediment is buried and turns into sedimentary rock. The remains inside the rock also turn to rock. The remains are replaced by minerals. The remains literally turn to stone. Fossilization is illustrated in **Figure** 6.2.

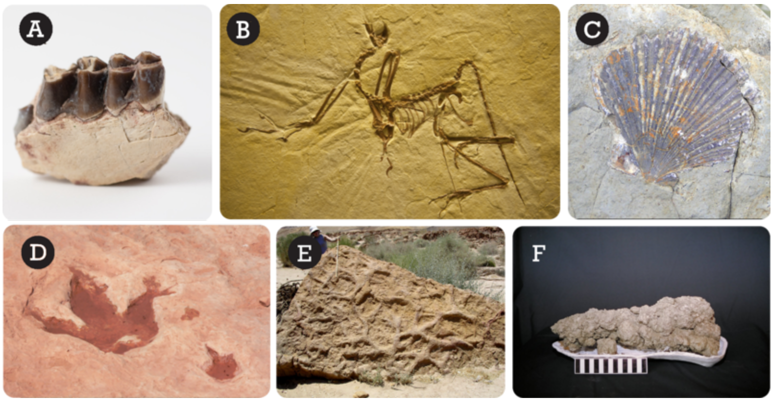


FIGURE 6.1
A variety of fossil types are pictured here. Preserved Remains: (A) teeth of a cow, (B) nearly complete dinosaur skeleton embedded in rock, (C) sea shell preserved in a rock. Preserved Traces: (D) dinosaur tracks in mud, (E) fossil animal burrow in rock, (F) fossil feces from a meat-eating dinosaur in Canada.

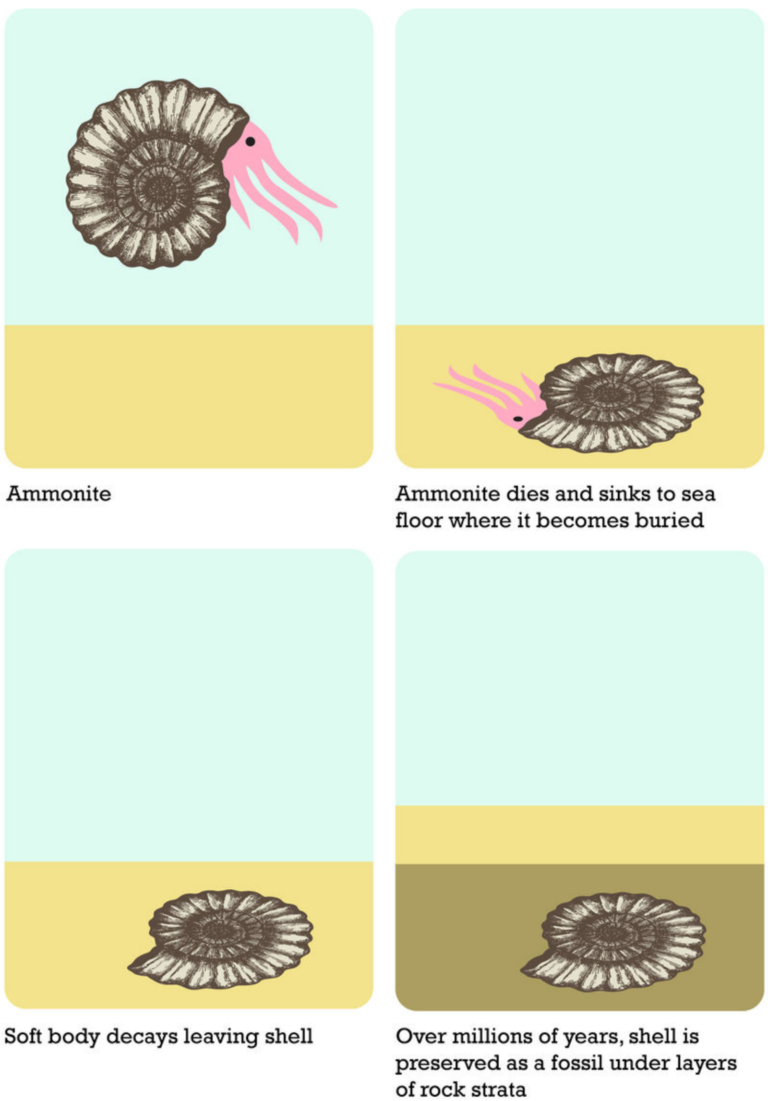


FIGURE 6.2
Fossilization. This flowchart shows how most fossils form.

Other Ways Fossils Form

Fossils may form in other ways. With complete preservation, the organism doesn't change much. As seen below, tree sap may cover an organism and then turn into amber. The original organism is preserved so that scientists might be able to study its DNA. Organisms can also be completely preserved in tar or ice. Molds and casts are another way organisms can be fossilized. A mold is an imprint of an organism left in rock. The organism's remains break down completely. Rock that fills in the mold resembles the original remains. The fossil that forms in the mold is called a cast. Molds and casts usually form in sedimentary rock. With compression, an organism's remains are put under great pressure inside rock layers. This leaves behind a dark stain in the rock.

You can read about them in **Figure** 6.3.

