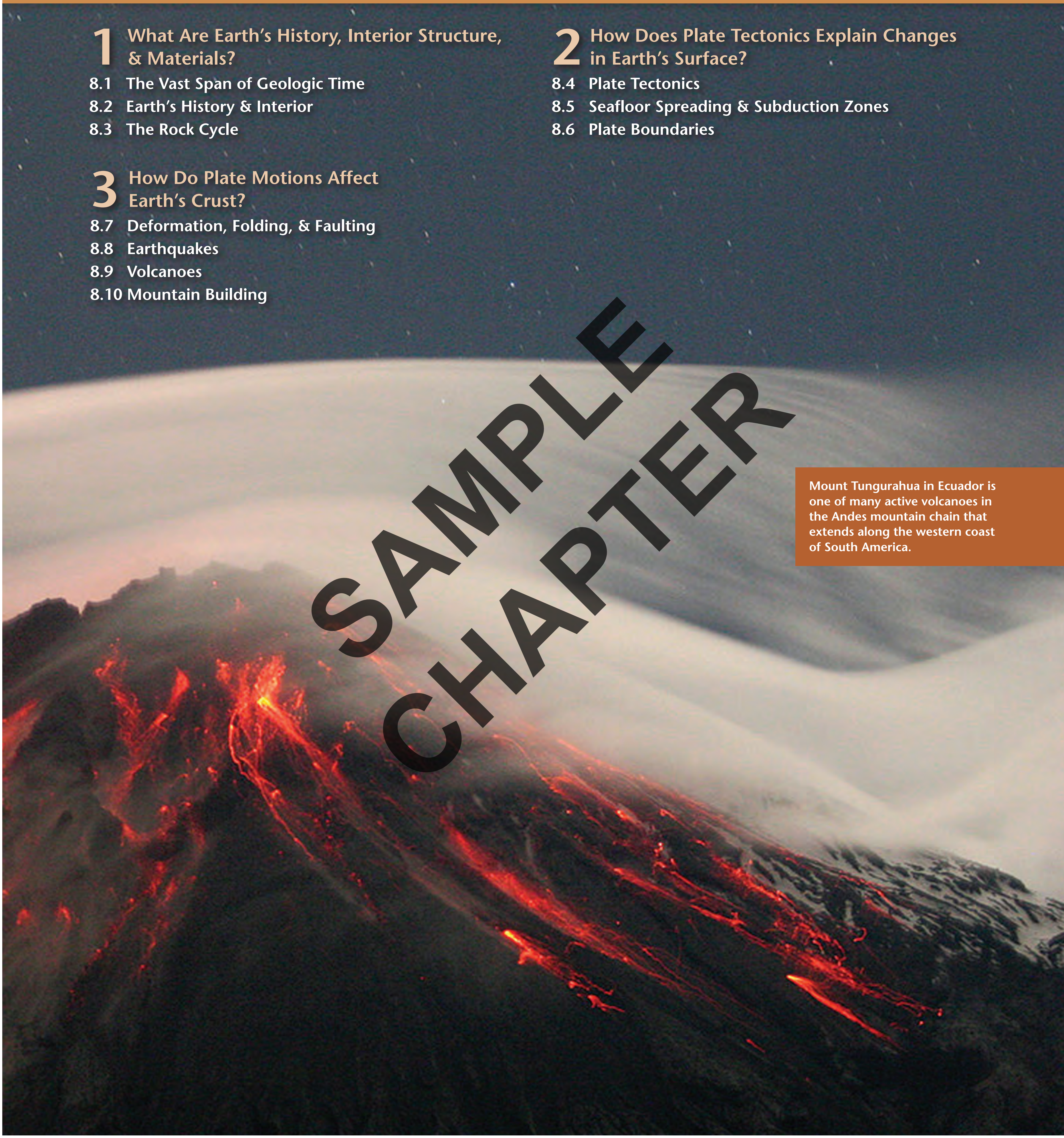
The Geosphere: Earth's Interior & Surface

8 Tectonics, Earthquakes, & Volcanism

During the twentieth century, new research revolutionized our understanding of Earth science. These discoveries explained how volcanoes such as Ecuador's Tungurahua were formed and how the continents and oceans came to their present arrangement. The theory of plate tectonics—the main subject of this chapter—provides a unified explanation for the patterns of earthquakes, volcanoes, and mountain building that dominate our planet. Events such as the March 2011 earthquake and tsunami that devastated Japan turn world attention to the Earth sciences, including physical geography, for explanations.



Mount Tungurahua in Ecuador is one of many active volcanoes in the Andes mountain chain that extends along the western coast of South America.

8.1 The Vast Span of Geologic Time

Key Learning Concepts

- ***Describe*** the geologic time scale.
- ***Distinguish*** between relative and absolute time.
- ***Explain*** how the principle of uniformitarianism helps geologists interpret Earth's history.

Earth is about 4.6 billion years old. The Moon, about 30 million years younger, formed when a Mars-sized object struck the early Earth and threw debris into orbit that then coalesced into the Moon. Geologists have used data from rocks to reconstruct these and other key events in Earth's history.

Eons, Eras, Periods, & Epochs

The **geologic time scale** is a summary timeline of all Earth history (▼**Fig. 8.1**). It names the time intervals for each segment of Earth's history, from vast *eons* through briefer *eras*, *periods*, and *epochs.* Breaks between some of the major time intervals also mark the five major mass extinctions, when the total number of living species drop dramatically. These range from a mass extinction 440 million years ago (m.y.a.) to the present-day sixth episode of extinctions caused by modern civilization.

geoCHECK ✔ Referring to Figure 8.1, list the geologic periods that make up the Cenozoic era.

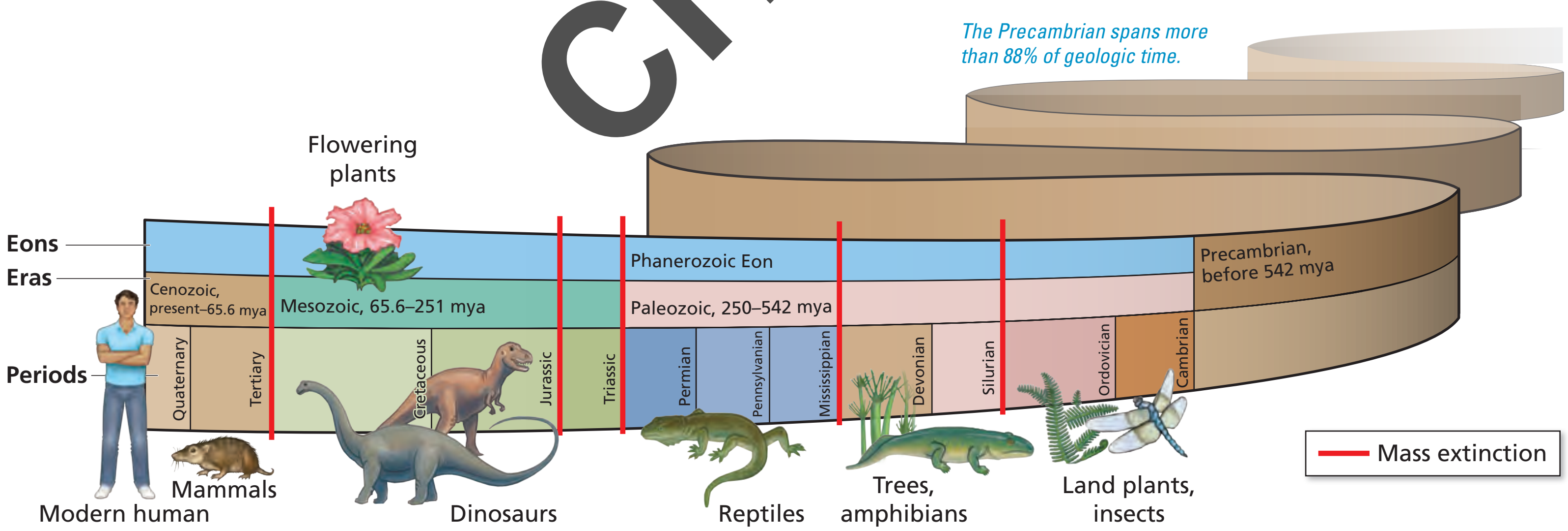
Absolute Time & Relative Time

The geologic time scale depicts two kinds of time: **absolute time** is the actual number of years before the present, and **relative time** is the sequence of events—what happened in what order. Scientific methods such as radiometric dating (Chapter 7) determine absolute time, the actual "millions of years ago" shown on the time scale. In contrast, relative time is based on the relative positions of rock strata (layers) above or below each other. The study of the relative positions of these strata is called *stratigraphy*. To establish relative time based on stratigraphy, geologists apply the **principle of superposition**, which states that *rock and sediment always are arranged with the youngest beds "superposed" toward the top of a rock formation and the oldest at the base, if they have not been disturbed*. Thus if you look at the stratigraphy of the Grand Canyon, the youngest layers are found at the canyon rim, and the oldest layers are found at the bottom (▶**Fig. 8.2**).

In the Grand Canyon, the principle of superposition places the extremely ancient strata of the Precambrian at the bottom of the canyon and the more recent, but still ancient, strata of the Permian period at the top. Rocks younger than the Permian, however, are missing from the canyon because they have worn away over time. Important time clues—namely, *fossils*, the remains of ancient plants and animals—lie embedded within the canyon walls. Since approximately 4 billion years ago, life has left its evolving imprint in Earth's rocks.

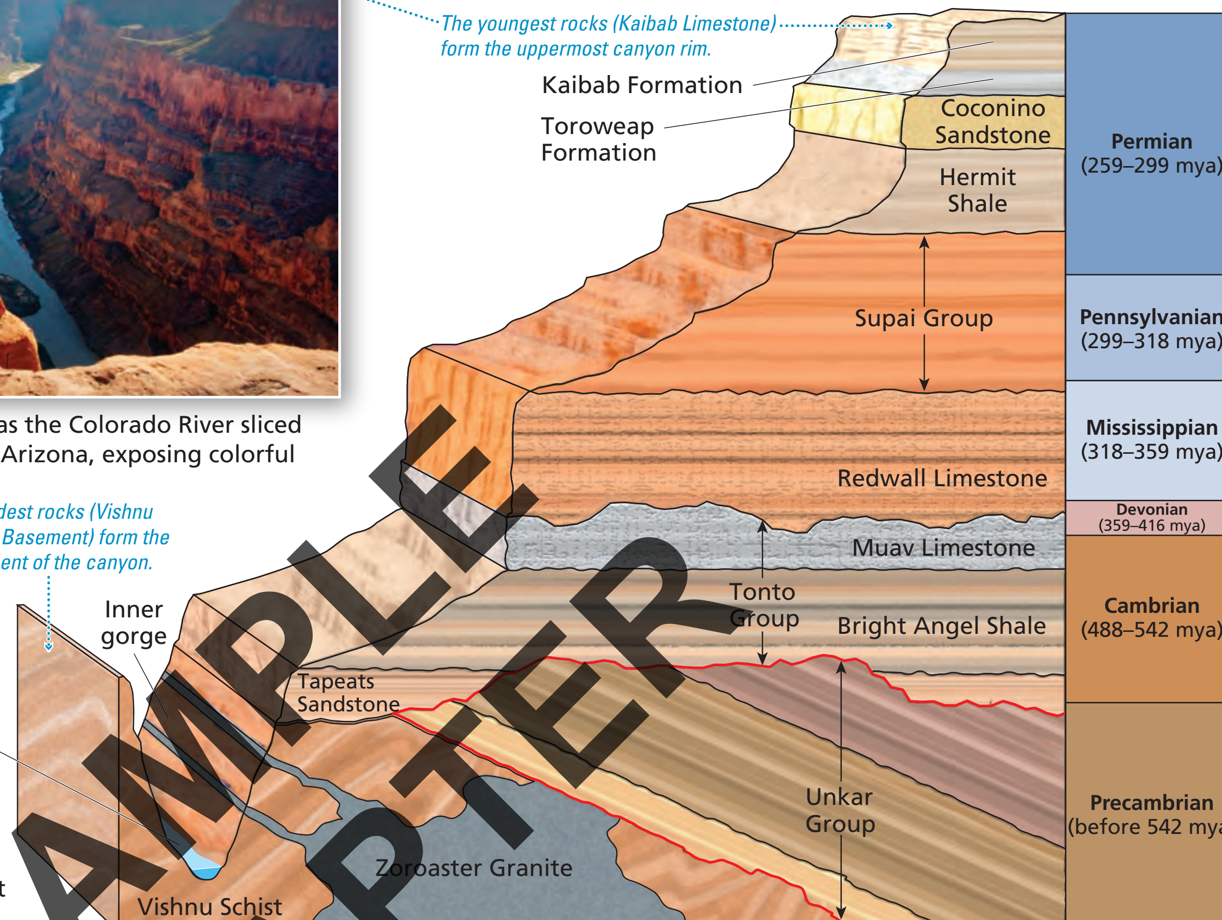
We now live in the Holocene epoch, which began about 11,500 years ago. Geologists are debating whether to add another epoch to the geologic time scale—the Anthropocene—beginning around the year 1800, which marks the start of the Industrial Revolution in Europe. As the impacts of humans on Earth systems increases, namely deforestation, land clearing for agriculture, and fossil-fuel burning, numerous scientists now agree that we are in a new epoch called the Anthropocene.

geoCHECK ✔ What is the difference between absolute and relative time?



▲**8.1 Geologic time scale, showing highlights of Earth's history**

(a) The Grand Canyon formed as the Colorado River sliced through a plateau in northern Arizona, exposing colorful rock layers.



Animation MG
Applying Relative Dating Principles
http://goo.gl/h09dOs

(b) The canyon's rocks range from 270 million years old at the top (Permian period) to more than 1 billion years old at the bottom (Precambrian).

▲**8.2 Superposition of rock layers in the Grand Canyon** The different types of rock that line the Grand Canyon formed during different geologic periods.

The Principle of Uniformitarianism

A guiding principle of Earth science is **uniformitarianism**—"the present is the key to the past"—which assumes that *the same physical processes active in the environment today have been operating throughout geologic time* (▼**Fig. 8.3**). For example, if streams carve valleys now, they must have done so 500 m.y.a.

▼**8.3 The principle of uniformitarianism** Although the ages and types of rocks vary by location, the same physical processes of erosion, transport, and deposition of sediment active in the environment today have been operating throughout geologic time. This stream-carved river valley is in the Pamir Mountains of Central Asia.

Evidence from the landscape record of volcanic eruptions, earthquakes, and processes that shape Earth's surface supports uniformitarianism. Although the ages and types of rock differ from place to place, the processes that form, erode, and deposit these rocks and sediment are *uniformly* similar. Uniformitarianism refers to the actual physical processes that create our different landforms, while geologic time provides the millions of years during which these processes operate. James Hutton first proposed this concept in his *Theory of the Earth* (1795). Charles Lyell further explored the implications of uniformitarianism in *Principles of Geology* (1830).

geoCHECK ✔ How do Earth scientists define uniformitarianism?

geoQUIZ

1. Imagine looking at a canyon wall of layered rock strata. According to the principle of superposition, how does the relative age of strata at the top of the canyon compare with the age of strata at the bottom of the canyon?
2. Explain why scientists may add a new geologic epoch—the Anthropocene—to the geologic time scale.
3. What does the principle of uniformitarianism suggest about how river deltas form in different parts of the world, such as the Nile Delta in Egypt and the Mississippi Delta in North America?

8.2 Earth History & Interior

Key Learning Concepts

- ***Summarize*** how and when Earth formed.
- ***Describe*** Earth's layered structure.

Our knowledge of Earth's interior comes from analyzing surface features such as road cuts, landslide scars, volcanic flows, and the stratigraphy of deep canyons. Scientists also gain information from seismic waves that travel at different rates through the interior layers of Earth. When scientists analyze these different sources of information, a clear picture of Earth's interior emerges. The structure of the interior also reflects the processes that formed our planet.

Earth's Formation

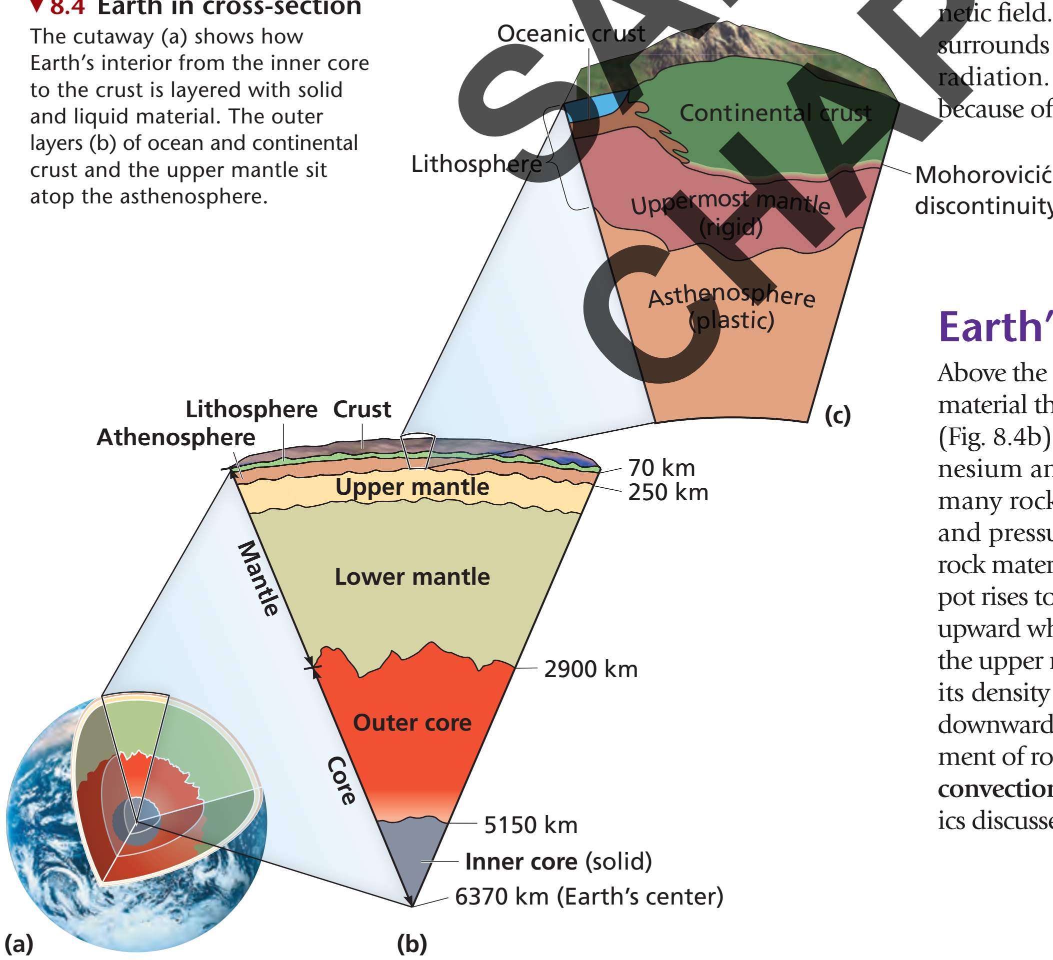
Along with the other planets and the Sun, Earth is thought to have condensed from a nebula of dust, gas, and icy comets about 4.6 billion years ago. Rocks in Western Australia date to between 4.2 and 4.4 billion years old and are possibly the oldest materials in Earth's crust.

As Earth solidified, gravity sorted materials by density. Denser substances such as iron gravitated slowly to its center, and less dense elements, such as oxygen, silicon, and aluminum, slowly welled upward to the surface and concentrated in the crust. Consequently, Earth's interior is sorted into roughly concentric layers, each one distinct in either chemical composition or temperature (▼ **Fig. 8.4a**). Thus Earth's core is nearly twice as dense as the mantle because it is composed of denser metallic iron-nickel alloy.

Earth's Internal Energy Source Heat left over from the planet's formation and heat produced by the decay of radioactive isotopes make Earth's interior extremely hot. This heat energy migrates outward from the center by conduction and by convection (review heat transfer in Chapter 2). This escaping heat—from Earth's origin and from radioactive decay—is the energy that drives plate tectonics. As explained below, this heat energy also affects processes on Earth's surface.

geoCHECK ✔ Why does Earth's interior have a layered structure?