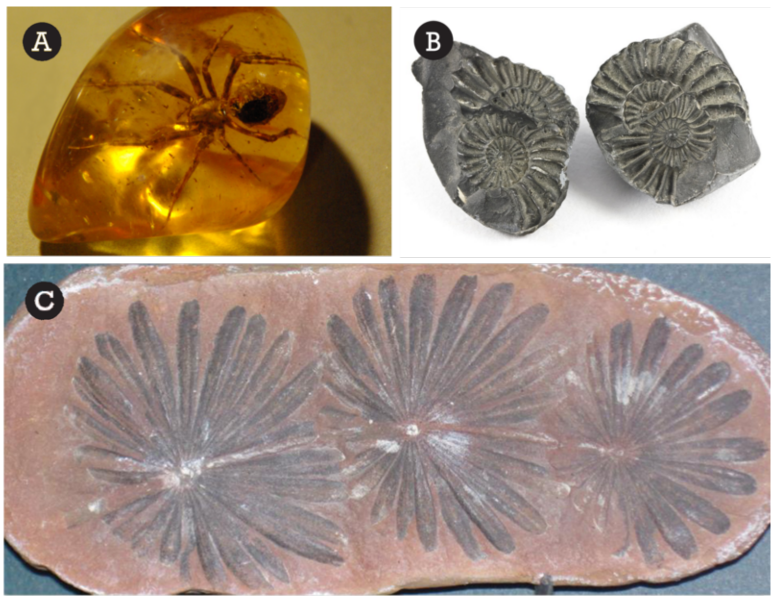


FIGURE 6.3
Ways Fossils Form. (A) Complete Preservation. This spider looks the same as it did the day it died millions of years ago! (B) Molds and Casts. A mold is a hole left in rock after an organism's remains break. A cast forms from the minerals that fill that hole and solidify. (C) Compression. A dark stain is left on a rock that was compressed. These ferns were fossilized by compression.

Why Fossilization is Rare

It's very unlikely that any given organism will become a fossil. The remains of many organisms are consumed. Remains also may be broken down by other living things or by the elements. Hard parts, such as bones, are much more likely to become fossils. But even they rarely last long enough to become fossils. Organisms without hard parts are the least likely to be fossilized. Fossils of soft organisms, from bacteria to jellyfish, are very rare.

Learning from Fossils

Of all the organisms that ever lived, only a tiny number became fossils. Still, scientists learn a lot from fossils. Fossils are our best clues about the history of life on Earth.

Fossil Clues

Fossils give clues about major geological events. Fossils can also give clues about past climates.

- Fossils of ocean animals are found at the top of Mt. Everest. Mt. Everest is the highest mountain on Earth. These fossils show that the area was once at the bottom of a sea. The seabed was later uplifted to form the Himalaya mountain range. An example is shown in the **Figure** 6.4.
- Fossils of plants are found in Antarctica. Currently, Antarctica is almost completely covered with ice. The fossil plants show that Antarctica once had a much warmer climate.

FIGURE 6.4
What can we learn from fossil clues like this fish fossil found in the Wyoming desert?

Index Fossils

Fossils are used to determine the ages of rock layers. **Index fossils** are the most useful for this. Index fossils are of organisms that lived over a wide area. They lived for a fairly short period of time. An index fossil allows a scientist to determine the age of the rock it is in.

Trilobite fossils, as shown in **Figure** 6.5, are common index fossils. Trilobites were widespread marine animals. They lived between 500 and 600 million years ago. Rock layers containing trilobite fossils must be that age. Different species of trilobite fossils can be used to narrow the age even more.

FIGURE 6.5
Trilobites are good index fossils. Why are trilobite fossils useful as index fossils?

Lesson Summary

- Fossils are preserved remains or traces of organisms that lived in the past. Most fossils form in sedimentary rock. Fossils can also be preserved in other ways. Fossilization is rare. It's very unlikely for any given organism to become a fossil.
- Fossils are the best form of evidence about the history of life on Earth. Fossils also give us clues about major geological events and past climates. Index fossils are useful for determining the ages of rock layers.

Lesson Review Questions

Recall

1. What are fossils?

2. Give examples of trace fossils.

3. Why are most preserved remains teeth, bones, or shells?

4. Describe how fossils form in sedimentary rock.

5. Why is fossilization rare?

Apply Concepts

6. Create an original diagram to explain the concept of index fossil. Your diagram should include sedimentary rock layers and fossils.

Think Critically

7. Compare and contrast the frog fossil in **Figure** 6.3 and the fossil dinosaur tracks in **Figure** 6.1. Infer what you might learn from each type of fossil.

8. Earth's climate became much cooler at different times in the past. Predict what fossil evidence you might find for this type of climate change.

Points to Consider

Fossils can help scientists estimate the ages of rocks. Some types of evidence show only that one rock is older or younger than another. Other types of evidence reveal a rock's actual age in years.

- What evidence might show that one rock is older or younger than another?
- What evidence might reveal how long ago rocks formed?

6.2 Relative Ages of Rocks

Lesson Objectives

- Explain how stratigraphy can be used to determine the relative ages of rocks.
- State how unconformities occur.
- Identify ways to match rock layers in different areas.
- Describe how Earth's history can be represented by the geologic time scale.

Vocabulary

- geologic time scale
- key bed
- law of superposition
- relative age
- stratigraphy
- unconformity

Introduction

The way things happen now is the same way things happened in the past. Earth processes have not changed over time. Mountains grow and mountains slowly wear away, just as they did billions of years ago. As the environment changes, living creatures adapt. They change over time. Some organisms may not be able to adapt. They become **extinct**, meaning that they die out completely.

Historical geologists study the Earth's past. They use clues from rocks and fossils to figure out the order of events. They think about how long it took for those events to happen.

Laws of Stratigraphy

The study of rock strata is called **stratigraphy**. The laws of stratigraphy can help scientists understand Earth's past. The laws of stratigraphy are usually credited to a geologist from Denmark named Nicolas Steno. He lived in the 1600s. The laws are illustrated in **Figure** 6.6. Refer to the figure as you read about the laws below.

Law of Superposition

Superposition refers to the position of rock layers and their relative ages. **Relative age** means age in comparison with other rocks, either younger or older. The relative ages of rocks are important for understanding Earth's history.

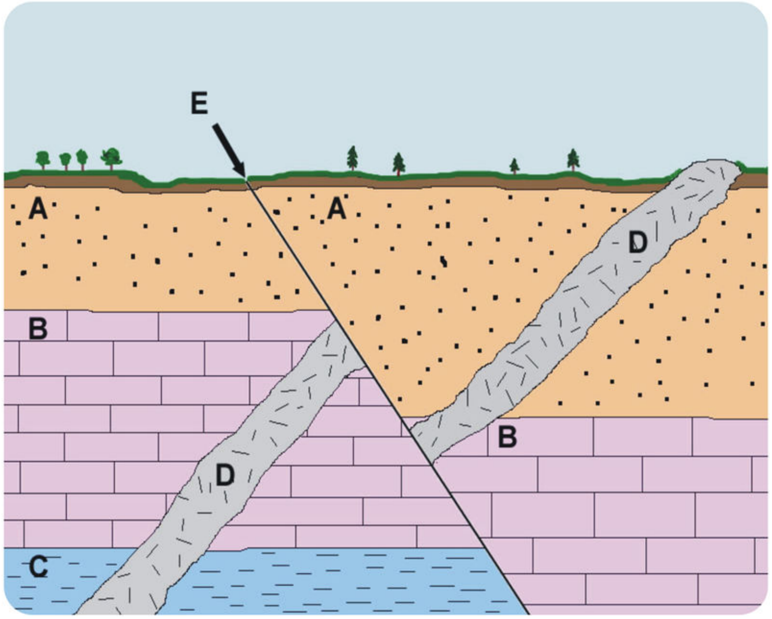


FIGURE 6.6

Laws of Stratigraphy. This diagram illustrates the laws of stratigraphy. A = Law of Superposition, B = Law of Lateral Continuity, C = Law of Original Horizontality, D = Law of Cross-Cutting Relationships

New rock layers are always deposited on top of existing rock layers. Therefore, deeper layers must be older than layers closer to the surface. This is the **law of superposition**. You can see an example in **Figure** 6.7.

FIGURE 6.7

Superposition. The rock layers at the bottom of this cliff are much older than those at the top. What force eroded the rocks and exposed the layers?

Law of Lateral Continuity

Rock layers extend laterally, or out to the sides. They may cover very broad areas, especially if they formed at the bottom of ancient seas. Erosion may have worn away some of the rock, but layers on either side of eroded areas will still "match up."

Look at the Grand Canyon in **Figure** 6.8. It's a good example of lateral continuity. You can clearly see the same

rock layers on opposite sides of the canyon. The matching rock layers were deposited at the same time, so they are the same age.

FIGURE 6.8
Lateral Continuity. Layers of the same rock type are found across canyons at the Grand Canyon.

Law of Original Horizontality

Sediments were deposited in ancient seas in horizontal, or flat, layers. If sedimentary rock layers are tilted, they must have moved after they were deposited.

Law of Cross-Cutting Relationships

Rock layers may have another rock cutting across them, like the igneous rock in **Figure** 6.9. Which rock is older? To determine this, we use the law of cross-cutting relationships. The cut rock layers are older than the rock that cuts across them.

Unconformities

Geologists can learn a lot about Earth's history by studying sedimentary rock layers. But in some places, there's a gap in time when no rock layers are present. A gap in the sequence of rock layers is called an **unconformity**.

Look at the rock layers in **Figure** 6.10. They show a feature called Hutton's unconformity. The unconformity was discovered by James Hutton in the 1700s. Hutton saw that the lower rock layers are very old. The upper layers are much younger. There are no layers in between the ancient and recent layers. Hutton thought that the intermediate rock layers eroded away before the more recent rock layers were deposited.

Hutton's discovery was a very important event in geology! Hutton determined that the rocks were deposited over time. Some were eroded away. Hutton knew that deposition and erosion are very slow. He realized that for both to occur would take an extremely long time. This made him realize that Earth must be much older than people thought. This was a really big discovery! It meant there was enough time for life to evolve gradually.

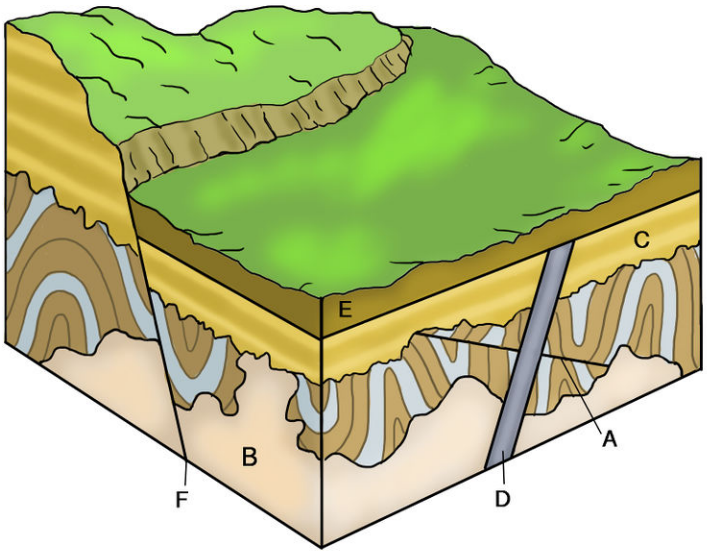


FIGURE 6.9
Cross-cutting relationships in rock layers. Rock D is a dike that cuts across all the other rocks. Is it older or younger than the other rocks?