▼ **8.4 Earth in cross-section**
The cutaway (a) shows how Earth's interior from the inner core to the crust is layered with solid and liquid material. The outer layers (b) of ocean and continental crust and the upper mantle sit atop the asthenosphere.



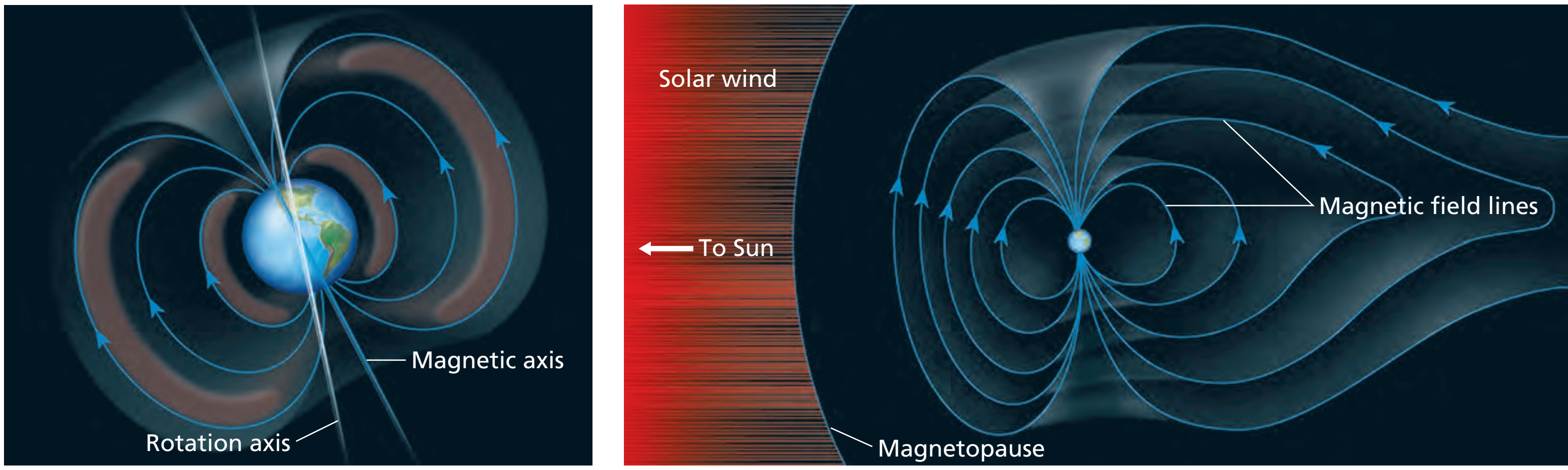
Earth's Core & Magnetism

At Earth's center lies the dense, metallic core, divided into an inner core and outer core (▼ **Fig. 8.4b**). The core makes up one third of Earth's entire mass, but only one sixth of its volume. The inner core of solid impure iron is well above the melting temperature of iron at surface conditions, but remains solid because of tremendous pressure caused by the weight of the overlying materials. The outer core is molten iron and has a lower density than the inner core. The rotation of Earth affects the fluid outer core, generating Earth's magnetic field. Recall from Chapter 1 that the magnetosphere surrounds and protects Earth from solar wind and cosmic radiation. A compass needle points to magnetic north because of Earth's magnetic field (▸ **Fig. 8.5**).

geoCHECK ✔ What do scientists think causes Earth's magnetic field?

Earth's Mantle

Above the core lies the mantle, a layer of hot, but mostly solid material that represents about 80% of Earth's total volume (Fig. 8.4b). The mantle is rich in oxides of iron and magnesium and in *silicates*—silicon dioxide, a component of many rocks and minerals. The extremely high temperature and pressure in the lower mantle softens and deforms solid rock material over millions of years. Just as boiling water in a pot rises to the surface, rocks in the warmer lower mantle rise upward where they slowly cool as their heat is transferred to the upper mantle (▸ **Fig. 8.6**). As the rock material cools, its density increases, and the rocks begin to sink and move downward, also aided by gravity. The up-and-down movement of rock material in Earth's interior is the result of these **convection currents**, which power the process of plate tectonics discussed below.



(a) Earth has geographic poles and magnetic poles. The magnetic field draws a compass needle to point to magnetic north.

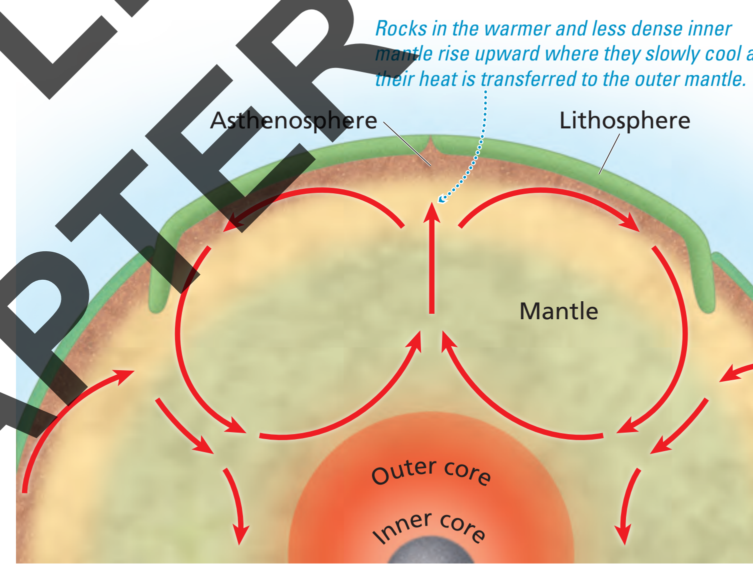
(b) The magnetosphere that surrounds and protects Earth from solar wind and cosmic radiation. The magnetosphere encircling Earth is the strongest of all the solid planets.

▲ **8.5 Earth's magnetic field** Scientists think motions within Earth's molten outer core produce the planet's magnetic field.

In the upper mantle, closer to Earth's crust, the temperature and pressure decline, so the rocks are more rigid. The asthenosphere (from Greek *asthenos*, meaning "weak") lies just below the lithosphere and extends from about 70 km beneath Earth's surface to a depth of 250 km (43 mi to 155 mi). The asthenosphere is the least rigid part of the mantle. Geologists describe the rock of the asthenosphere as being "plastic." This means that its weak material can bend or flow slowly over long periods of time.

The asthenosphere contains pockets of increased heat from radioactive decay. This partly explains why about 10% of this layer is molten in uneven patterns and hot spots and why slow convective currents occur in its hot, plastic material. The resulting slow movement in the asthenosphere disturbs the overlying crust and creates tectonic folding, faulting, and deformation of surface rocks.

geoCHECK ✔ Describe the characteristics of the asthenosphere.



▲ **8.6 Convection currents in Earth's interior** Differences in temperature and density within the mantle produce convection currents, in which hot, but solid material slowly rises through the mantle as cooler material near the top of the sinks downward.

Earth's Lithosphere & Crust

Above the asthenosphere, the uppermost 70 km (43 mi) of mantle and Earth's crust are collectively called the lithosphere (Fig. 8.4b). This layer "floats" on the asthenosphere and is broken into "plates" (discussed in Module 8.4) that are moved during tectonic processes. The **Mohorovičić discontinuity**, or ***Moho*** separates the crust from the mantle. The Moho is named for the Croatian scientist who determined that seismic waves generated by earthquakes change at this boundary because of the change in Earth materials and densities.

Above the Moho lies the crust—Earth's rocky outer shell made up of the continents and the rocks that form the bottom of ocean basins. The crust represents only a fraction of Earth's overall diameter and varies in thickness. Crustal areas below mountain masses are 50–60 km (31–37 mi) in thickness. Crustal areas beneath continental interiors are about 30 km (l19 mi) in thickness. Oceanic crust averages only 5 km (3 mi). Figure 8.4c illustrates the relation of the crust to the rest of the lithosphere and to the asthenosphere below.

geoCHECK ✔ Identify the layers immediately above and below the Moho.

geoQUIZ

1. Describe the main layers that comprise Earth's interior.
2. How does Earth's inner core differ from the outer core?
3. What is the relationship between the asthenosphere, the Moho, and the crust?

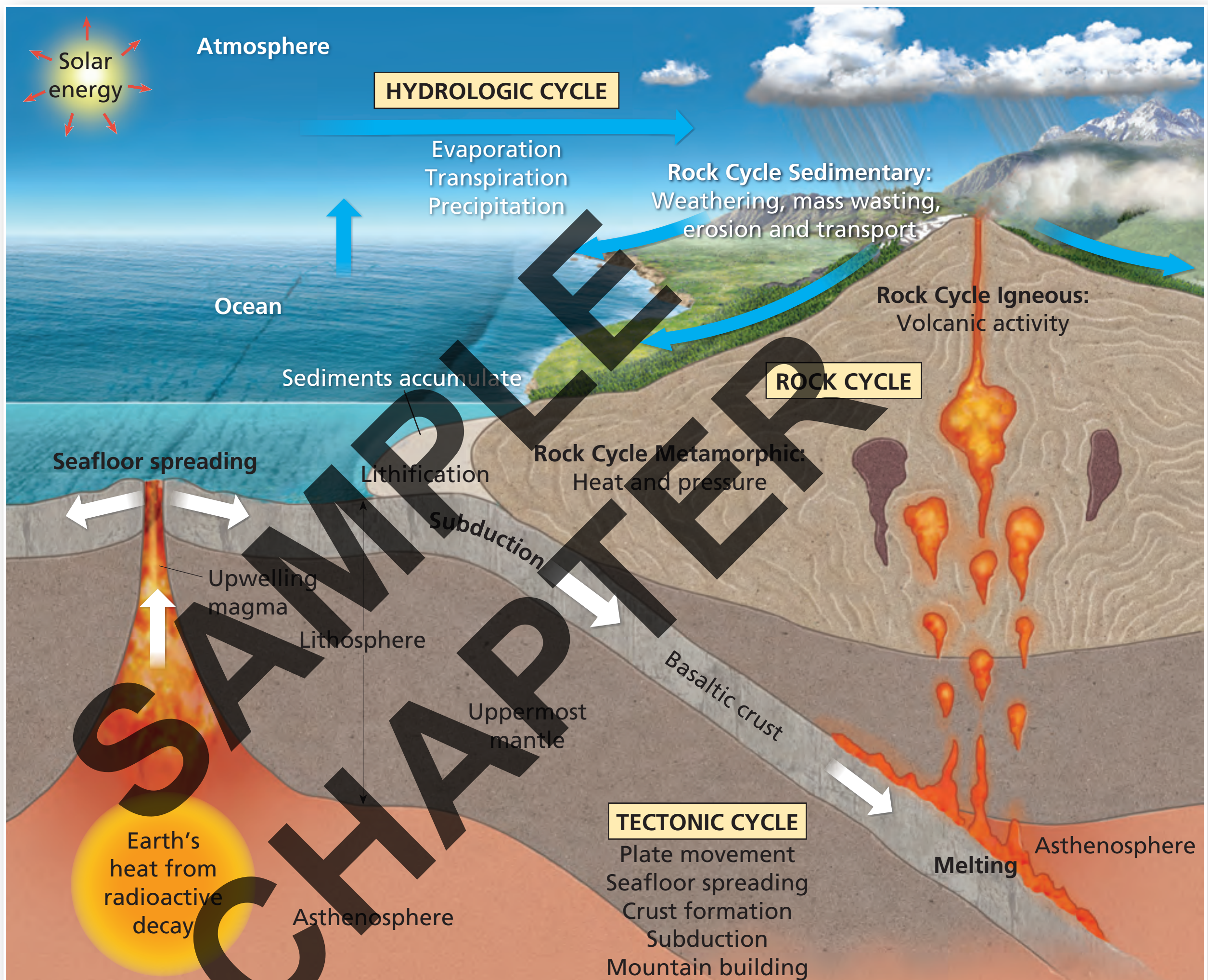
8.3 The Rock Cycle

Key Learning Concepts

- ***Analyze*** how Earth's geologic cycle relates the tectonic, rock, and hydrologic cycles.
- ***Explain*** how rocks cycle through geologic time.
- ***Differentiate*** the processes that create igneous, sedimentary, and metamorphic rocks.

While the internal forces such as plate motions and volcanism build landforms, surface processes such as weathering and erosion work to reshape them. Although the processes occur slowly over geologic time, the result is a restless planet where these two opposing forces interact in a process called the **geologic cycle**. Earth's internal heat and external solar energy fuel the geologic cycle, which is also influenced by the force of gravity.

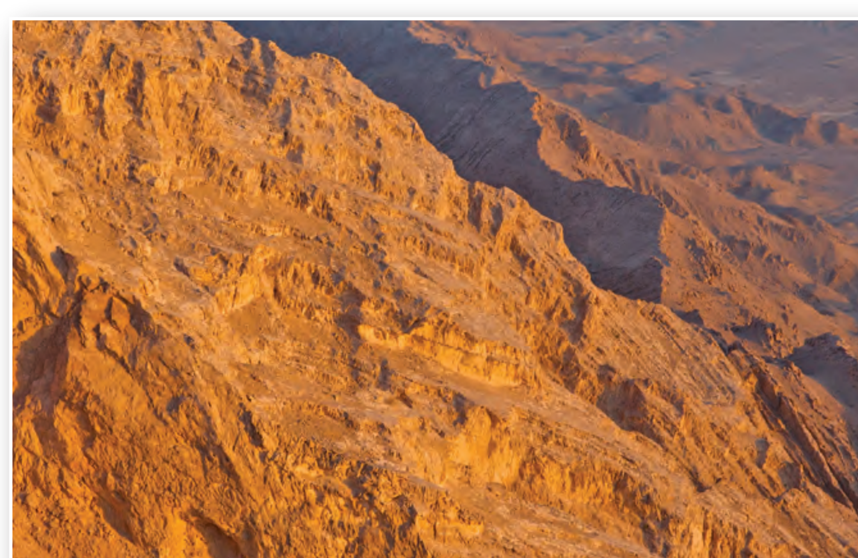
▼**8.7 The geologic cycle** A systems model comprising the hydrologic, rock, and tectonic cycles, the geologic cycle shows how the interaction of exogenic (external) and endogenic (internal) forces creates distinctive landscapes.



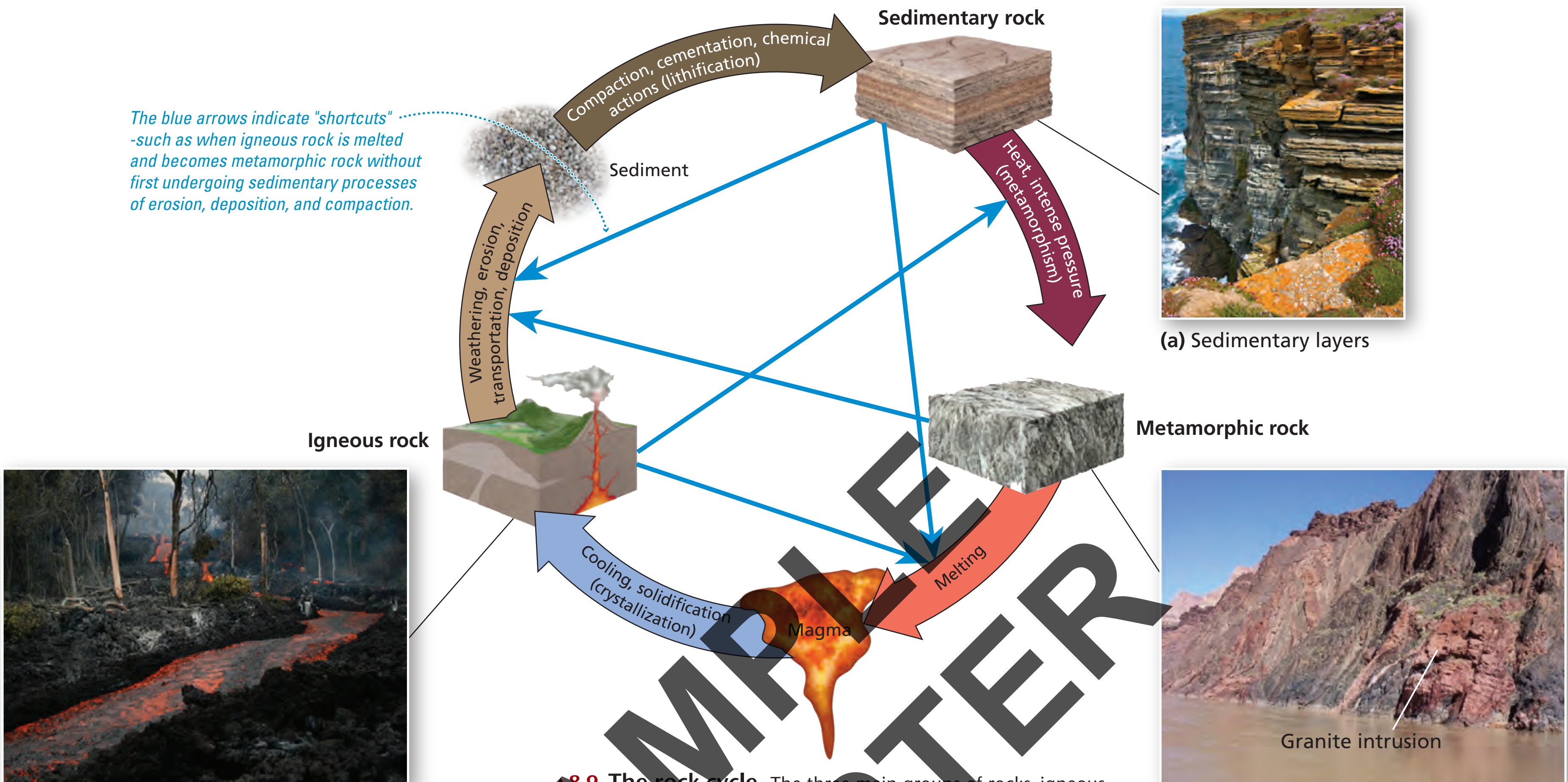
Subcycles within the Geologic Cycle

Three subcycles compose the geologic cycle (▲ **Fig. 8.7**). The *rock cycle* explained in the next section produces the igneous, metamorphic, and sedimentary rocks found in the crust (▶ **Fig. 8.9**). The *tectonic cycle* brings heat energy and new material to the surface and recycles material, creating movement and deformation of the crust as shown in Figure 8.8. The *hydrologic cycle* processes Earth materials with the chemical and physical action of water, ice, and wind. This chapter explores the rock cycle. (You learned about the hydrologic cycle in Chapter 5).

geoCHECK Explain the roles of endogenic and exogenic processes in the geologic cycle.



▶ **8.8 From seafloor to summit** Jebel Hafeet soars 1240 m (4068 ft) above the Arabian Desert. The colliding Arabian and Eurasian tectonic plates pushed up sedimentary rocks, containing fossils—easily spotted in the rocks—that formed in an ancient sea.



(a) Sedimentary layers

(b) Active lava flow and surrounding basalt

(c) Metamorphic schist (with pink granitic intrusion)

▲**8.9 The rock cycle** The three main groups of rocks–igneous, sedimentary, and metamorphic–form through the series of processes that makes up the rock cycle.

Minerals, Rocks, & the Rock Cycle

The **rock cycle** is a natural recycling process by which rocks form and then, over time, change and re-form into another type of rock (▲ **Fig. 8.9**). To understand the rock cycle, you need to become familiar with basic Earth materials—elements, minerals, and rocks. Eight natural elements (oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium) compose 98.5% of Earth's crust by weight. These elements combine to form many minerals.

What Is a Mineral? A **mineral** is an inorganic (nonliving) natural substance with a specific chemical formula and usually a crystalline structure. This combination gives each mineral distinct physical properties such as hardness and density. For example, silicon dioxide, with a distinctive six-sided crystal, is the common mineral you know as quartz.

What Is a Rock? A **rock** is an assemblage of materials, including mineral and organic matter, bound together as part of the lithosphere. Examples of rocks range from granite (containing three minerals), to rock salt (made of one mineral), to coal (made of solid organic material). There are thousands of kinds of rocks, but all fall into one of three broad classes, depending how they formed.