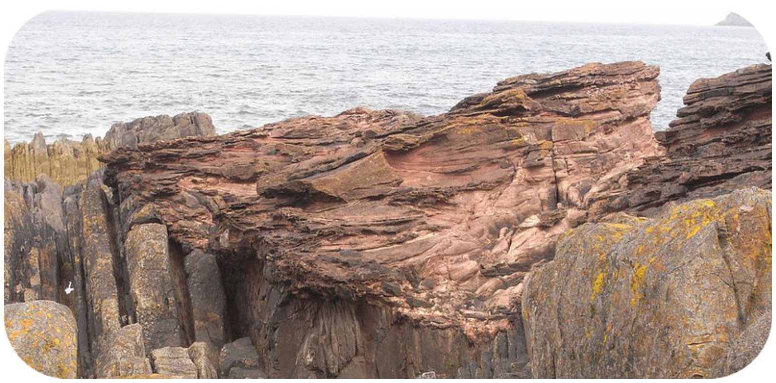


FIGURE 6.10
Hutton's unconformity, in Scotland.

Matching Rock Layers

When rock layers are in the same place, it's easy to give them relative ages. But what if rock layers are far apart? What if they are on different continents? What evidence is used to match rock layers in different places?

Widespread Rock Layers

Some rock layers extend over a very wide area. They may be found on more than one continent or in more than one country. For example, the famous White Cliffs of Dover are on the coast of southeastern England. These distinctive rocks are matched by similar white cliffs in France, Belgium, Holland, Germany, and Denmark (see **Figure** 6.11). It is important that this chalk layer goes across the English Channel. The rock is so soft that the Channel Tunnel connecting England and France was carved into it!

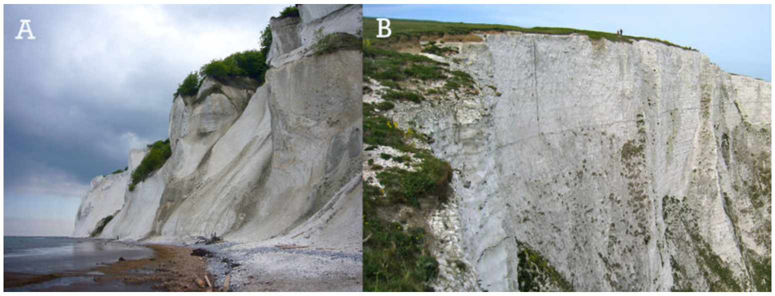


FIGURE 6.11
Chalk Cliffs. (A) Matching chalk cliffs in Denmark and (B) in Dover, U.K.

Key Beds

Like index fossils, key beds are used to match rock layers. A **key bed** is a thin layer of rock. The rock must be unique and widespread. For example, a key bed from around the time that the dinosaurs went extinct is very important. A thin layer of clay was deposited over much of Earth's surface. The clay has large amount of the element iridium. Iridium is rare on Earth but common in asteroids. This unusual clay layer has been used to match rock up layers all over the world. It also led to the hypothesis that a giant asteroid struck Earth and caused the dinosaurs to go extinct.

Using Index Fossils

Index fossils are commonly used to match rock layers in different places. You can see how this works in **Figure** 6.12. If two rock layers have the same index fossils, then they're probably about the same age.

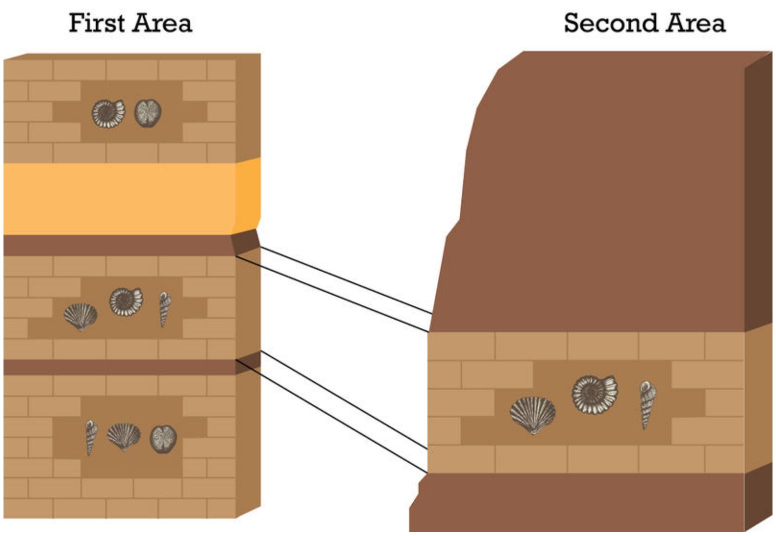


FIGURE 6.12
Using Index Fossils to Match Rock Layers. Rock layers with the same index fossils must have formed at about the same time. The presence of more than one type of index fossil provides stronger evidence that rock layers are the same age.

The Geologic Time Scale

Earth formed 4.5 billion years ago. Geologists divide this time span into smaller periods. Many of the divisions mark major events in life history.

Dividing Geologic Time

Divisions in Earth history are recorded on the **geologic time scale**. For example, the Cretaceous ended when the dinosaurs went extinct. European geologists were the first to put together the geologic time scale. So, many of the names of the time periods are from places in Europe. The Jurassic Period is named for the Jura Mountains in France and Switzerland, for example.

Putting Events in Order

To create the geologic time scale, geologists correlated rock layers. Steno's laws were used to determine the relative ages of rocks. Older rocks are at the bottom and younger rocks are at the top. The early geologic time scale could only show the order of events. The discovery of radioactivity in the late 1800s changed that. Scientists could determine the exact age of some rocks in years. They assigned dates to the time scale divisions. For example, the Jurassic began about 200 million years ago. It lasted for about 55 million years.

Divisions of the Geologic Time Scale

The largest blocks of time on the geologic time scale are called "eons." Eons are split into "eras." Each era is divided into "periods." Periods may be further divided into "epochs." Geologists may just use "early" or "late." An example is "late Jurassic," or "early Cretaceous." **Figure** 6.13 shows you what the geologic time scale looks like.

EON	ERA	PERIOD	MILLIONS OF YEARS AGO
Phanerozoic	Cenozoic	Quaternary	1.6
		Tertiary	66
	Mesozoic	Cretaceous	138
		Jurassic	205
		Triassic	240
	Paleozoic	Permian	290
		Pennsylvanian	330
		Mississippian	360
		Devonian	410
		Silurian	435
		Ordovician	500
		Cambrian	570
Proterozoic	Late Proterozoic Middle Proterozoic Early Proterozoic		2500
Archean	Late Archean Middle Archean Early Archean		3800?
Pre-Archean			

FIGURE 6.13
The Geologic Time Scale.

Life and the Geologic Time Scale

The geologic time scale may include illustrations of how life on Earth has changed. Major events on Earth may also be shown. These include the formation of the major mountains or the extinction of the dinosaurs. **Figure** 6.14 is a different kind of the geologic time scale. It shows how Earth's environment and life forms have changed.

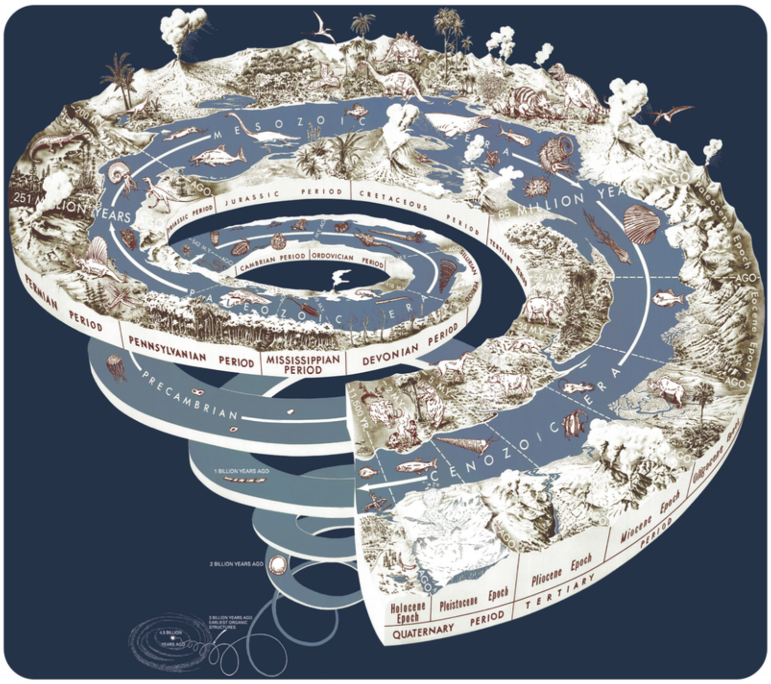


FIGURE 6.14
The evolution of life is shown on this spiral.

Your Place in Geologic Time

We now live in the Phanerozoic Eon, the Cenozoic Era, the Quaternary Period, and the Holocene Epoch. "Phanerozoic" means visible life. During this eon, rocks contain visible fossils. Before the Phanerozoic, life was microscopic. The Cenozoic Era means new life. It encompasses the most recent forms of life on Earth. The Cenozoic is sometimes called the Age of Mammals. Before the Cenozoic came the Mesozoic and Paleozoic. The Mesozoic means middle life. This is the age of reptiles, when dinosaurs ruled the planet. The Paleozoic is old life. Organisms like invertebrates and fish were the most common lifeforms.

Lesson Summary

- The study of rock layers is called stratigraphy. Laws of stratigraphy help scientists determine the relative ages of rocks. The main law is the law of superposition. This law states that deeper rock layers are older than layers closer to the surface.
- An unconformity is a gap in rock layers. They occur where older rock layers eroded away completely before new rock layers were deposited.
- Other clues help determine the relative ages of rocks in different places. They include key beds and index fossils.
- Scientists use the geologic time scale to illustrate the order in which events on Earth have happened.

- The geologic time scale was developed after scientists observed changes in the fossils going from oldest to youngest sedimentary rocks. They used relative dating to divide Earth's past in several chunks of time when similar organisms were on Earth.
- The geologic time scale is divided into eons, eras, periods, and epochs.