Pathways of the Rock Cycle A series of processes called the *rock cycle* forms these three groups of rocks:

- **Igneous rocks** form from material that melts under the high temperature and pressure found inside the mantle and crust. Igneous rocks are further subdivided into two types. **Intrusive igneous rocks** form from mantle material injected into the crust, where it cools and hardens beneath the surface. These rocks then reach the surface after subsequent uplift and erosion. **Extrusive igneous rocks** form through volcanic activity when molten material from the mantle melts through the crust and onto Earth's surface, where the molten material hardens into solid rock.
- **Sedimentary rocks** often form from fragments of eroded rocks (sediments) that are deposited in low depressions such as valleys, lakes, or oceans, and then are compacted to form new rocks. Other types of sedimentary rocks form through chemical and biological processes. Chemical sedimentary rocks form when materials dissolve in water and precipitate (harden) into rock layers. Organic sedimentary rocks form when material from plant and animal remains compact into sediment, or when organisms still living secrete material that hardens into rock.
- **Metamorphic rocks** are any rocks that chemically re-form under tremendous pressure and accompanying heat that occurs as a result of deep burial inside the crust, or—on a smaller scale—through "contact metamorphism," the intense heat resulting from direct contact with igneous rock as it moves into the mantle or flows onto Earth's surface.

geoCHECK ✔ Identify the processes that form igneous, sedimentary, and metamorphic rocks.

8.3 (cont'd) The Rock Cycle

Igneous Processes

You can think of the rock cycle as beginning when an igneous rock solidifies and crystallizes from molten magma that forms beneath the surface (refer to Fig. 8.9). **Magma** is molten rock that contains dissolved gases under tremendous pressure. **Lava** is magma that reaches the surface. Either magma *intrudes* into crustal rocks, cooling and hardening below the surface to form intrusive igneous rock such as granite, or it *extrudes* onto the surface as lava and cools to form extrusive igneous rock, such as basalt. The texture of igneous rocks is based on the size of their crystals, which is directly related to how the rocks formed. Slow cooling, intrusive igneous rocks such as granite have larger, coarse-grained crystals (▸ **Fig. 8.10a**). Faster cooling rocks result in smaller, fine-grained crystals, as in extrusive igneous rocks such as basalt and rhyolite (Fig. 8.10b, c). Darker igneous rocks contain more iron, while lighter igneous rocks contain more silicates.

A mass of slow cooling intrusive igneous rock forms a **pluton**. Multiple plutons larger than 100 km^2 (40 mi^2) in area compose a **batholith**. Huge batholiths, exposed at the surface by uplift and erosion, often form the core of a mountain range, such as the Sierra Nevada.

Igneous rocks make up 90% of Earth's crust, although sedimentary rocks, soil, or oceans frequently cover them. Continental crust is made up largely of light-colored, lower-density rocks such as granite, an intrusive igneous rock. Oceanic crust is made up of dark-colored, higher-density rocks such as basalt, an extrusive igneous rock.

(a) Granite (b) Basalt flows (c) Rhyolite

▲8.10 **Igneous rocks**

geoCHECK Compare and contrast the formation and characteristics of granite and basalt. Which rock is more likely to be found in a batholith?

Sedimentary Processes

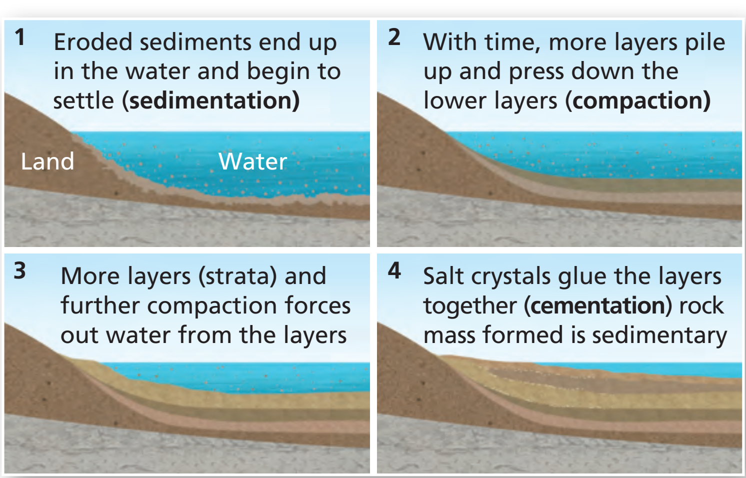
The rock cycle continues as sedimentary rocks form from pieces of other rocks (refer to Fig. 8.9). Most sedimentary rocks form when eroding fragments of existing rock or organic materials are transported downslope by water, ice, wind, and gravity.

Clastic & Organic Sedimentary Rocks Clastic means rock fragments, and once deposited in a low basin or water body, this sediment compacts under the weight of overlying layers, cements, and hardens into *clastic* sedimentary rock, such as conglomerate, sandstone or shale. A similar process forms sedimentary rocks made of organic materials such as the shells and skeletons of marine organisms (coquina limestone) and the decayed remains of plants (coal).

Chemical Sedimentary Rocks In marine and saline inland sea environments, some minerals separate out from the water to form solid sedimentary deposits, such as calcium carbonate, which forms the sedimentary rock limestone. Chemical sediments from inorganic sources are also deposited when water evaporates and leaves behind a residue of salts. These *evaporites* may exist as common salts, such as potash or sodium chloride (table salt). Chemical deposition also occurs in the water of natural hot springs from chemical reactions between minerals and oxygen.

Sedimentary Rock Strata Layered sedimentary rocks record the past. Because sedimentary rocks are formed in a sequence of layers from the oldest rocks on the bottom to the youngest on the top, the sequence of layers yields clues about how past environments and living things changed over time. Figure 8.11 shows sandstone formed in a marine environment. Note the multiple layers in the formation and how differently they resist weathering processes.

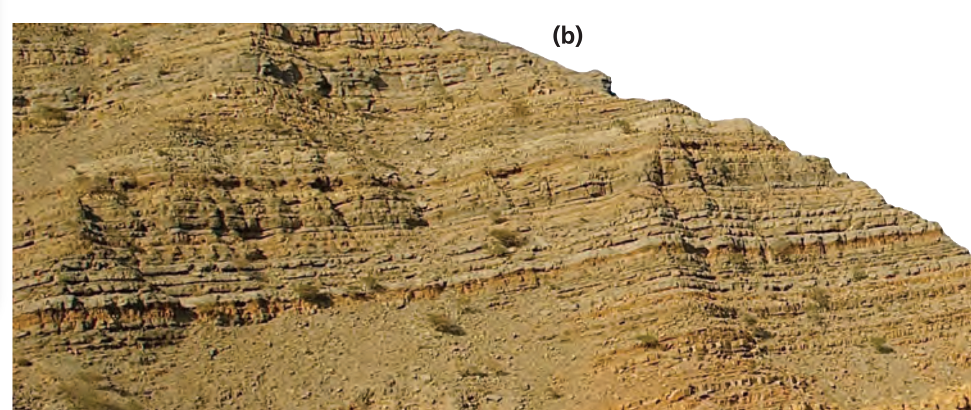
geoCHECK List the steps in the process that forms a clastic sedimentary rock.

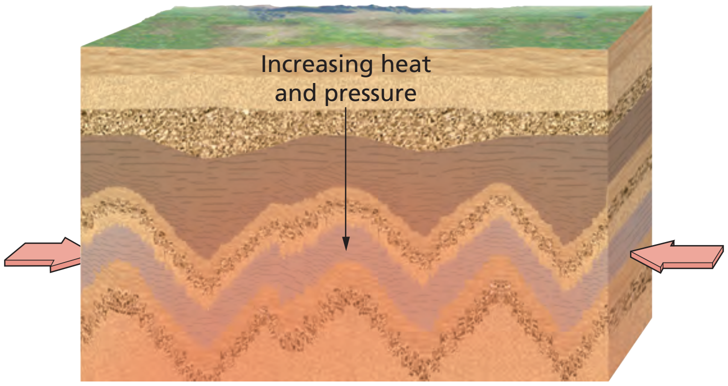


(a)

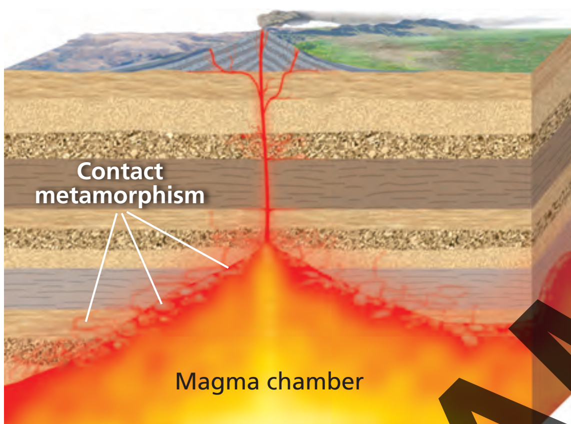
▼8.11 **Sedimentary rocks** (a) Sediment deposited by water, wind, or glacial ice builds up in layers, which are compacted and cemented to form solid rock. (b) Layers of sedimentary rock strata are clearly visible along this shoreline of Khor ash-Sham, in Oman's Musandam Peninsula.

(b)

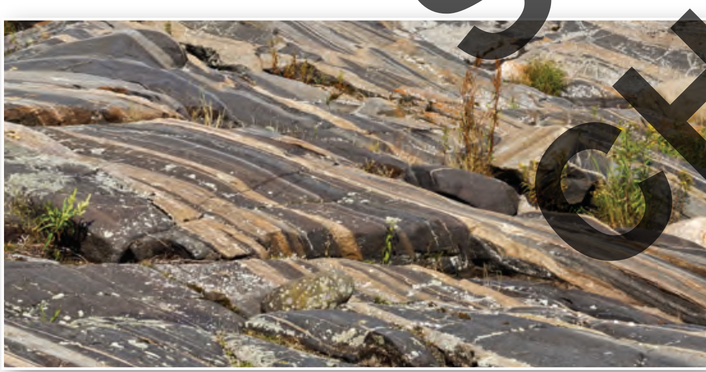




(a) Regional metamorphism Compression forces in the crust, the weight of overlying rock and the heat of Earth's interior combine to cause metamorphism of deeply buried rocks.



(b) Contact metamorphism The intense heat of contact metamorphism quickly alters neighboring rocks.



(c) Foliated rock Gneiss forms when granite or sedimentary rocks undergo extreme heat and pressure.

(e) Nonfoliated rock Marble forms when limestone is exposed to high temperature and pressure. The strength and resistance to erosion makes this non-foliated metamorphic rock an excellent building material.

Metamorphic Processes

Through the rock cycle, any rock can become a metamorphic rock (refer to Fig. 8.9). Metamorphic rocks have undergone intense heat and pressure that alter their physical and chemical properties. This process typically makes rocks harder and more resistant to weathering and erosion.

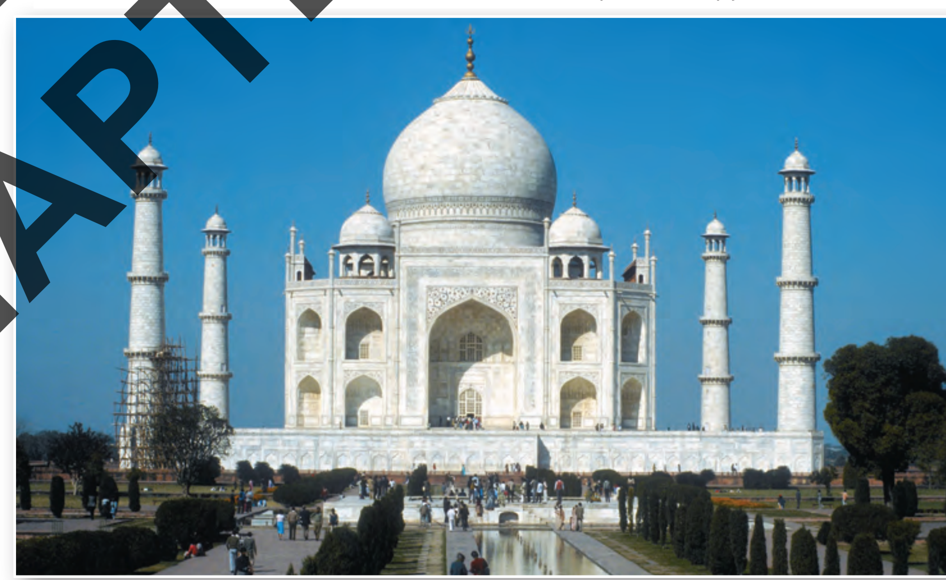
Regional metamorphism occurs when rocks buried inside the crust are subjected to high temperatures and pressures over millions of years (▼ Fig. 8.12a). This can take place when rocks compress during tectonic collisions between slabs of Earth's lithosphere. The shearing and stressing along earthquake fault zones is another cause of metamorphism.

Regional metamorphism can also occur when the weight of sediments collecting in broad depressions in Earth's crust creates enough pressure in the bottommost layers to cause metamorphism. However, on a smaller scale, magma rising into the crust may "cook" adjacent rock, a process known as *contact metamorphism* (Fig. 8.12b).

Metamorphic rocks have textures that are *foliated* or *nonfoliated*, depending on the arrangement of minerals after metamorphism. *Foliated* rocks (Fig. 8.12c) have thin wavy lines, as seen in slate (formed from shale) and gneiss (formed from granite). Nonfoliated rocks (Figs. 8.12d and 8.12e) have a crystalline texture, as seen in marble (formed from limestone) and quartzite (formed from sandstone).

geoCHECK ✔ Describe how a metamorphic rock is formed.

◄ **8.12 Metamorphic rocks** Compression forces in the crust, the weight of overlying rock and the heat of Earth's interior combine to cause metamorphism of deeply buried rocks.



(d) Taj Mahal The marble walls of India's Taj Mahal have withstood the elements for over 360 years.

Animation MG
Foliation of Metamorphic Rock
http://goo.gl/zDmhVN

geoQUIZ

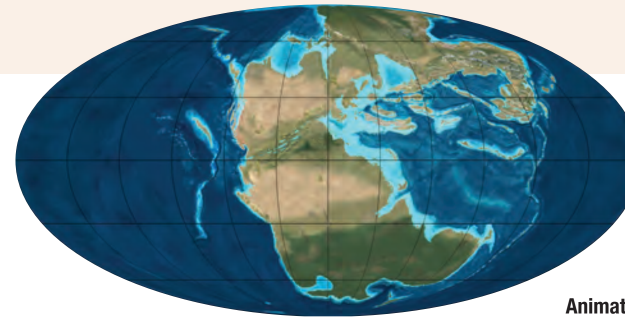
1. What role does each of the three subcycles play within the geologic cycle?
2. What is the relationship between elements, minerals, and rocks?
3. Use examples to describe the main differences between igneous, sedimentary, and metamorphic rocks.

8.4 Plate Tectonics

Key Learning Concepts

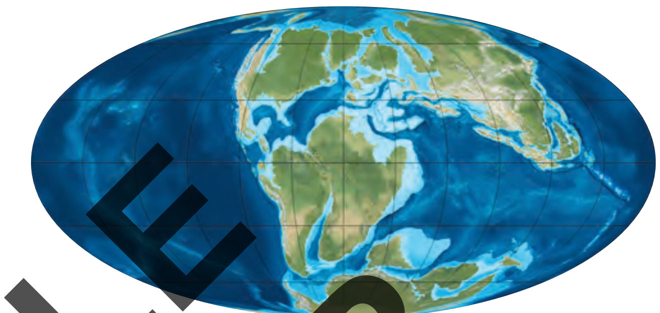
- ▶ ***Summarize*** Wegener's hypothesis of continental drift, the formation and breakup of Pangaea, and why scientists at the time rejected the hypothesis.
- ▶ ***Describe*** how the processes of plate tectonics transform Earth's surface over time.

Looking at a world map, you may have noticed that some continents have matching shapes like pieces of a jigsaw puzzle—particularly South America and Africa. Scientists had wondered about this "fit" of the continents since the first accurate world maps were produced hundreds of years ago.



(a) 220 million years ago

Animation MG
Breakup of Pangaea
https://goo.gl/I7bYav



(b) 135 million years ago

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Plate Motions Through Time
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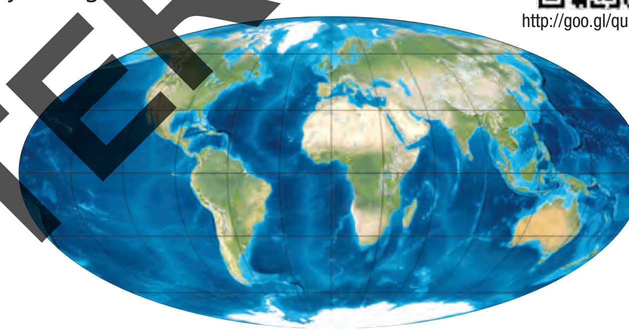


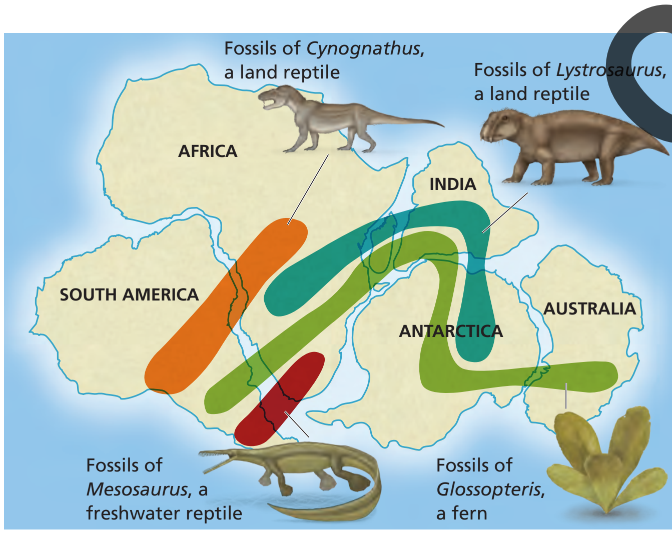
(c) Earth today

▲ 8.13 **Continents adrift, from Pangaea to the present** The formation and breakup of the supercontinent Pangaea were part of a repeated cycle in which pieces of the lithosphere move together, split apart, and eventually reform again. Over the 4 billion years of Earth history, this cycle may have repeated itself a dozen times.

Wegener's Hypothesis of Continental Drift

In 1912, German geophysicist Alfred Wegener proposed a hypothesis to explain the continental puzzle: that the continents had moved together by the end of the Paleozoic, forming the supercontinent of **Pangaea,** which then started to break apart near the beginning of the Mesozoic (▶ **Fig. 8.13**). According to Wegener's hypothesis, the moving continents slowly plowed across the seafloor in the process of *continental drift*. As proof that the now widely separated landmasses had once been joined together, Wegener cited several types of evidence, including matching rock formations on opposite sides of the Atlantic Ocean and matching fossils, from Africa and South America, of organisms that could not have migrated across oceans (▼ **Fig. 8.14**). Wegener could not, however, provide a plausible mechanism to explain why continental drift occurred. Most scientists of Wegener's time rejected the hypothesis, because it lacked a mechanism for driving continental movement.

geoCHECK ✔ Explain how fossil evidence supports the existence and subsequent breakup of Pangaea.

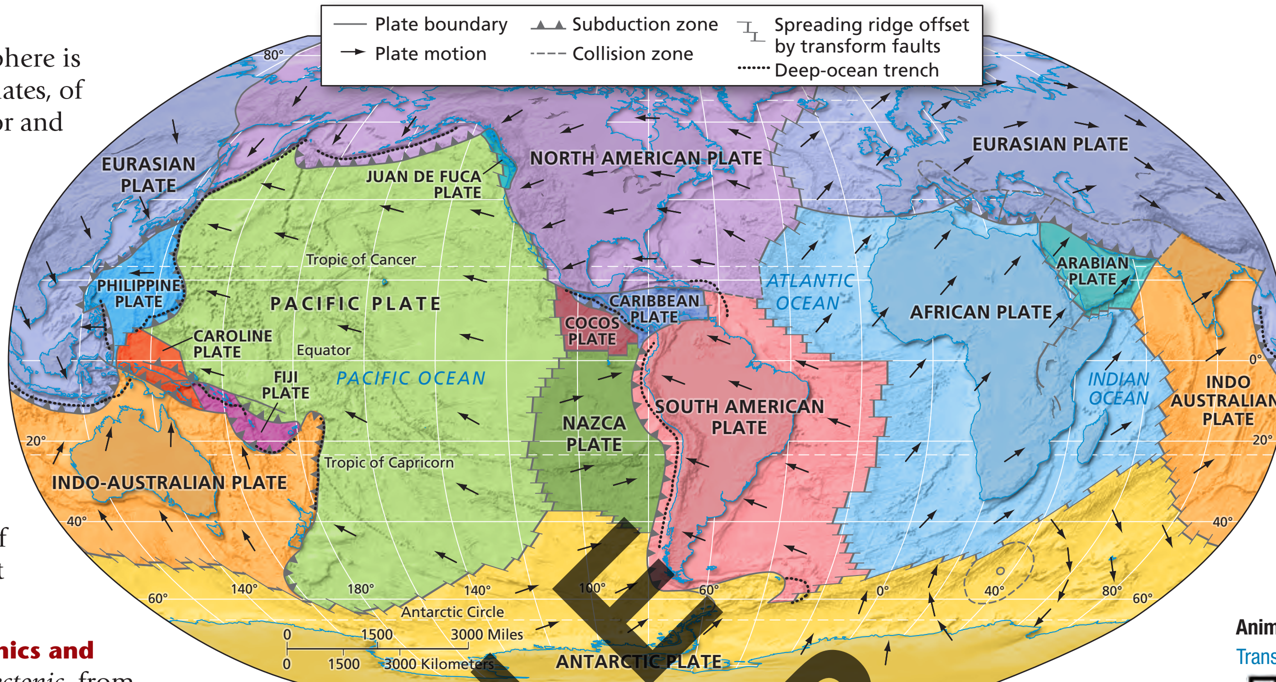


▲ 8.14 **Fossil evidence for plate tectonics** As Pangaea broke apart, the drifting continents marooned species on separate landmasses. These species left fossil evidence on every continent of their earlier distribution.

The Theory of Plate Tectonics

Today, we know that most of Wegener's hypothesis was correct: Continental pieces once did fit together, and they not only migrated to their present locations, but also continue moving at an average rate of about 6 cm (2.4 in.) per year. Since the 1950s and 1960s, modern science has built the theory of **plate tectonics**, the now universally accepted scientific theory that the lithosphere is divided into several moving plates that float on the asthenosphere (above the mantle) and along whose boundaries occur the formation of new crust, mountain building, and the seismic activity that causes earthquakes.

Lithospheric Plates The continents move as part of pieces of lithosphere called **lithospheric plates**, also called tectonic plates. These enormous and unevenly shaped slabs of the outer crust and upper mantle are usually composed of both continental and oceanic lithosphere (as shown in ▶ **Fig. 8.15**). Plates can vary greatly size from 300 km (186 mi) across, to those that cover entire continents. Plates vary in thickness from less than 15 km (9 mi) in oceanic lithosphere, to 200 km (120 mi) for interior continental lithosphere. Oceanic lithosphere is made up mostly of basalt, whereas continental lithosphere has a foundation of mostly granitic-type rocks.



Earth's present lithosphere is divided into at least 14 plates, of which about half are major and half are minor in terms of area (▸ **Fig. 8.15**). Hundreds of smaller pieces and perhaps dozens of microplates migrating together make up these broad, moving plates. Arrows in the figure indicate the direction in which each plate is presently moving, and the length of the arrows suggests the relative rate of movement during the past 20 million years.

▴ **8.15 Earth's major lithospheric plates** As the plates move, their interactions slowly change Earth's surface. The arrows in the figure indicate the direction in which each plate is presently moving, and the length of the arrows suggests the relative rate of movement during the past 20 million years.

Animation Transform Faults
http://goo.gl/KXG42e

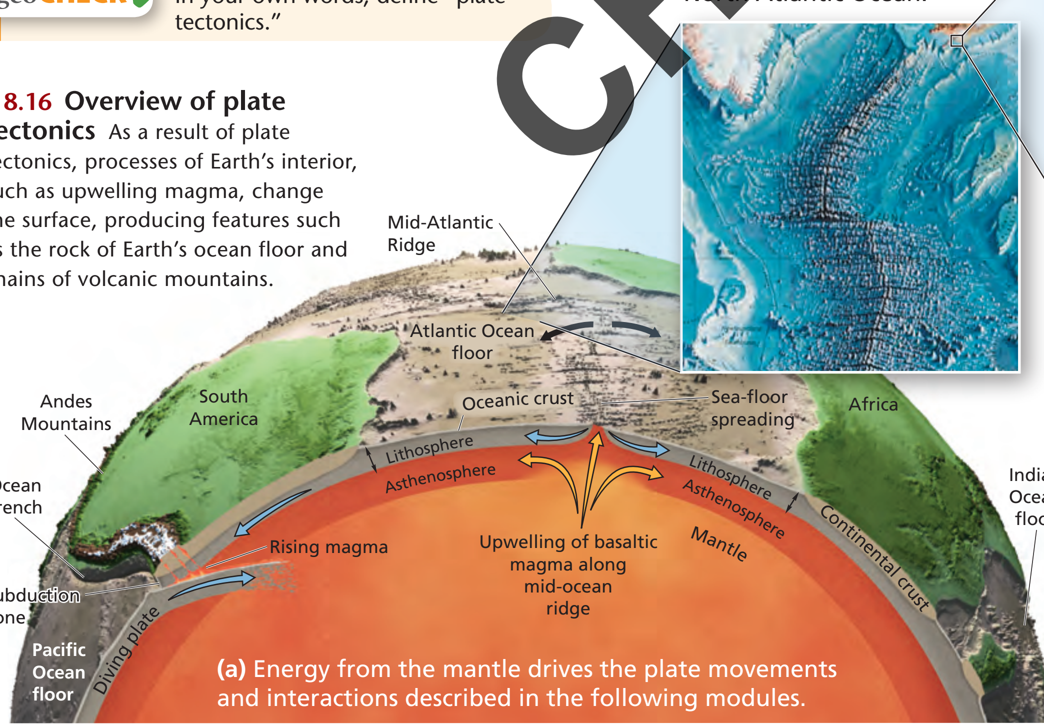
Processes of Plate Tectonics and Their Effects The word *tectonic*, from the Greek *tektonikùs*, meaning "building," refers to changes in the configuration of Earth's crust as a result of internal forces. Plate tectonics includes several processes: upwelling of magma, lithospheric plate movements, and seafloor spreading and subduction (processes that create and destroy the seafloor). The effects of plate motions include earthquakes, volcanic activity, and deformations of the lithosphere, such as warping, folding, and faulting, that result in mountain building. Figure 8.16 shows how the processes of plate tectonics form and cause changes in Earth's continental and oceanic lithosphere. You will learn more about these processes and their effects throughout the rest of this chapter.

Animation Forming a Divergent Boundary
http://goo.gl/8XVrzZ

Animation Motions at Plate Boundaries
http://goo.gl/LNnG80

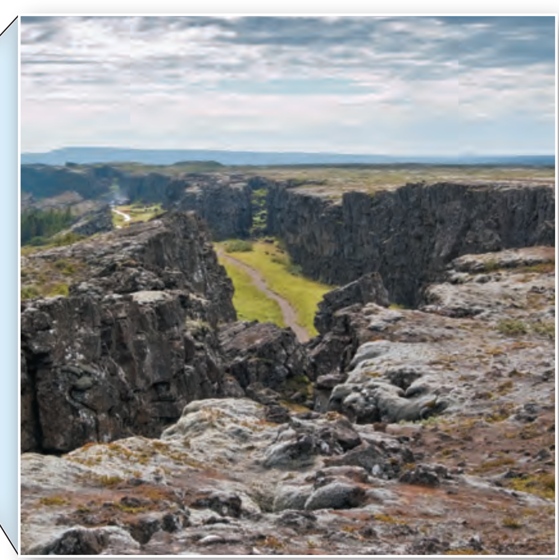
geoCHECK In your own words, define "plate tectonics."

▸ **8.16 Overview of plate tectonics** As a result of plate tectonics, processes of Earth's interior, such as upwelling magma, change the surface, producing features such as the rock of Earth's ocean floor and chains of volcanic mountains.



(a) Energy from the mantle drives the plate movements and interactions described in the following modules.

(b) Like the seam of a baseball, the boundary between the North American and Eurasian plates winds through the North Atlantic Ocean.



(c) This rockwalled valley in Iceland is part of a zone where two plates meet.

geoQUIZ

1. Why did scientists of Wegener's time reject his hypothesis of continental drift?
2. Compare and contrast continental and oceanic lithosphere.
3. How are earthquakes, volcanic eruptions, and faulting linked to plate tectonics?

8.5 Seafloor Spreading & Subduction Zones

Key Learning Concepts

- ***Describe*** the roles of seafloor spreading and subduction in forming and destroying the ocean floor.
- ***Explain*** how geomagnetism supports the concept of seafloor spreading.
- ***State*** the relationship between subduction, earthquakes, and volcanoes.
- ***Identify*** two mechanisms of plate motion.

For hundreds of years, people sailed Earth's oceans but knew almost nothing about the topography of the seafloor. Only in the mid-20th century did mapping the seafloor on a wide scale using SONAR (SOund NAvigation Ranging) become feasible. This technique involves bouncing sound waves off the ocean floor, then measuring the time it takes for them to return. The first maps of the seafloor revealed an interconnected worldwide mountain chain, forming a ridge some 64,000 km (40,000 mi) long and averaging more than 1000 km (600 mi) in width. This feature, called the *mid-ocean ridge system*, provided important evidence for the theory of plate tectonics.

Seafloor Spreading

The key to establishing that the continents indeed move was understanding **mid-ocean ridges** (also called *spreading centers*) and the related process of **seafloor spreading**. The mid-ocean ridges are segments of the global ridge system. Mid-ocean ridges occur at *divergent plate boundaries*, cracks in the lithosphere where plates move apart and pockets of magma form beneath the surface, as shown in Figure 8.17a. Some magma rises and erupts through fractures and small volcanoes along the ridge, forming new seafloor. As the plates continue to move apart, more magma rises from below to fill the gaps. Over millions of years, seafloor spreading has produced the oceanic lithosphere covering more than 70% of Earth's surface.

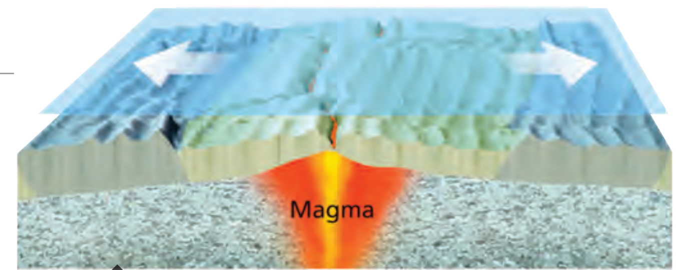
geoCHECK ✔ Summarize the steps in the process that produces the seafloor.

Evidence for Seafloor Spreading: Geomagnetism

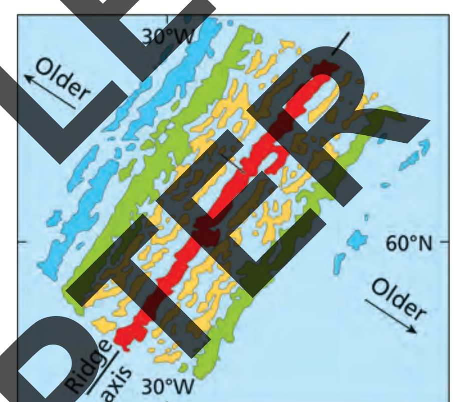
A physical property of igneous rocks—**geomagnetism**—results from the process by which the rocks form and also provides evidence for sea-floor spreading. As lava erupts along a mid-ocean ridge, magnetic particles in the cooling lava align toward magnetic north. As the lava hardens, these particles lock in this alignment, creating an ongoing magnetic record in the lithosphere of Earth's polarity (▲ **Fig. 8.17b**). Earth's magnetic field has a property called *polarity*, in which the magnetic poles have either positive or negative polarity. Over geologic time, the magnetic field's polarity reverses (switches from positive to negative, or vice versa) at irregular intervals. This chronology of reversals in Earth's magnetic field produces a clear record of ages for rocks on the ocean floor. Notice in Figure 8.17b that the magnetic record pattern of strips of rock is the same on both sides of the ridge. This symmetrical pattern reflects the fact that the corresponding strips on each side of the ridge were formed at the same time. Thus the youngest lithosphere anywhere on Earth is the new lava at the spreading centers of the mid-ocean ridges. With increasing distance from these centers, the lithosphere grows steadily older (Fig. 8.17c).

Overall, the seafloor is relatively young. Nowhere is it more than 200 million years old—remarkable when you remember that Earth's age is 4.6 billion years.

geoCHECK ✔ What is geomagnetism?

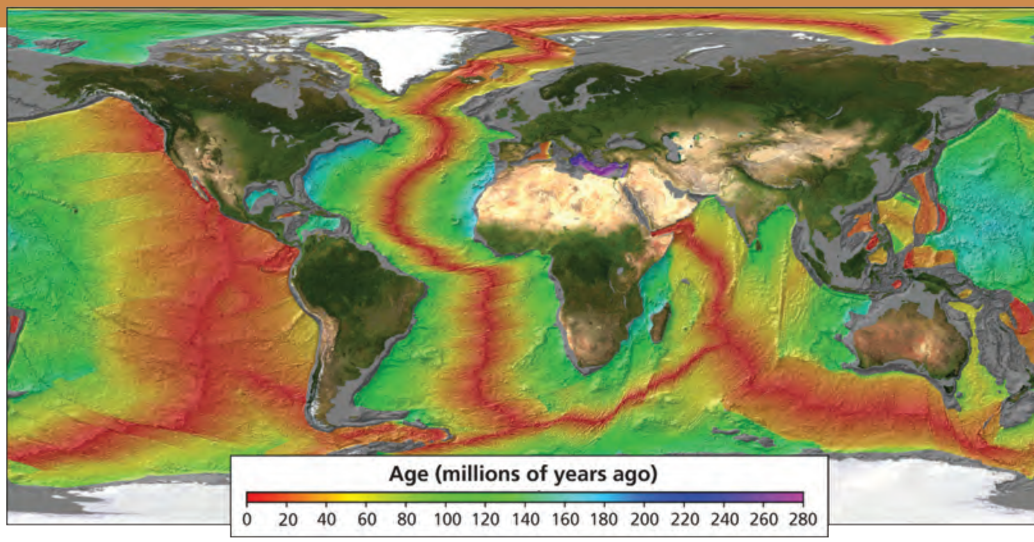


(a) Upwelling magma erupts along the spreading center, hardening to form new oceanic lithosphere.



(b) Strips of magnetized rock on either side of the mid-ocean ridge form a matching pattern based on the rock's age.

▲ **8.17 The process of sea-floor spreading** Volcanic activity along Earth's mid-ocean ridge system produces the rock that makes up the ocean floor and drives the process of seafloor spreading. Map (c) on the facing page shows the result in terms of the age of the ocean floor.



(c) The youngest rocks (red) are along the mid-ocean ridges. Moving away from the ridges, the rocks become progressively older (blue).

Subduction Zones

What explains the absence of old oceanic lithosphere? In contrast to the older continental lithosphere, the oceanic lithosphere is short-lived because the lithosphere formed along the mid-ocean ridges sinks into **deep-ocean trenches** elsewhere. On the left side of Figure 8.18a, note how one plate is diving beneath another into the mantle. Recall that the basaltic ocean crust has a greater density than the lighter continental crust. As a result, when they slowly collide, the denser ocean floor will slide beneath the less-dense continental crust, thus forming a **subduction zone,** or deep-ocean trench.

Subduction occurs where plates are colliding. The denser subducting slab of lithosphere exerts a gravitational pull on the rest of the plate—pulling the plate into the trench. The subducted portion slides down into the asthenosphere, where it remelts and eventually recycles as magma, rising again toward the surface through deep fissures and cracks in crustal rock. This process effectively destroys older oceanic lithosphere.

Major subduction zones and their trenches occur around the edges of the Pacific plate. Volcanic mountains such as the Andes in South America, the Cascade Range from northern California to the Canadian border, and the Aleutian Islands in Alaska form inland of these subduction zones as a result of rising plumes of magma (Figure 8.18b, c). As subduction occurs, plate motions trigger powerful earthquakes. The strongest earthquakes ever recorded have occurred in subduction zones.

geoCHECK Explain what occurs in a subduction zone.

geoQUIZ

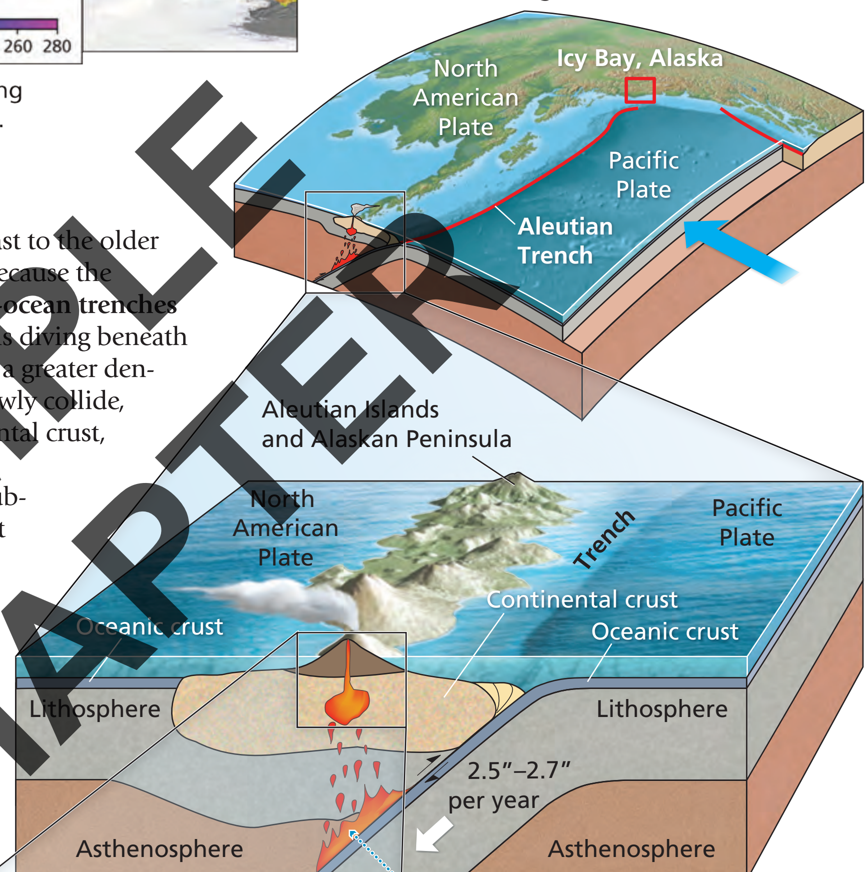
1. How does geomagnetism provide evidence for plate tectonics?
2. Within seafloor-spreading zones, where are the youngest, and the oldest, rocks located? Explain.
3. What is the geologic relationship between volcanic chains, such as the Andes and Cascade Range, and subduction zones?

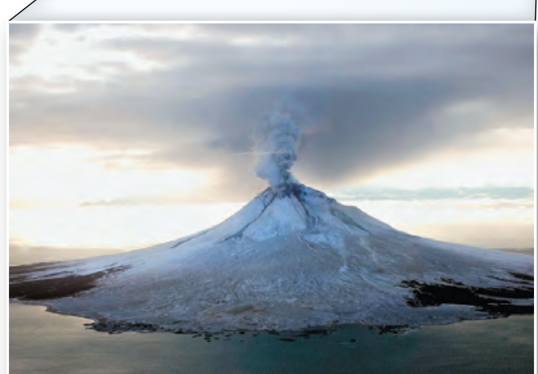
Animation Subduction Zones
http://goo.gl/oXhhXS

Animation Seafloor Spreading and Plate Boundaries
http://goo.gl/8dhbVQ

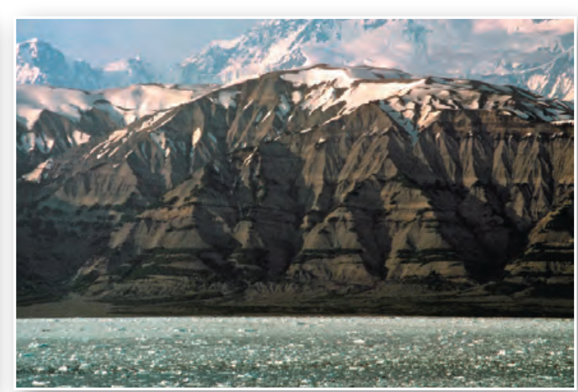
▼8.18 Subduction in Alaska

(a) For 2,500 km (1552 m) the Gulf of Alaska and the Aleutian Islands form the boundary where the more dense Pacific Plate is subducting underneath the less dense (and lighter) North American Plate.