Lesson Review Questions

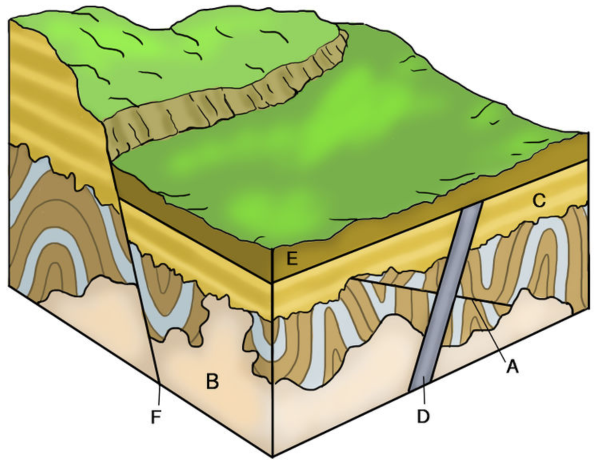
Recall

1. Define stratigraphy.
2. What is the relative age of a rock?
3. State the law of superposition.
4. What are unconformities?
5. How do key beds help date rock layers?

Apply Concepts

6. Apply laws of stratigraphy to explain the rock formation below.

7. Which rock in the illustration below formed first, the igneous rock (A) or the sedimentary rock (B)? Apply lesson concepts to support your answer.



8. Why did early geologic time scales not include the number of years ago that events happened?

Think Critically

9. Use the law of lateral continuity to explain why the same rock layers are found on opposite sides of the Grand Canyon.

10. Dinosaurs went extinct about 66 million years ago. Which period of geologic time was the last in which dinosaurs lived?

11. Why are sedimentary rocks more useful than metamorphic or igneous rocks in establishing the relative ages of rock?

Points to Consider

In this lesson, you read how scientists determine the relative ages of sedimentary rock layers. The law of superposition determines which rock layers are younger or older than others.

- What about the actual ages of rocks? Is there a way to estimate their ages in years?
- And what about other kinds of rocks? For example, is there a way to estimate the ages of igneous rocks?

6.3 Absolute Ages of Rocks

Lesson Objectives

- Describe radioactive decay.
- Explain radiometric dating.

Vocabulary

- absolute age
- carbon-14 dating
- half-life
- isotope
- radioactive decay
- radiometric dating

Introduction

The age of a rock in years is its **absolute age**. Absolute ages are much different from relative ages. The way of determining them is different, too. Absolute ages are determined by radiometric methods, such as carbon-14 dating. These methods depend on radioactive decay.

Radioactive Decay

Radioactive decay is the breakdown of unstable elements into stable elements. To understand this process, recall that the atoms of all elements contain the particles protons, neutrons, and electrons.

Isotopes

An element is defined by the number of protons it contains. All atoms of a given element contain the same number of protons. The number of neutrons in an element may vary. Atoms of an element with different numbers of neutrons are called **isotopes**.

Consider carbon as an example. Two isotopes of carbon are shown in **Figure** 6.15. Compare their protons and neutrons. Both contain 6 protons. But carbon-12 has 6 neutrons and carbon-14 has 8 neutrons.

Almost all carbon atoms are carbon-12. This is a stable isotope of carbon. Only a tiny percentage of carbon atoms are carbon-14. Carbon-14 is unstable. **Figure** 6.16 shows carbon dioxide, which forms in the atmosphere from carbon-14 and oxygen. Neutrons in cosmic rays strike nitrogen atoms in the atmosphere. The nitrogen forms carbon-14.

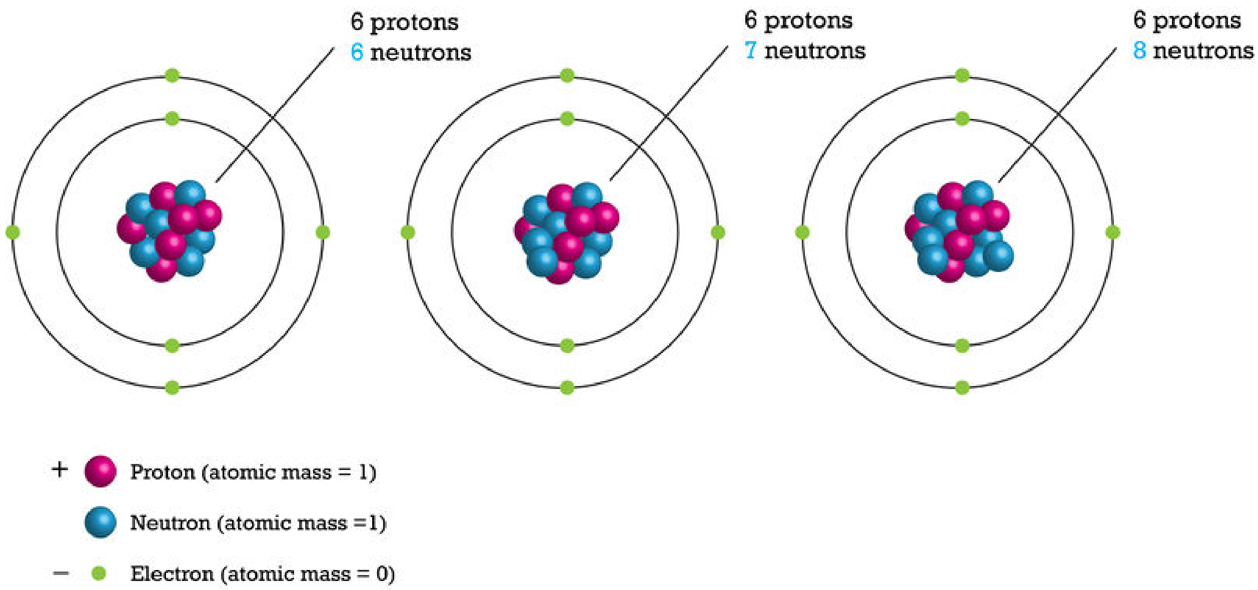


FIGURE 6.15
Isotopes are named for their number of protons plus neutrons. If a carbon atom had 7 neutrons, what would it be named?