(b) Liquid magma rises to the surface in the form a string of 80 volcanoes, including Mt. Augustine shown here.



(c) Continental and ocean sediments from both plates is deposited onto the North American Plate, where folding and faulting uplifts it above sea level in Icy Bay, Alaska.

8.6 Plate Boundaries

Key Learning Concepts

- ***Describe*** the types of plate boundaries and the movement associated with each.
- ***Explain*** how earthquake and volcanic activity relate to plate boundaries.
- ***Identify*** the cause and effect of hot spots.

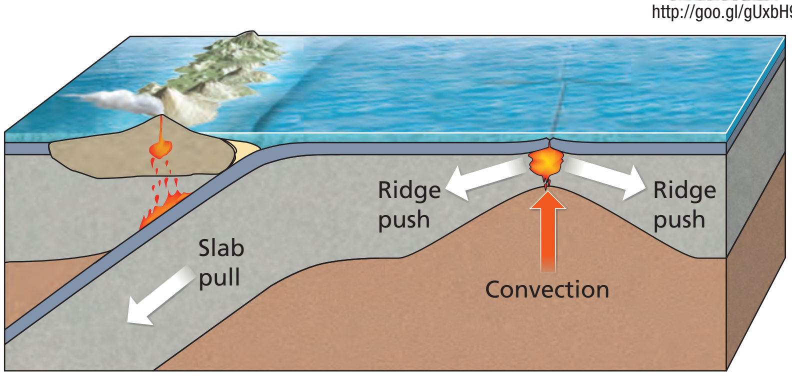
Plate boundaries are dynamic places where lithospheric plates interact, producing profound changes in Earth's surface. For example, new lithosphere forms where plates pull apart, but where plates meet, lithosphere is profoundly altered by either sliding down into the asthenosphere or colliding upward to form mountains. Where plates slide past each other, lithosphere is neither created nor destroyed. Frequent earthquakes occur at all three types of plate boundaries. What causes plate movements? Driven by the heat energy of Earth's interior, plate motions result from differences in temperature and density within the plates themselves.

Mechanisms of Plate Motion

Mid-ocean ridges and subduction zones are critical to two processes that scientists think drive plate motion (▼ Fig. 8.19), along with the mantle convection currents resulting from differences in rock temperatures and density and the role of gravity discussed earlier in Module 8.2. The addition of new rock along a mid-ocean ridge pushes the plate away from the ridge in the process of **ridge push.** Because the mid-ocean ridges are elevated, ridge push causes the oceanic lithosphere to slide "downhill" toward a trench. Along the way, the plate cools and becomes more dense. Reaching the trench, gravity pulls the plate downward in the process of **slab pull.**

Animation MG
Convection and Plate Tectonics
http://goo.gl/gUxbH9

geoCHECK ✔ What force is responsible for ridge push and slab pull?



▲ **8.19 Ridge push and slab pull** Gravity drives ridge push and slab pull, in which oceanic lithosphere cools and becomes denser as it moves away from spreading centers and is eventually subducted into the mantle.

Interactions at Plate Boundaries

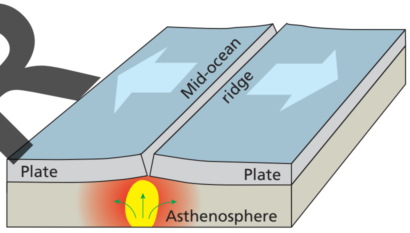
The block diagrams in Figure 8.20 show the three general types of plate motion and interaction that occur along the boundaries.

Divergent Boundaries Plates pull apart along *divergent boundaries*. These boundaries occur at seafloor spreading centers, where upwelling material from the mantle forms new seafloor and lithospheric plates are under tension and spread (or "pull") apart. Whereas most divergent boundaries occur at mid-ocean ridges, a few occur within continents themselves. An example is the Great Rift Valley of East Africa, where crust is rifting apart.

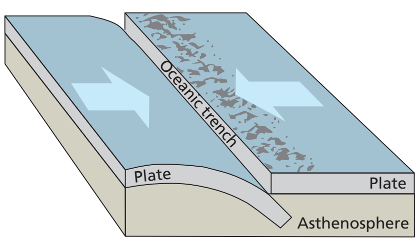
Convergent Boundaries Continental and oceanic lithosphere collide along *convergent boundaries*. These are zones where subduction can occur and where compression forces squeeze the crust until it fractures, causing earthquakes, volcanic activity, and mountain formation (▼ Fig. 8.20). Examples include the ocean off the west coast of South and Central America, along the Aleutian trenches, and along the east coast of Japan, where the magnitude 9.0 earthquake struck in 2011. Areas where two plates of continental crust collide include the collision zone between India and Asia. Areas where oceanic plates collide are found along the deep trenches in the western Pacific Ocean.

Transform Boundaries Where plates slide laterally past one another at right angles, *transform boundaries* occur. Along transform boundaries, plates neither diverge nor converge, and there are usually no volcanic eruptions. These are the right-angle fractures stretching across the mid-ocean ridge system worldwide.

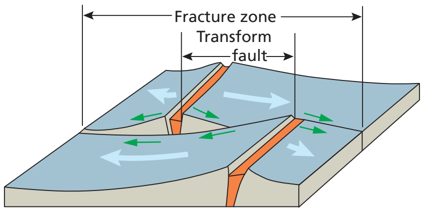
Mid-ocean ridges intersect with transform faults (also called strike-slip faults) ranging from 300 km (186 mi) to over 1000 km (over 600 mi) long. These faults are parallel to the direction of plate movement. The resulting fracture zone is active only along the fault section between ridges. The motion produces horizontal displacement; no new crust is formed or old crust subducted.



(a) Divergent plate boundary— plates diverge in areas of seafloor spreading at mid-ocean ridges and along rift valleys in continental crust.



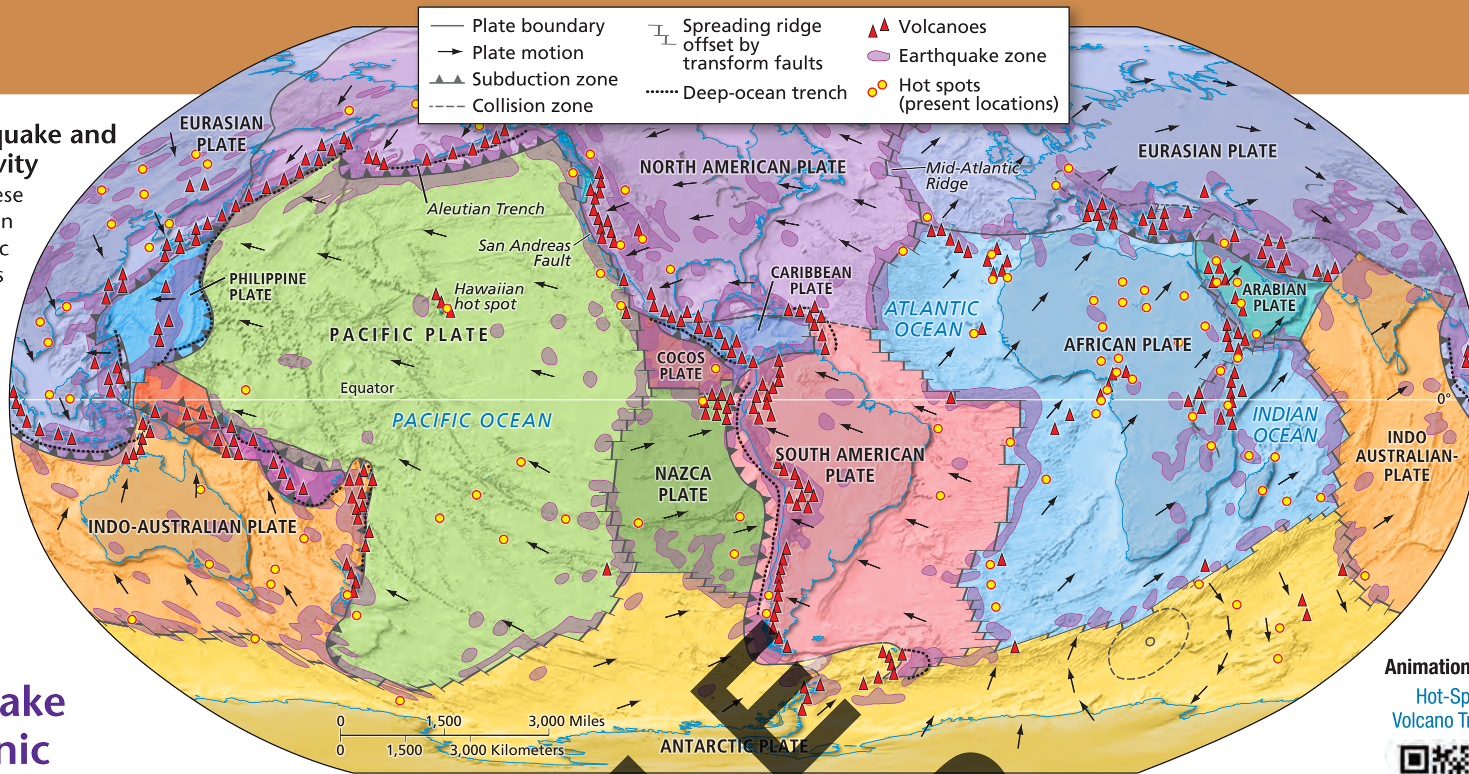
(b) Convergent plate boundary— plates converge, producing a subduction zone. Coastal area features mountains, volcanoes, and earthquakes.



(c) Transform boundary— plates slide past each other, forming a fracture zone including a transform fault in which plates move past each other in opposite directions; along the fracture zone outside of the active fault, plates move in the same direction.

▲ **8.20 Movements of lithospheric plates** The three types of plate interactions are (a) divergent, (b) convergent, and (c) transform.

geoCHECK ✔ List and describe the three types of plate boundaries.



▸ 8.21 Earthquake and volcanic activity locations These appear in relation to major tectonic plate boundaries and principal hot spots.

Animation MG
Plate Boundaries
http://goo.gl/r9mxVK

Earthquake & Volcanic Activity Related to Plate Boundaries

Plate boundaries are the primary location of earthquakes and volcanoes. The correlation of these phenomena is important to the theory of plate tectonics for two reasons. First, the correlation proves that moving plates "shake" the earth, causing earthquakes. Secondly, rock material subducting into the asthenosphere becomes molten and then injects upward back into the crust as new intrusive igneous rock or extrusive volcanic rock. For example, in Figure 8.21 notice the "Ring of Fire" surrounding the Pacific Basin, named for its many volcanoes. In several subduction zones, the subducting edge of the Pacific Plate thrusts deep into the crust and mantle and produces upwelling magma that forms active volcanoes along the Pacific Rim. Such processes also occur at plate boundaries throughout the world.

geoCHECK ✔ Summarize the process by which plate tectonics "recycles" rock along convergent boundaries.

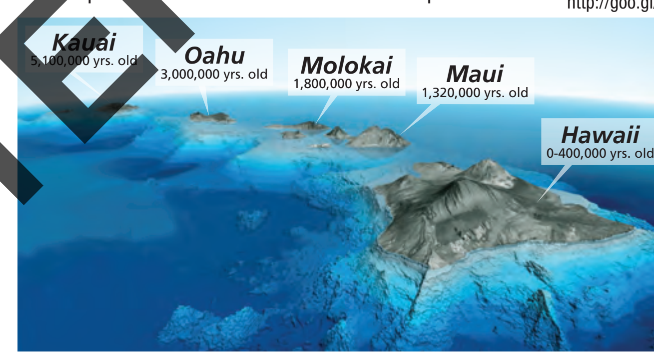
Hot Spots

Sites, not associated with plate boundaries, that send upwelling magma to the surface are called **hot spots**. Scientists estimate there are 50 to 100 hot spots across Earth's surface. They occur beneath both oceanic and continental crust, and some are found far from plate boundaries. Some hot spots anchor deep in the stiff lower mantle, remaining fixed relative to migrating plates; others appear to be above plumes that move themselves or shift with plate motion. Thus, the area of a plate that is above a hot spot is heated for the brief geologic time—a few hundred thousand or million years—when that part of the plate is there.

The Hawaiian Islands illustrates volcanic activity at a hot spot. The Pacific Plate has been moving across a hot, upward-erupting plume over the last 80 million years, creating an island chain stretching northwestward away from the fixed hot spot (▸ **Fig. 8.22**). The oldest island of the chain is Kauai (5 million years), now eroded into deep canyons and valleys. The big island of Hawaii, the newest, currently sits above the hot spot, and took less than 1 million years to form.

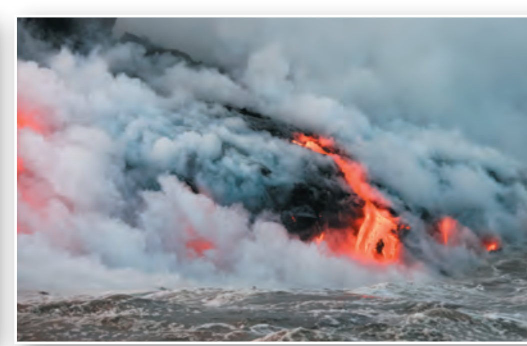
▾ 8.22 Hot spots Upwelling magma melts through Earth's plates to reach the surface at hot spots.

Animation MG
Hot-Spot Volcano Tracks
http://goo.gl/1JfH7k



(a) Age of Hawaiian islands.

(b) Eroded shoreline of Kaua'i.



(c) Fresh lava on Hawai'i reaches the sea.

geoCHECK ✔ What is a hot spot?

geoQUIZ

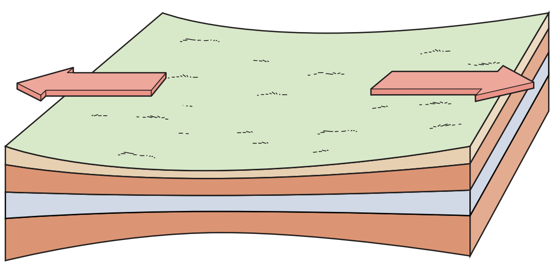
1. Describe the three types of plate boundaries, and identify at least one place in the world where they are found.
2. Identify the specific characteristics of plate boundaries that produce earthquakes and volcanoes.
3. Explain why some volcanic chains, such as the Hawaiian Islands, are found far from a plate boundary.

8.7 Deformation, Folding, & Faulting

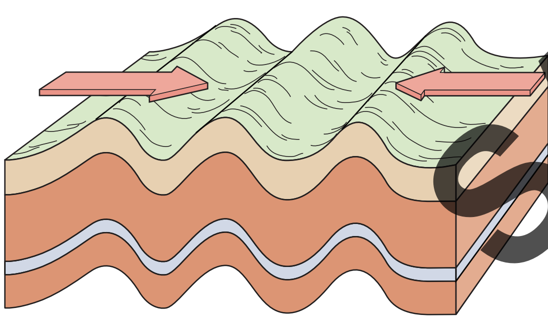
Key Learning Concepts

- ***Identify*** the forces that deform the crust and the effects of deformation.
- ***Describe*** folding and warping and their resulting landforms.
- ***Compare and contrast*** the different types of faults.

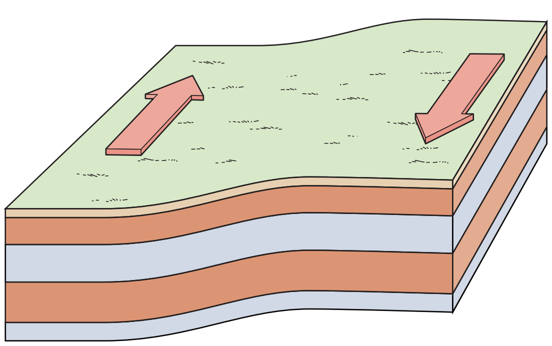
Plate motions, ultimately driven by mantle convection, create tremendous forces that change Earth's crust. Over time, these forces wrinkle the crust like a rug, bend it like a soft candy bar, or break it like a cracker, gradually changing the appearance of Earth's surface.



(a) Tension



(b) Compression



(c) Shear

▲ **8.23 Three kinds of stress and strain and the resulting surface expressions**

Animation MG
Folds, Anticlines, and Synclines
http://goo.gl/40nQS4

How Stress Affects Rock: Deformation

Rocks in Earth's crust undergo powerful stress caused by tectonic forces, gravity, and the weight of overlying rocks. Figure 8.23 shows three types of differential stress: *tension* stretches rock, *compression* shortens it, and *shear* twists or tears it. Rocks respond to this *strain* by *folding* (bending) or *faulting* (breaking). In other words, stress is a force acting on the rock, and the resulting strain is the deformation in the rock. Whether a rock bends or breaks depends on rock composition, the amount of pressure, and whether the rock is *brittle* or *ductile.* Brittle rocks fracture easily, while ductile rocks bend slowly. The effects of stress on rocks are clearly visible in the landforms we see today, especially in mountains.

geoCHECK ✓ Construct a table listing the three types of stress and how each deforms rocks.

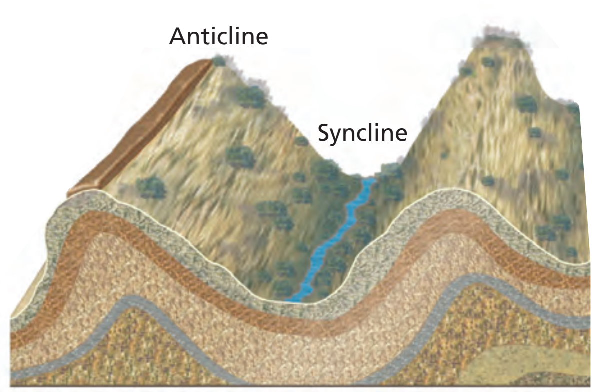
Folding & Broad Warping

Folding occurs when rocks are deformed as a result of compressional stress and shortening. We can visualize this process by stacking sections of thick fabric on a table and slowly pushing on opposite ends of the stack. The cloth layers will bend and rumple into folds similar tho those in the landscape of (▼ **Figure 8.24**). An arch-shaped upward fold is an **anticline**, in which the rock layers slope downward away from an imaginary center axis. A trough-shaped downward fold is a **syncline**, in which the layers slope upward away from the center axis.

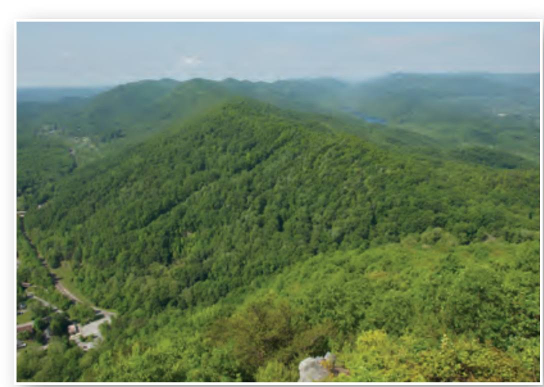
In addition to folding, broad *warping* can cause continental crust to arch upward as if pushed from below. Features formed by warping can be small, fold-like structures called *basins* and *domes*, or regional features the size of the Ozark Mountains in Arkansas and Missouri, the Colorado Plateau, and the Richat Dome in Mauritania.

geoCHECK ✓ How do you distinguish between an anticline and syncline?

▼ **8.24 Folded landscapes** Compression forces can fold the crust, producing anticlines and synclines.



(a) Compression forces cause the folding that produces anticlines and synclines.



(b) The folded Appalachian Mountains of the Cumberland Gap on the tri-state borders of Kentucky, Tennessee, and Virginia.

Faulting

When rocks are stressed beyond a certain point the strain creates a break, or fracture. Rocks on either side of the fracture move relative to the other side in a process known as **faulting**. Thus, *fault zones* are areas where fractures in the rock demonstrate crustal movement. At the moment of fracture, a sharp release of energy occurs, producing an **earthquake**.

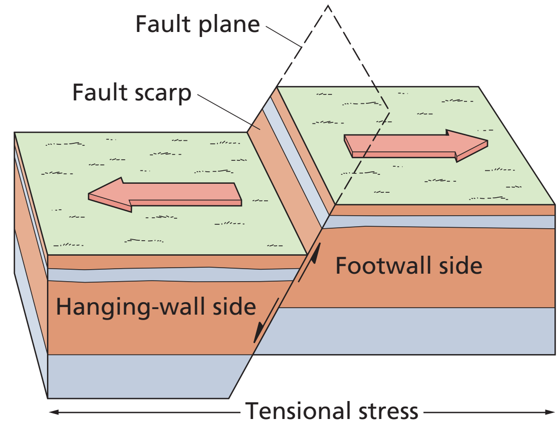
The two sides of a fault move along a *fault plane*. Three types of faults are distinguished by direction of movement along the fault as well as the tilt and orientation of the fault plane.

Normal Faults A **normal fault** forms when rocks are pulled apart by *tensional* stress (▶ **Fig. 8.25a**). When the break occurs, rock on one side moves vertically along an inclined fault plane. The downward-shifting side is the *hanging wall*; it drops relative to the *footwall block*. A cliff formed by faulting is called a *fault scarp*, or *escarpment*.

Reverse Faults *Compressional* forces associated with converging motion that forces rocks to move *upward* along the fault plane produce a **thrust** or **reverse fault**, in which the hanging wall shifts up and over the footwall (Fig. 8.25b). On the surface, thrust faults appear similar to a normal fault, although more collapse and landslides may occur from the hanging wall. In the Alps, thrust faults result from compressional forces of the colliding African and Eurasian Plates. Beneath the Los Angeles Basin, thrust faults caused many earthquakes, including the $30 billion 1994 Northridge earthquake.

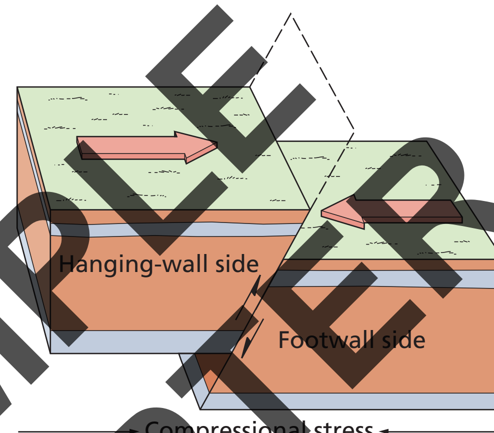
Strike-Slip Faults A **strike-slip** fault (also called *transform fault*) forms when rocks are torn by *lateral-shearing* stress (Fig. 8.25c). The horizontal movement along a strike-slip fault produces movement that is *right-lateral* or *left-lateral*, depending on the motion perceived on one side of the fault relative to the other side. Although strike-slip faults do not produce scarps, they can create linear valleys such as those along the San Andreas fault system of California.

geoCHECK ✔ Compare and contrast the structure and movement of a normal fault with that of a reverse (or thrust) fault.

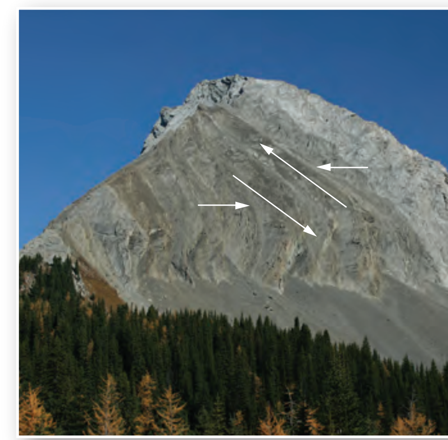


(a) Normal fault (tension)

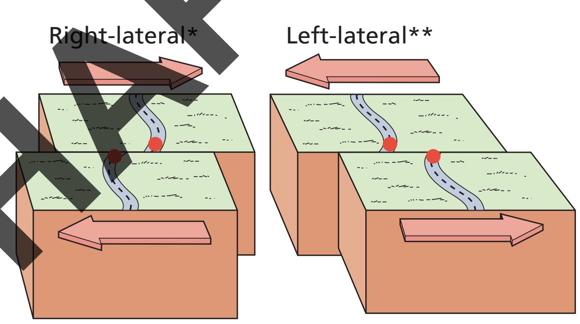
(d) Sierra Nevada, California



(b) Thrust or reverse fault (compression)



(e) Mount Galatea, Alberta, Canada



(c) Strike-slip fault (lateral shearing)

* Viewed from either dot on each road, movement of opposite side is *to the right*.
** Viewed from either dot on each road, movement of opposite side is *to the left*.

(f) San Andreas fault, California

▲ **8.25 Types of faults** (d) **Normal fault** Sierra Nevada, California. (e) **Thrust fault** (f) **Strike-slip fault** San Andreas fault, California

geoQUIZ

1. Describe the process that creates a landscape of anticlines and synclines.
2. Explain why a normal fault develops a fault scarp, but a strike-slip fault does not.
3. Compare and contrast the effects of warping, folding, and faulting on a landscape.

Mobile Field Trip MG
San Andreas Fault
https://goo.gl/Fi67ZP

Animation MG
Transform Faults
http://goo.gl/KXG42e

8.8 Earthquakes

Key Learning Concepts

- ***Explain*** what happens during an earthquake.
- ***Distinguish*** between earthquake intensity and magnitude.
- ***Discuss*** why scientists cannot yet predict earthquakes.
- ***Give examples*** of earthquake hazards in different parts of the world.

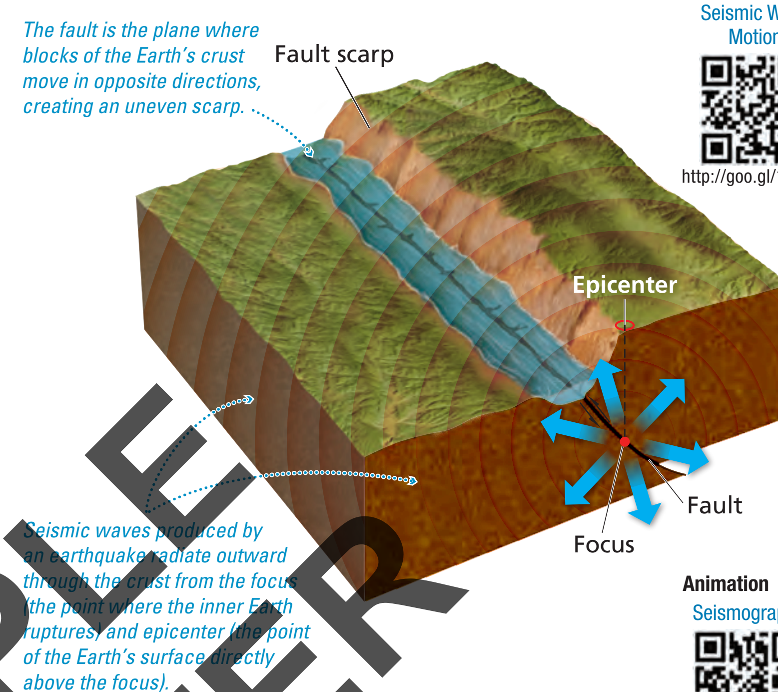
Tremendous stored energy exists along plate boundaries and faults. Recall that *stress* is the force of plates moving in opposite directions that builds *strain*, which causes deformation in rocks. But if the strain exceeds the strength of the rock, the rock eventually will break—"Earthquake!"

Before, During, & After an Earthquake

Crustal plates do not glide smoothly past one another. Instead, tremendous friction exists along plate boundaries. The stress, or force, of plate motion builds strain, or deformation, in the rocks until friction is overcome and the sides along plate boundaries or fault lines suddenly break loose. The sharp release of energy that occurs at the moment of fracture, producing **seismic waves**, is an **earthquake**, or *quake*. The two sides of the fault plane then lurch into new positions, moving distances ranging from centimeters to several meters, and release enormous amounts of seismic energy into the surrounding crust. Seismic waves transmit this energy throughout the planet, diminishing with distance.

The subsurface area along a fault plane, where an earthquake begins, is the *focus*, or hypocenter, of an earthquake (▶ **Fig. 8.26**). The area at the surface directly above the focus is the *epicenter*. Shock waves produced by an earthquake radiate outward through the crust from the focus and epicenter. An *aftershock* may occur after the main shock, sharing the same general area of the epicenter. Some aftershocks rival the main earthquake in magnitude.

geoCHECK ✔ Explain the role of seismic waves in an earthquake.



▲ **8.26 Anatomy of an earthquake**

Animation MG
Seismic Wave Motion
http://goo.gl/1T8y4x

Animation MG
Seismographs
http://goo.gl/ilduMn

Earthquake Intensity & Magnitude

A worldwide network of more than 4000 **seismograph** instruments records vibrations transmitted as waves of energy throughout Earth. Using seismographs and actual observations, scientists rate earthquakes on either a *qualitative* damage intensity scale, or a *quantitative* scale that measures the magnitude of energy released.

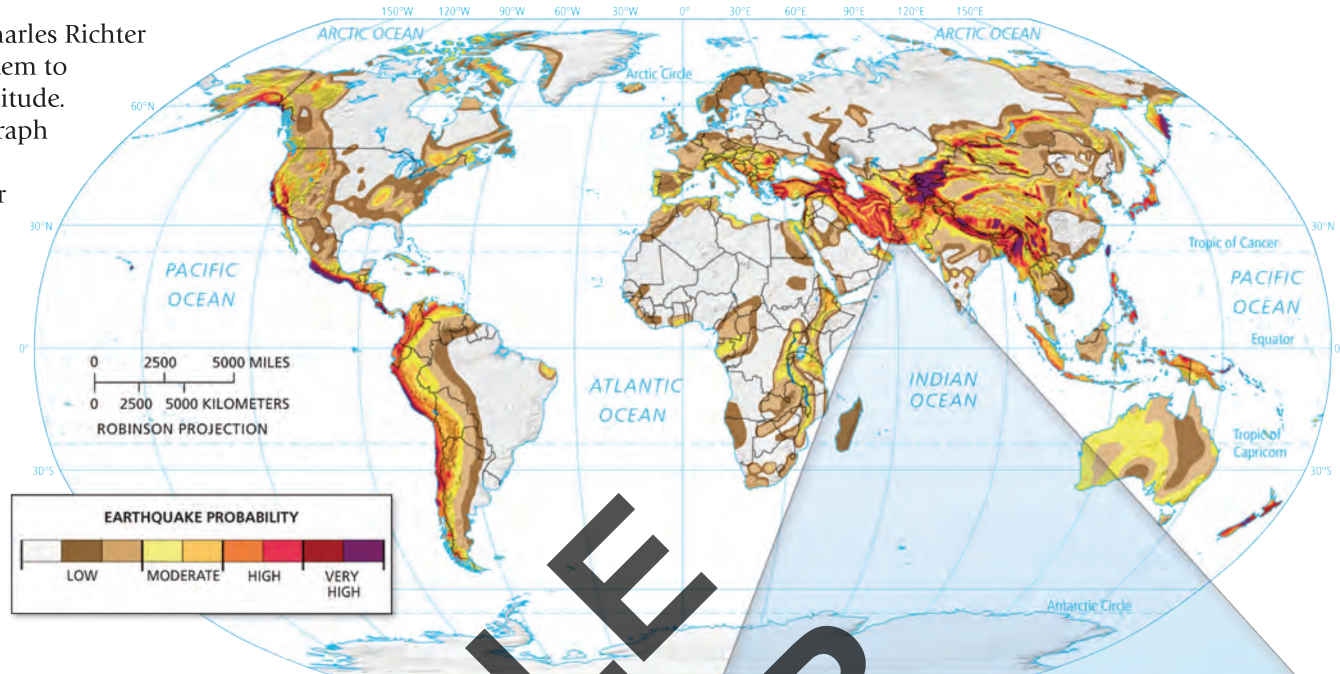
Modified Mercalli Scale Developed in 1903, the *Mercalli intensity scale* is a *qualitative* scale that uses Roman numerals from I to XII to represent intensities from "barely felt" to "catastrophic total destruction." Table 8.1 shows this scale and the number of earthquakes in each category that scientists expect each year.

Table 8.1 Magnitude, Intensity, & Frequency of Earthquakes

Description	Effects on Populated Areas	Moment Magnitude Scale	Modified Mercalli Scale	Number per Year*
Great	Damage nearly total	8.0 and higher	XII	1
Major	Great damage	7–7.9	X–XI	17
Strong	Considerable to serious damage to buildings; railroad tracks bent	6–6.9	VIII–IX	134
Moderate	Felt by all, with slight building damage	5–5.9	V–VII	1,319
Light	Felt by some to felt by many	4–4.9	III–IV	13,000 (estimated)
Minor	Slight, some feel it	3–3.9	I–II	130,000 (estimated)
Very minor	Not felt, but recorded	2–2.9	None–I	1,300,000 (estimated)

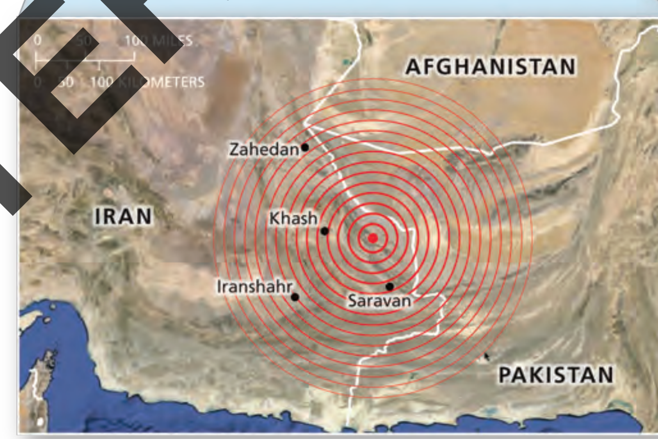
*Based on observations since 1990.
Source: USGS, Earthquake Information Center.

Richter Scale In 1935, Charles Richter designed a *quantitative* system to estimate earthquake magnitude. In this method, a seismograph located at least 100 km (62 mi) from the epicenter of the quake records the amplitude of seismic waves. The measurement is then charted on the **Richter scale**. The scale is logarithmic: Each whole number on it represents a 10-fold increase in the measured wave amplitude (equal to a 31.5-fold increase in energy released). Thus, a magnitude of 3.0 on the Richter scale represents 31.5 times more energy than a 2.0 and 992 times more energy than a 1.0.



(a) Seismic hazard risk zones.

Moment Magnitude Scale The **moment magnitude scale**, in use since 1993, is more accurate for determining the magnitude of large earthquakes than is the Richter scale. Moment magnitude considers the amount of fault slippage produced by the earthquake, the size of the surface (or subsurface) area that ruptured, and the nature of the materials that faulted, such as whether they exhibit brittle or ductile characteristics. The moment magnitude scale takes into account extreme ground acceleration (movement upward), which the Richter scale method underestimated. A reassessment of past earthquakes has changed the magnitude rating of some. As an example, the 1964 earthquake at Prince William Sound in Alaska had a Richter magnitude of 8.6, but on the moment magnitude scale, it increased to M 9.2.



(b) Seismic waves from a 2013 earthquake in Iran.

Earthquake Prediction

Figure 8.27 plots global earthquake hazards and shows the waves from a 2013 quake in Iran. Note that almost all earthquakes occur along plate boundaries where the plates diverge, converge, or slide past each other. The challenge is to discover how to predict the *specific time and place* for an earthquake in the short term in regions of prior earthquake experience. One approach, the study of *paleoseismology*, examines the history of each plate boundary in order to determine the frequency of past earthquakes. A second approach observes and measures phenomena that might precede an earthquake. For example, the affected region may tilt and swell in response to strain—changes that can be measured by tiltmeters. Another indicator is an increase in radon (a naturally occurring, slightly radioactive gas) dissolved in groundwater. Even with these advances, earthquakes are complex natural events that remain extremely difficult to predict.

(c) A woman sits in front of her devastated home from a 2013 earthquake in Iran.

▲ **8.27 Global seismic hazards**

geoCHECK ✔ Describe two approaches taken in efforts to predict earthquakes.

8.8 (cont'd) Earthquakes

Earthquake Hazards & Safety

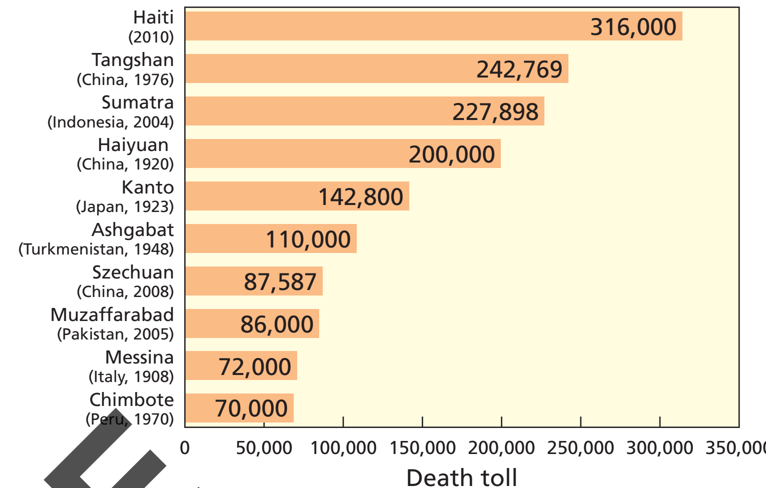
Earthquakes are often terrifying events. Unlike other natural disasters such as floods, windstorms, and volcanic eruptions, the Earth shakes with no warning over large geographic areas. Although ground shaking is the initial hazard, surface displacement through faulting, liquefaction of soil (when water-saturated soils suddenly turning into liquid mud when an earthquake strikes), tsunamis, and flooding often accompany earthquakes.

Since 1900, over 1.5 million people have perished from earthquakes around the world (▸ **Fig. 8.28**). However, earthquake magnitude is but one factor in determining the overall number of casualties. Other dynamics include population density, building codes, the time of day, and other events triggered by the earthquake, such as tsunamis, fires, and debris flows. These factors are discussed with the examples below.

Nepal, 2015 In the spring of 2015, a 7.8 magnitude earthquake and numerous aftershocks leveled parts of Kathmandu, the capital city of Nepal (▾ **Fig. 8.29**). Over 8000 people died within the city limits and in villages throughout this Himalayan country. Substandard building codes led to the collapse of both new and ancient structures, and Nepal's remote location complicated rescue and relief efforts. After the quake, heavy rains drenched thousands of suddenly homeless people, contributing to the high death toll.

Megathrust Earthquakes Powerful *megathrust* earthquakes occur in convergent subduction zones where one tectonic plate is thrust under another. These "Great Quakes" can generate a magnitude 9.0 or greater event. Recent examples include Japan 2012, Indonesia 2010, Chile 1960, and Alaska, 1964. In the United States, only the Alaska-Aleutian and Cascadia (southern British Columbia to northern California) subduction zones are capable of generating megathrust quakes. The immense energy released during these seismic events often triggers accompanying disasters such as earth and debris flows, flooding, and tsunamis (▾ **Fig. 8.30**).

Virginia, 2011 Some earthquakes occur distant from plate boundaries. In 2011 a 5.8 earthquake centered 64 km (40 mi) northwest of Richmond, Virginia, shook the eastern United States. It was the region's most powerful temblor since 1897 and sent people scurrying from homes and offices from Maine to South Carolina (▸ **Fig. 8.31**). The earthquake forced the evacuation of many government buildings in Washington, D.C., cracked foundation stones in the Washington Monument, and temporarily closed nuclear power reactors in Virginia while officials checked for damage.