Carbon in the atmosphere combines with oxygen to form carbon dioxide. Plants take in carbon dioxide during photosynthesis. In this way, carbon-14 enters food chains.

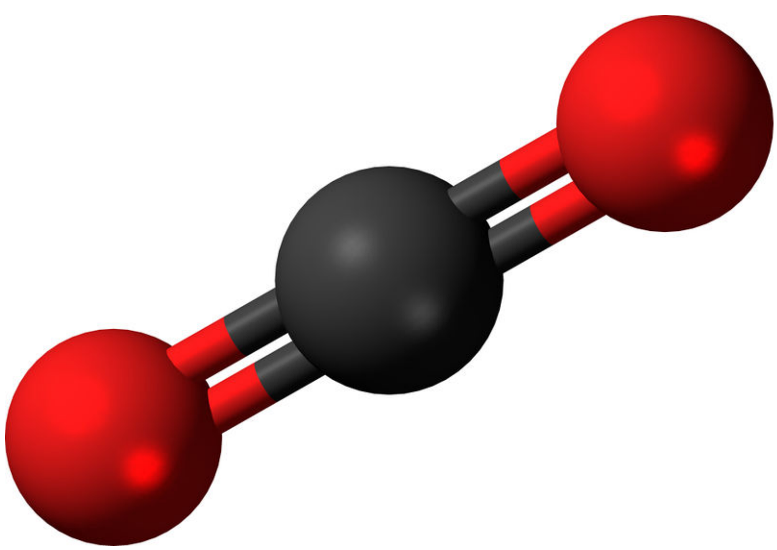


FIGURE 6.16
Carbon-14 forms in the atmosphere. It combines with oxygen and forms carbon dioxide. How does carbon-14 end up in fossils?

Decay of Unstable Isotopes

Like other unstable isotopes, carbon-14 breaks down, or decays. For carbon-14 decay, each carbon-14 atom loses an alpha particle. It changes to a stable atom of nitrogen-14. This is illustrated in **Figure** 6.17.

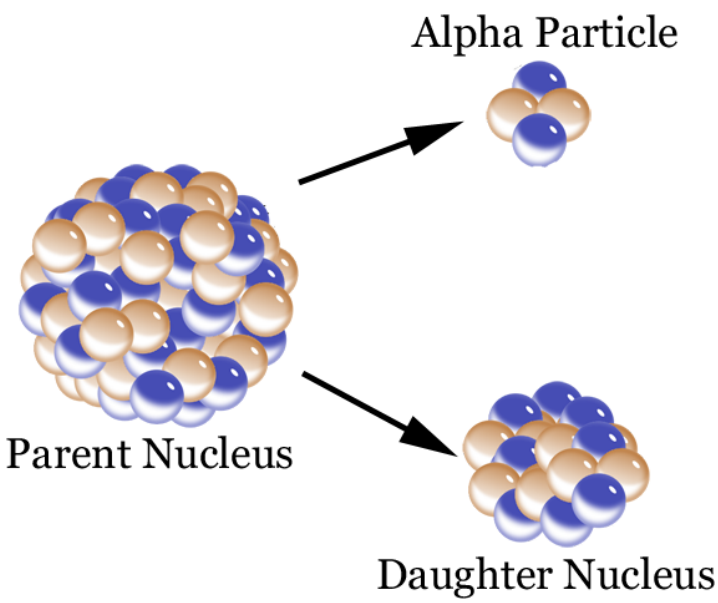


FIGURE 6.17
Unstable isotopes, such as carbon-14, decay by losing atomic particles. They form different, stable elements when they decay. In this case, the daughter is nitrogen-14.

The decay of an unstable isotope to a stable element occurs at a constant rate. This rate is different for each isotope pair. The decay rate is measured in a unit called the half-life. The **half-life** is the time it takes for half of a given amount of an isotope to decay. For example, the half-life of carbon-14 is 5730 years. Imagine that you start out with 100 grams of carbon-14. In 5730 years, half of it decays. This leaves 50 grams of carbon-14. Over the next 5730 years, half of the remaining amount will decay. Now there are 25 grams of carbon-14. How many grams will there be in another 5730 years? **Figure** 6.18 graphs the rate of decay of carbon-14.

Radiometric Dating

The rate of decay of unstable isotopes can be used to estimate the absolute ages of fossils and rocks. This type of dating is called **radiometric dating**.

Carbon-14 Dating

The best-known method of radiometric dating is **carbon-14 dating**. A living thing takes in carbon-14 (along with stable carbon-12). As the carbon-14 decays, it is replaced with more carbon-14. After the organism dies, it stops taking in carbon. That includes carbon-14. The carbon-14 that is in its body continues to decay. So the organism contains less and less carbon-14 as time goes on. We can estimate the amount of carbon-14 that has decayed by measuring the amount of carbon-14 to carbon-12. We know how fast carbon-14 decays. With this information, we can tell how long ago the organism died.