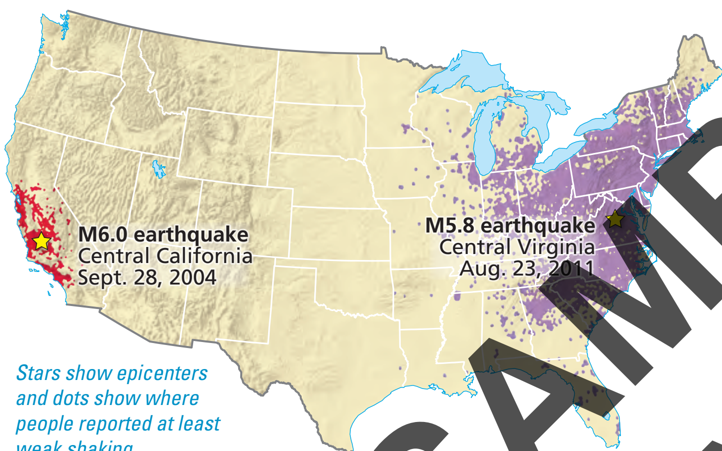
▴ **8.28 Major earthquakes' death toll** Collapsing buildings and tsunamis cause many earthquake-related casualties.

▾ **8.29 Nepal, 2015** Damage was severe because most structures in Nepal are not designed to withstand earthquakes.

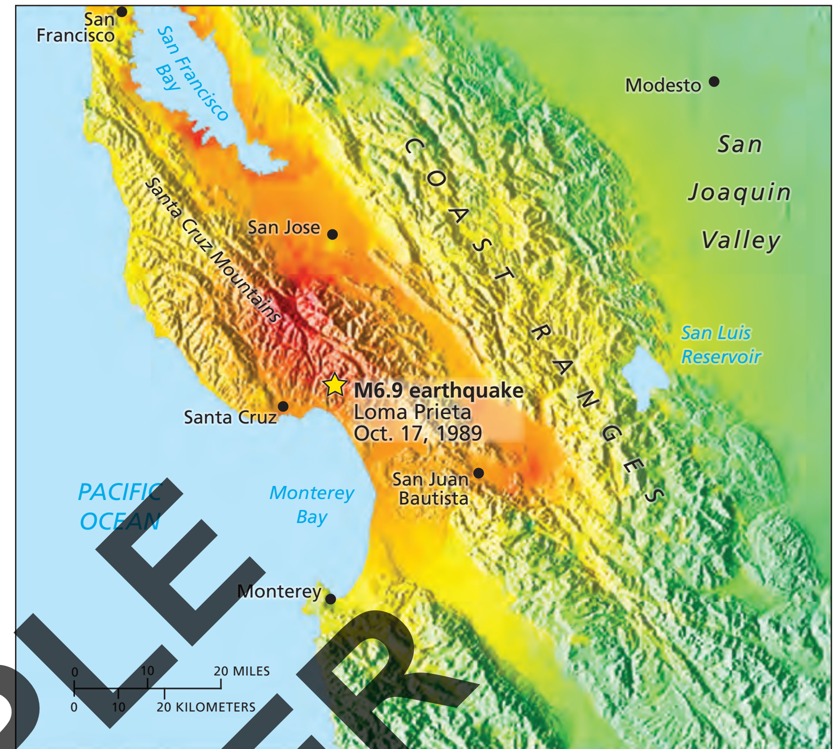
▴ **8.30 Japan, 2011** (a)The tsunami that followed the 2011 earthquake devastated settlements along Japan's northern Pacific coast.

San Andreas Fault, California Earthquakes are frequent in a zone along the San Andreas fault, the transform boundary where the North American and Pacific Plates meet. In 1989, a magnitude 6.9 quake rocked California's San Francisco Bay Area, causing 6 billion dollars in damage and claiming 67 lives—47 of them when a section of the Bay Bridge collapsed (▸ **Fig. 8.32**). The 1989 earthquake is often compared to the 1906 "Great Quake" and fires that killed over 3000 people and destroyed 80% of San Francisco. Although the 7.9 magnitude of the 1906 temblor was much greater, the lower death toll in 1989 is attributed to progress in developing and enforcing better building codes and earthquake safety procedures.

geo**CHECK** ✔ Where do megathrust earthquakes occur?



▲ **8.31 Mapping Earthquake Shaking** The United States Geologic Survey maps reports of earthquake shaking. Notice how the 2011 Virginia quake was felt across a much wider area than the 2004 California quake of similar magnitude.

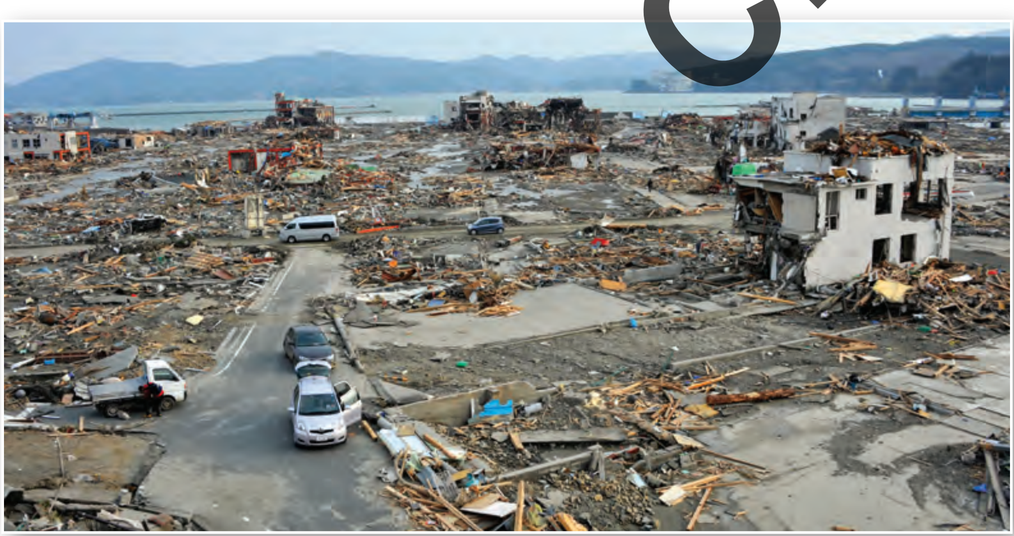


PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

(a)

(b)

▲ **8.32 San Francisco Bay Area, 1989** The magnitude 6.9 Loma Prieta earthquake caused significant damage in scattered parts of the San Francisco Bay area. (a) After the 1989 earthquake, geologists used the Modified Mercalli scale to rate the amount of shaking across the area affected by the quake. (b) Damage from the 1989 earthquake.



(b) Almost nothing was left of this coastal town after the tsunami struck.

geo**QUIZ**

1. What physical factors trigger an earthquake?
2. What is the relationship between an earthquake's focus and epicenter?
3. Describe the difference between earthquake intensity and magnitude.

8.9 Volcanoes

Key Learning Concepts

- ▶ ***Describe*** the distribution of volcanic activity.
- ▶ ***Distinguish*** between effusive eruptions and explosive eruptions and the volcanic landforms each produces.
- ▶ ***Identify*** the structural features of a volcano, types of lava, and related volcanic landforms.
- ▶ ***Give examples*** of volcano hazards in different parts of the world

Over 1300 volcanic cones and mountains exist on Earth, of which 600 are classified as **active**, meaning that they have erupted in the last 10,000 years. Globally, about 50 volcanoes erupt on Earth's land surface each year. Volcanoes are spectacular to witness from a safe distance, but worldwide, more than 500 million people live within a volcanic hazard zone.

Distribution of Volcanic Activity

Volcanic eruptions reveal Earth's internal energy and match plate tectonic activity (▼ **Fig. 8.33**). Most volcanic activity occurs in three settings:

- Along subduction zones where continental and oceanic plates converge (the Cascade Range in the Pacific Northwest and the Andes of South America) or where two oceanic plates converge (Philippines and Japan).
- Along sea-floor spreading centers (Iceland, on the Mid-Atlantic Ridge; off the coast of Oregon and Washington) and along areas of rifting on continental plates (the rift zone in East Africa).
- At hot spots, where plumes of magma rise through the crust (Hawaii and Yellowstone).

The 70 volcanoes in North America are mostly inactive. Mount St. Helens in Washington is the most active.

geoCHECK ✔ Compare and contrast volcanic activity at divergent and convergent boundaries.

Types of Volcanic Activity

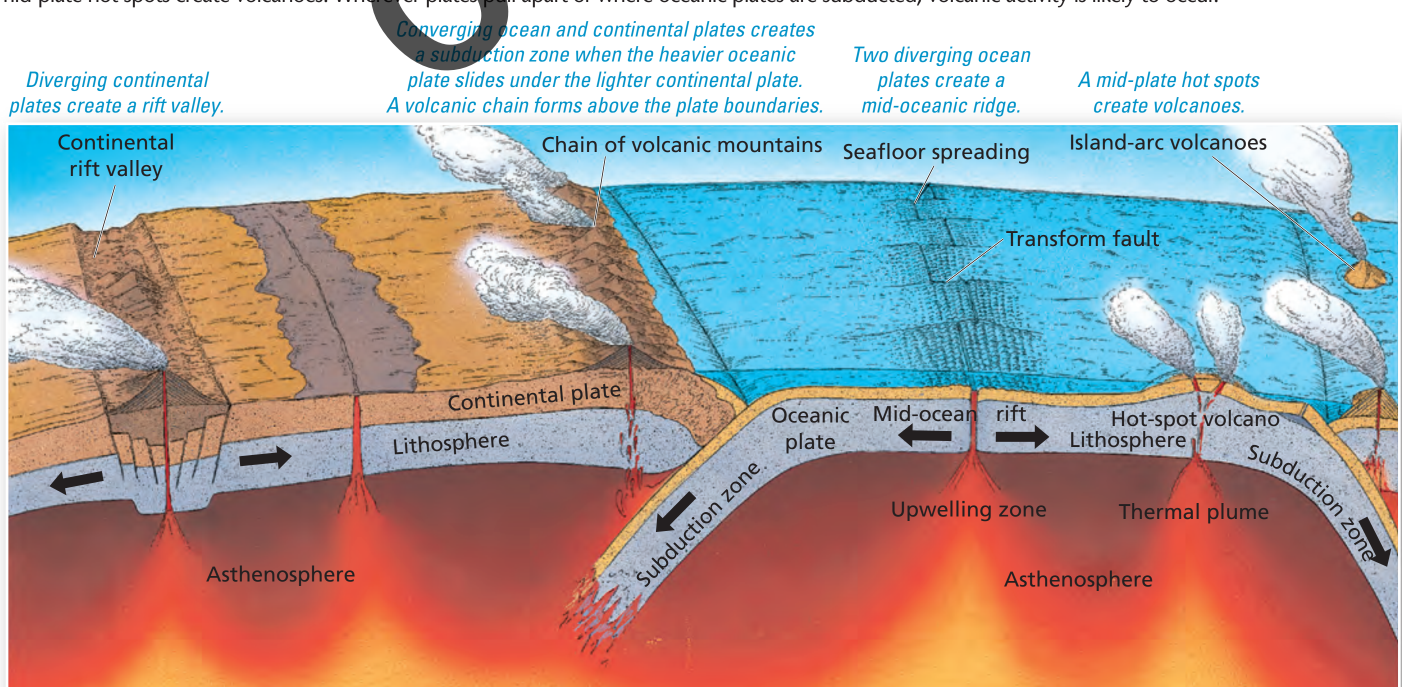
The eruption type and resulting lava is determined by the magma's mineral composition, which is related to its source, and by the magma's viscosity. Viscosity is the magma's "thickness," or resistance to flow, which ranges from low viscosity (very fluid) to high viscosity (thick and slow flowing).

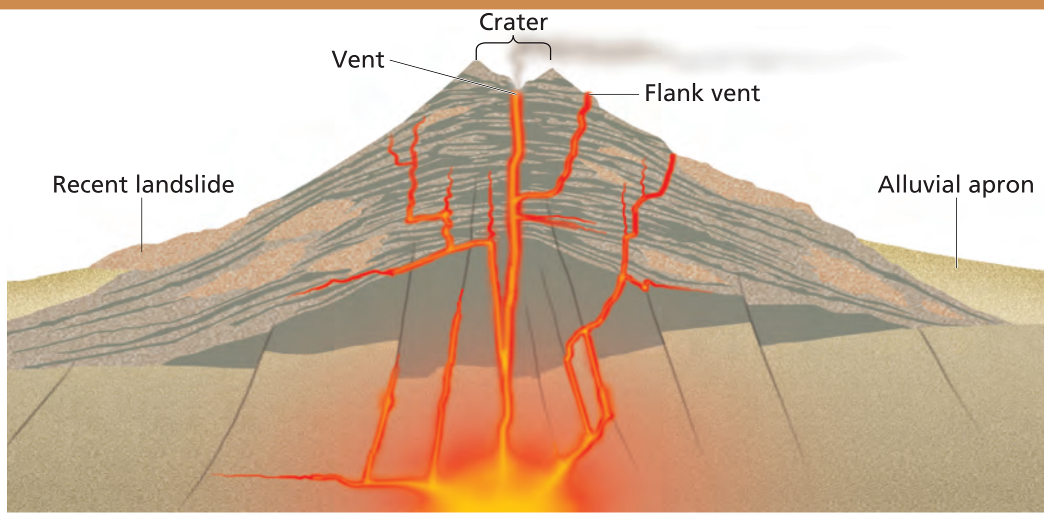
Effusive Eruptions Originating from the asthenosphere and upper mantle, **effusive eruptions** are relatively gentle, with enormous lava flows on the seafloor, or occur in hot spots such as Hawaii and Iceland. The low-viscosity lava cools into a basaltic rock, low in silica and rich in iron and magnesium. Gases readily escape from this fluid magma, producing gentle eruptions with little volcanic debris, although trapped gases can generate lava fountains. Repeated eruptions create a gently sloping **shield volcano** (► **Fig. 8.34c**).

Explosive Eruptions Magma produced by subducting oceanic plates is more viscous and forms **explosive eruptions.** The high silica and aluminum content produces magma so viscous that it prevents the gases from escaping by blocking the magma conduit. Pressure of the trapped gases increases until it causes an explosive eruption. Repeated eruptions of alternating ash, rock, and lava form a steep-sided and more conical **composite volcano**, also called a *stratovolcano* (Fig. 8.34b). Explosive eruptions produce less lava than effusive eruptions, but more **pyroclastics**—ash, dust, cinders, scoria, pumice, and aerial bombs.

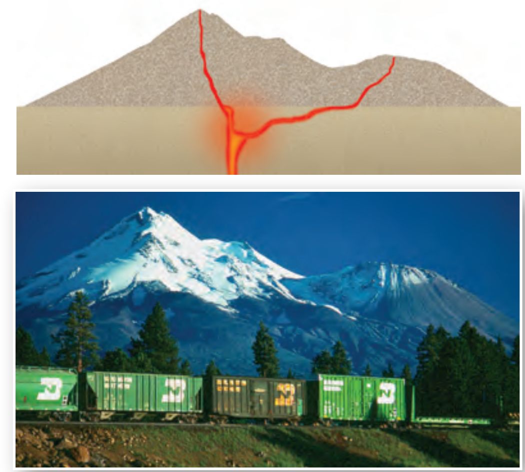
▼ **8.33 Tectonic settings of volcanic activity** (a) Diverging continental plates create a rift valley. (b) Converging ocean and continental plates creates a subduction zone when the heavier oceanic plate slides under the lighter continental plate. A volcanic chain forms above the plate boundaries. (c) Two diverging ocean plates create a mid-oceanic ridge. (d) A mid-plate hot spots create volcanoes. Wherever plates pull apart or where oceanic plates are subducted, volcanic activity is likely to occur.

Animation MG
Volcano Types
http://goo.gl/a7OlaJ



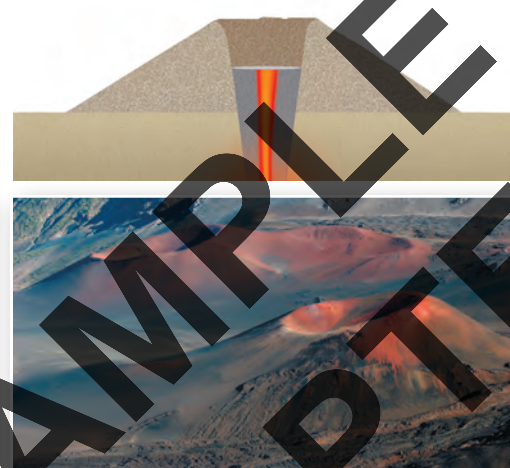


(a) Cross-section of a volcano.

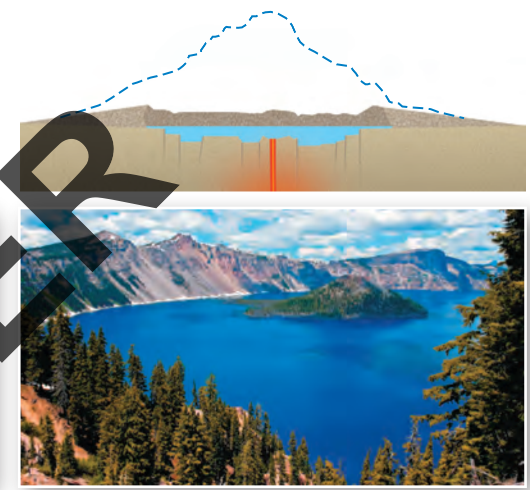


(b) Composite volcano: Mount Shasta, California

(c) Profile of a shield volcano.



(d) Profile of a cinder cone.



(e) Crater Lake in Oregon is a caldera.

▲ **8.34 Volcano structure and types**

In addition to lava and pyroclastic materials, a volcanic eruption can spread particulates, gases, and aerosol clouds and can alter Surface albedo or atmospheric albedo? Ash plumes reflecting sunlight are what typically cause post-eruption cooling.

geoCHECK ✔ List and describe the different types of pyroclastics.

Volcanic Features

A **volcano** forms at the end of a vent that rises from the asthenosphere and upper mantle through the crust to create a volcanic mountain, as shown in Figure 8.34a. Effusive eruptions are outpourings of slow moving magma that produce enormous volumes of lava annually on the seafloor and in places such as Hawaii and Iceland. Repeated eruptions slowly build a gently sloping **shield volcano**. On the other hand, repeated explosive eruptions produce a **composite volcano** of multiple layers of lava, ash, rock, and pyroclastics. A **crater** usually forms on or near the summit. Magma rises and collects in a chamber deep below the volcano until the tremendous heat and pressure is sufficient to cause an eruption.

Recall that magma that reaches the surface is called lava. Lava, gases, and pyroclastics, eject through the vent to build volcanic landforms. Flowing basaltic lava takes two principal forms that differ in texture—both have Hawaiian names (▸ **Fig. 8.35**). The rough texture occurs when lava loses trapped gases, flows slowly, and develops a thick skin that cracks into jagged surfaces. In contrast, **pahoehoe** forms a thin crust of "ropy" folds. Both forms can erupt together, and pahoehoe can turn into aa downslope.

A **cinder cone** is a cone-shaped hill usually less than 450 m (1500 ft) high, with a truncated top formed from cinders (a type of pyroclastic rock full of air bubbles) that accumulate during moderately explosive eruptions (Fig. 8.34d). A **caldera** (Spanish for "kettle") is a large depression that forms when summit material on a volcano collapses inward after an eruption (Fig. 8.34e).

geoCHECK ✔ Explain the difference between a cinder cone and a caldera.

▼ **8.35 Two types of basaltic lava from Hawaii** Pahoehoe (left) has a rough texture, while aa (right) has smoothly folded texture.

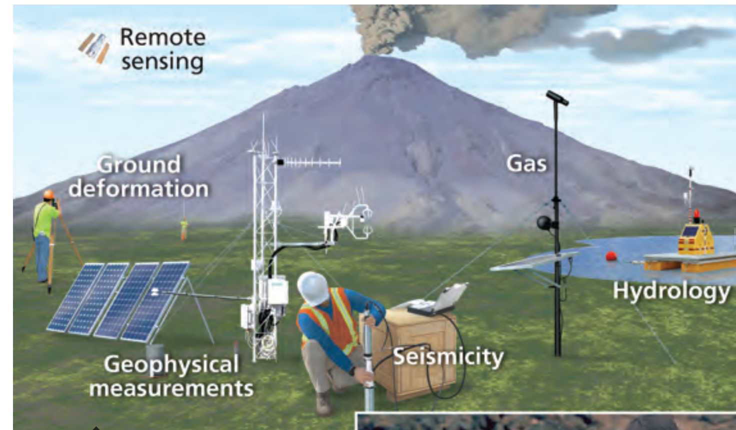
8.9 (cont'd) Volcanoes

Volcano Hazards & Monitoring

The danger to humans from active volcanoes includes flowing lava, volcanic bombs, and explosive ash and pyroclastic materials, among others. Volcanism also triggers earth and debris flows, flooding from melting ice and snow, and earthquakes. In the 20th century alone, almost 100,000 people died from volcanic activity, and another 5.6 million people suffered some degree of injury, evacuations, and property damage. In the past 30 years alone, volcanism has killed 29,000 people, forced 800,000 evacuations, and caused $3 billion in damage, spurring researchers' efforts to improve hazard mapping and enhance early warning systems.