Carbon-14 has a relatively short half-life. It decays quickly compared to some other unstable isotopes. So carbon-14 dating is useful for specimens younger than 50,000 years old. That's a blink of an eye in geologic time. But

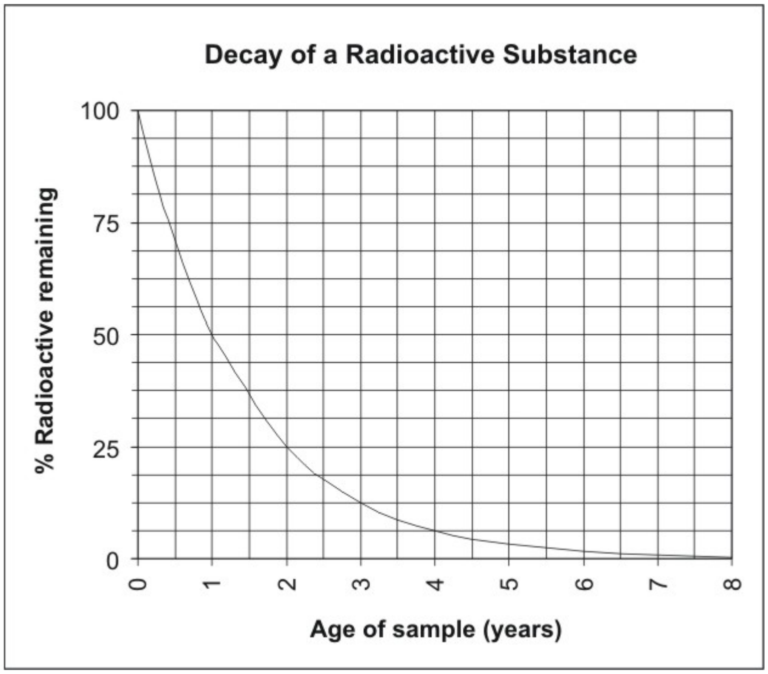


FIGURE 6.18
The rate of decay of carbon-14 is stable over time.

radiocarbon dating is very useful for more recent events. One important use of radiocarbon is early human sites. Carbon-14 dating is also limited to the remains of once-living things. To date rocks, scientists use other radioactive isotopes.

Other Radioactive Isotopes

The isotopes in **Table** 6.1 are used to date igneous rocks. These isotopes have much longer half-lives than carbon-14. Because they decay more slowly, they can be used to date much older specimens. Which of these isotopes could be used to date a rock that formed half a million years ago?

TABLE 6.1: Isotope Rock Dating

Unstable Isotope	Decays to	At a Half-Life of (years)	Dates Rocks Aged (years old)
Potassium-40	Argon-40	1.3 billion	100 thousand – 1 billion
Uranium-235	Lead-207	700 million	1 million – 4.5 billion
Uranium-238	Lead-206	4.5 billion	1 million – 4.5 billion

Lesson Summary

- The age of a rock in years is its absolute age. The main evidence for absolute age comes from radiometric dating methods, such as carbon-14 dating. These methods depend on radioactive decay.
- Radioactive decay is the breakdown of unstable isotopes into stable elements. For example, carbon-14 is an unstable isotope of carbon that decays to the stable element nitrogen-14. The rate of decay of an isotope is measured in half-lives. A half-life is the time it takes for half a given amount of an isotope to decay.
- Radiometric dating uses the rate of decay of unstable isotopes to estimate the absolute ages of fossils and rocks. Carbon-14 can be used to date recent organic remains. Other isotopes can be used to date igneous rocks that are much older.

Think Critically

7. Explain how carbon-14 dating works.

8. Compare and contrast carbon-14 dating and potassium-40 dating.

Points to Consider

Scientists estimate the ages of rock layers in order to better understand Earth's history and the history of life.

- What do you already know about Earth's history? For example, do you know how Earth formed?
- How old is Earth? When did the planet first form? And when did life first appear?

6.4 References

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2. (A) Flickr:furtwangl; (B) Hannes Grobe/AWI; (C) Ben Salter (Flickr:Capt' Gorgeous); (D) edmondo gnerre; (E) Mark A. Wilson (Department of Geology, The College of Wooster); (F) Courtesy of the U.S. Geological Survey. (A) http://www.flickr.com/photos/furtwangl/3283595757/; (B) http://commons.wikimedia.org/wiki/File:Archaeopteryx-8-senkenberg_hg.jpg; (C) http://www.flickr.com/photos/ben_salter/2103829606/; (D) http://www.flickr.com/photos/edgnerre/2891672667/; (E) http://commons.wikimedia.org/wiki/File:ThalassinoidesIsrael.JPG; (F) http://commons.wikimedia.org/wiki/File:Coprolite.jpg . (A) CC BY 2.0; (B) CC BY 3.0; (C) CC BY 2.0; (D) CC BY 2.0; (E) Public Domain; (F) Public Domain
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5. Courtesy of the National Park Service. http://www.nps.gov/imr/photosmultimedia/photogallery.htm?id=F17B1C64-155D-451F-6765341D9B8E553F . Public Domain
6. Daderot. http://wikimedia.commons.org/wiki/File:Asaphellus_species,_intact_Trilobite_fossils,_Early_Ordovician_Period,_Dra_Valley,_Morocco_-_Royal_Ontario_Museum_-_DSC09851.JPG . Public Domain
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