Monitoring Volcanoes Unlike earthquakes, which cannot be accurately predicted, reliable indications usually precede volcanic eruptions. When a volcano begins to show signs of activity, scientists monitor data on gas emissions, ground deformation, and seismic activity (▸ **Fig. 8.36**). Governments use this data to determine the timing and nature of warnings intended to mitigate the loss of life and property. The following examples portray how ongoing volcanic activity threatens the well-being of human life and property (▾ **Fig. 8.37**). (Note that Figure 8.40 shows the locations of these recent eruptions.)

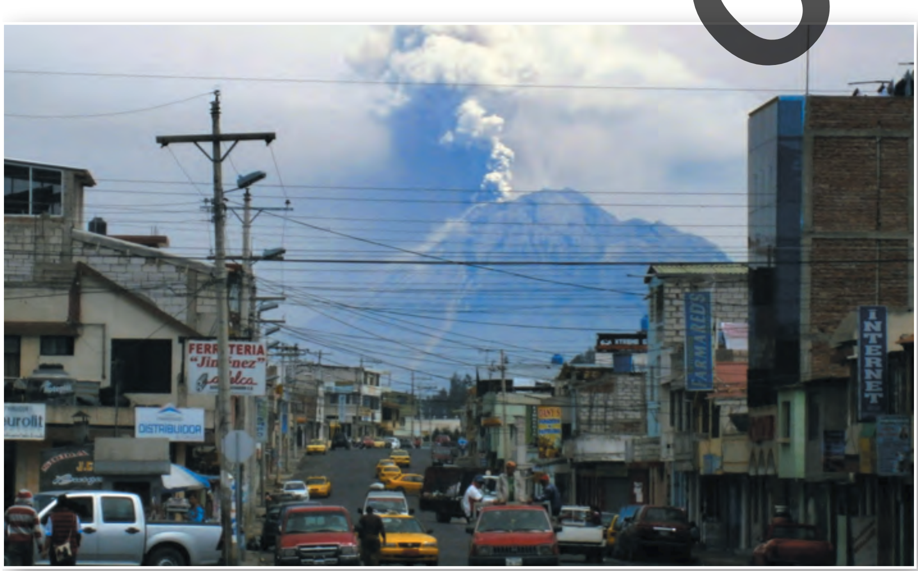
Andes Mountains Tungurahua is an active stratovolcano in the Andes Mountains of South America. In February 2014, an eruption sent clouds of ash and other pyroclastic material 8 km (5 mi) into the atmosphere, wreaking havoc over the Ecuadorian cities of Baños and Ambato (▾ **Fig. 8.37**). Dormant until 1999, Tungurahua, meaning "throat of fire" in the indigenous Quechua language, is one of eight active volcanoes in Ecuador. In 2015, it continued to spew ash and sulfur dioxide and trigger small earthquakes as molten lava flowed from the mantle into volcanic vents near the earth's surface.



▴ **8.36 Monitoring volcanic activity** Geologists use a variety of instruments to monitor the physical changes that precede a volcanic eruption.

Farther south in the Andean chain, Calbuco, a dormant volcano in Chile, suddenly erupted in April 2015. The plume of smoke and ash reached 10 km (6 mi) into the atmosphere (▾ **Fig. 8.38**). Within days, the drifting cloud deposited up to 1 m (3.3 ft) of ash on roadways and homes, forcing the evacuation of people and farm animals.

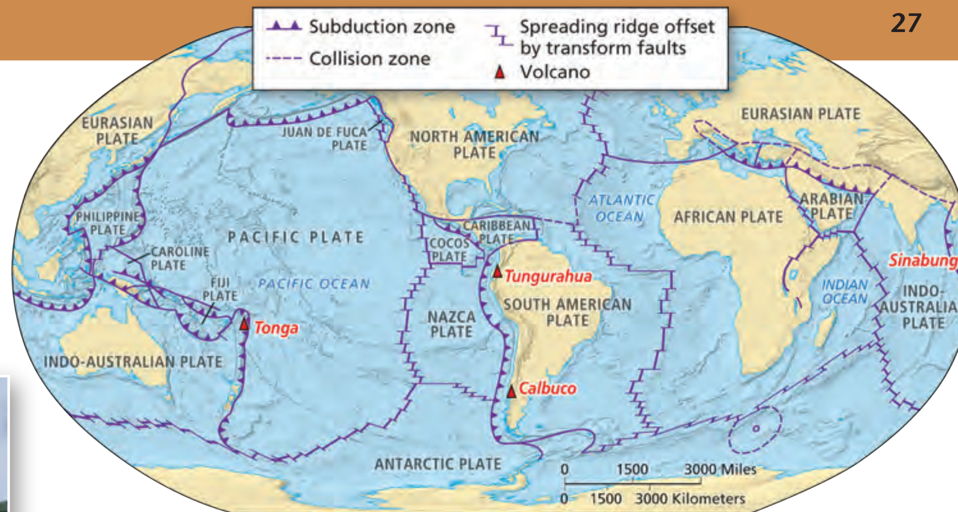
▾ **8.37 Andean outburst, Ecuador, 2014** Tungurahua is an active composite volcano in the Andes Mountains of South America. This February 2014 eruption sent clouds of ash and other pyroclastic material to 8 km (5 mi) in altitude, causing havoc over the Ecuadorian cities of Baños and Ambato.



▾ **8.38 Ash deposits, Chile, 2014** (a) Calbuco, a volcano in southern Chile that had been dormant for 40 years, suddenly erupted in April 2015. (b) A plume of smoke and ash reached 10 km (6 mi) into the sky. (c) The drifting ash cloud deposited up to 1 m (3.3 ft) of ash on roadways and homes.

(a)

Indonesia In 2014, eruptions of volcanic gas and ash from erupting Mount Sinabung rose up to 2000 m (6561 ft) above dozens of small villages, sending lava, ash, and other pyroclastic material hurtling toward people, livestock, and fields (▼ **Fig. 8.39**). Located on the Pacific Ring of Fire, the many islands that compose Indonesia are home to 147 active volcanoes.



▲ **8.40 Recent volcanic eruptions**

▲ **8.39 Fleeing Mount Sinabung, Indonesia, 2014** Eruptions of volcanic gas and ash rose up to 2000 m (6561ft) above dozens of small villages. On this day, lava and pyroclastic material flowed downslope just 4.5 km (2.8 mi) away. Located on the Pacific Ring of Fire, the many islands that make up Indonesia are home to 147 active volcanoes.

Tonga In December 2014, an undersea volcano erupted in the Polynesian island Kingdom of Tonga, in the South Pacific Ocean. For over a month, periodic eruptions spewed lava and ash up to 4500 m (14,765 ft) into the sky. When the eruption ended in January 2015, a new island measuring 1 km (.6 mi) wide and 250 m (820 ft) high rose above the ocean surface (▶ **Fig. 8.41**). Although already home to shorebirds, persistent rainfall combined with a weak underlying geologic structure may level the island within a year.

▶ **8.41 New island rises in the South Pacific Ocean, 2014** (a) An undersea volcano erupted in the Polynesian island Kingdom of Tonga. (b) The new landscape measures 3 km^2 (1.1 mi^2) in size, and is already home to shorebirds. The highest peak is approximately 250 m (820 ft) above the ocean. Note how rainfall is actively carving channels into the soft volcanic rock.

(a)

(b)

(b)

(c)

geoCHECK ✔ What data make predicting volcanic eruptions more feasible than predicting earthquakes?

geoQUIZ

1. What is the relationship between the location of volcanic activity and plate tectonics?
2. Define viscosity and explain its relevance to the two main types of volcanic eruption.
3. Describe the difference between a shield volcano and a composite volcano, and provide an example of each.

8.10 Mountain Building

Key Learning Concepts

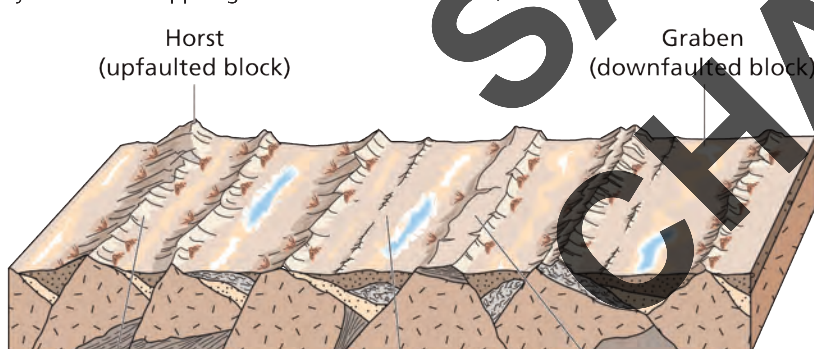
- ***Define*** orogenesis.
- ***Explain*** how mountains of different types support the plate tectonics model.

The geologic term for mountain building is **orogenesis**, meaning the birth of mountains (*oros* comes from the Greek for "mountain"). An *orogeny* is a mountain-building episode, occurring over millions of years as a large-scale deformation and uplift of the crust. For example, the Sierra Nevada of California formed when a granite batholith was exposed by erosion following uplift. No orogeny is a simple event: Movements of the crust along faults, the convergence of plates, and volcanic activity can be involved. Many orogenies occurred in Earth's past, and the processes continue today.

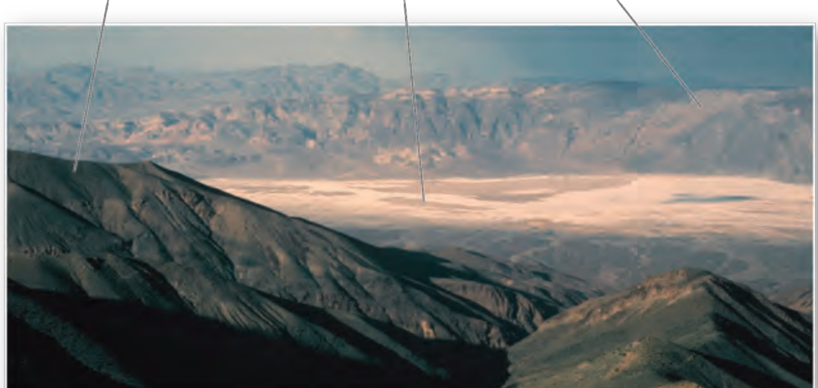
Types of Orogenesis

Earth's folded and faulted mountain chains correlate well with the plate tectonics model. Mountain chains are found either at the plate margins, or as a series of parallel mountain ranges extending inland a great distance from two colliding or subducting plates. Other mountains form in areas of crustal spreading, where a plate is under tension, because tectonic forces are pulling the plate apart.

▼ **8.42 Faulted landscapes** (a) Paired faults produce fault-block mountains in a horst-and-graben landscape. (b) Death Valley features parallel horsts, separated by the down-dropped graben.



(a)



(b)

Fault-Block Mountains Across some landscapes, pairs of normal faults act together to form a distinctive terrain made up of parallel mountains, often called *fault-block mountains*, separated by valleys. The term **horst** applies to upward-faulted blocks that form the mountains; **graben** refers to downward-faulted blocks that form the valleys (▼ **Fig. 8.42**). Examples include the Great Rift Valley of East Africa, associated with crustal spreading, and the Basin and Range landscapes of the American West.

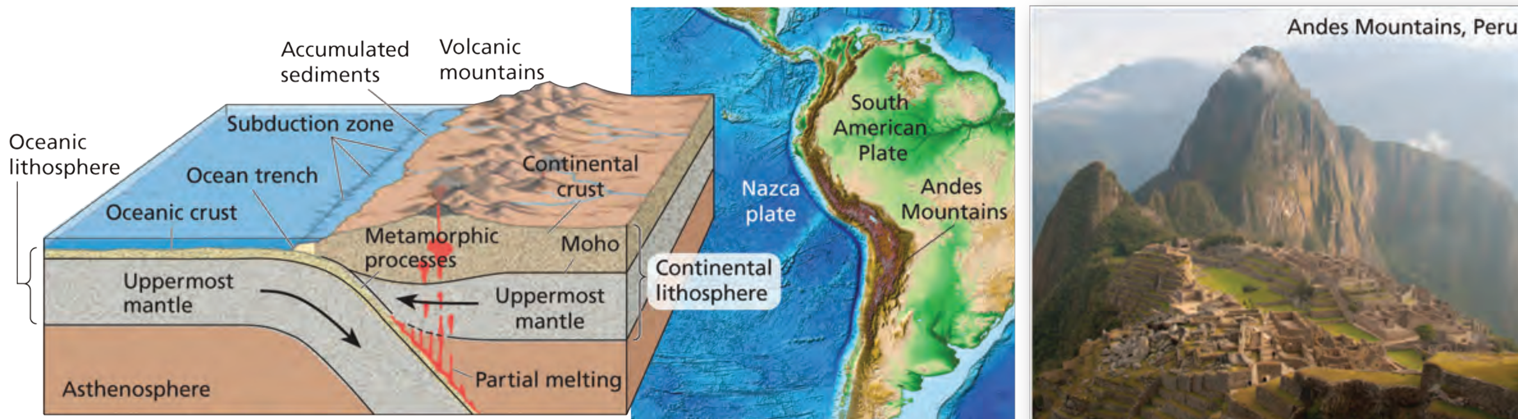
Mountains From Oceanic–Continental Plate Collisions Figure 8.43 illustrates three types of tectonic activity that cause orogenesis along convergent plate margins. The first type involves oceanic plate–continental plate collisions (► **Fig. 8.43a**) that occur along the Pacific coast of the Americas and has formed the Andes, Sierra of Central America, Rockies, and other western mountains. Folded sedimentary formations, with intrusions of magma forming granitic plutons compose these mountains. Also note the volcanic activity inland from the subduction zone and composite volcanoes.

Mountains From Oceanic–Oceanic Plate Collisions Another type of orogenesis, oceanic plate–oceanic plate collisions (► **Fig. 8.43b**), produces volcanic island arcs, such as Indonesia and Japan. The same process formed the island arcs that continue from the southwestern Pacific to the western Pacific, the Philippines, the Kurils, and portions of the Aleutians. Both of these collision types are active around the Pacific Rim's "Ring of Fire." These processes are thermal in nature, because the subducting plate melts and the magma then rises back toward the surface as molten rock.

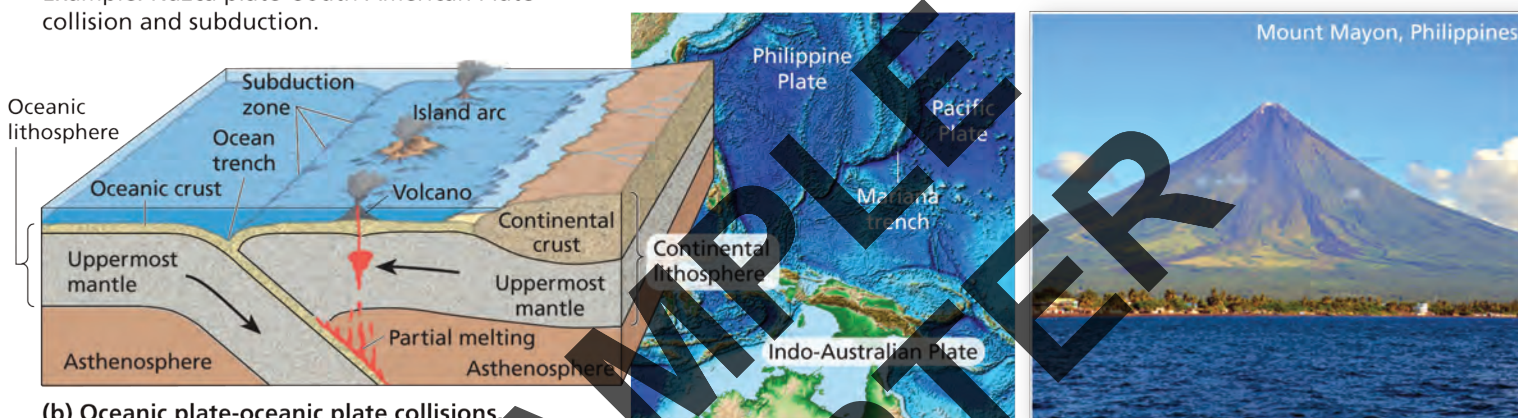
Mountains From Continental–Continental Plate Collisions A third type of orogenesis involves continental plate–continental plate collisions. In these instances, large masses of continental crust are mechanically subjected to intense folding, overthrusting, faulting, and uplifting (► **Fig. 8.43c**). The converging plates crush and deform both marine sediments and basaltic oceanic crust, pushing them up as the mountains grow. The European Alps and American Appalachian Mountains result from such compression, with associated crustal shortening and overturned folds.

The collision of India with Eurasia is uplifting the Himalayan-Karakoram-Hindu Kush-Pamir, and Tien Shan chains (Fig. 8.43c). The Indian Plate is moving northwestward into the Eurasian Plate up to 6 cm (2.3 in) a year. Over 40 million years, this collision has shortened the continental crust by 1000 km (600 mi), produced thrust faults at depths of 40 km (25 mi), and caused severe earthquakes. This region includes all 10 of the highest above-sea-level peaks on Earth.

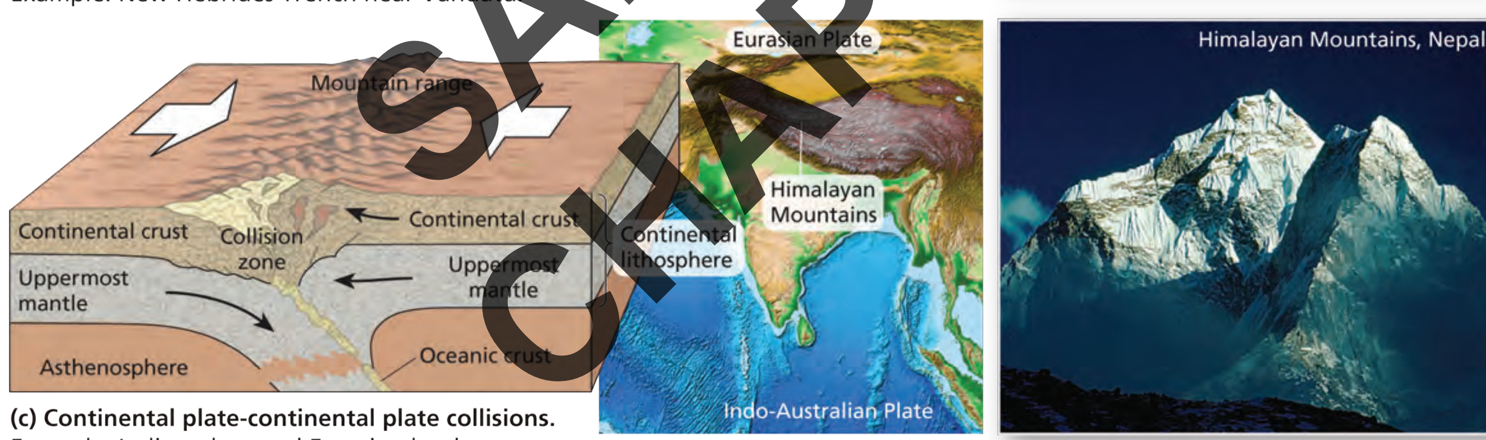
geoCHECK ✔ List and describe the three types of orogenesis.



(a) Oceanic plate-continental plate collisions.
Example: Nazca plate–South American Plate collision and subduction.



(b) Oceanic plate-oceanic plate collisions.
Example: New Hebrides Trench near Vanuatu.



(c) Continental plate-continental plate collisions.
Example: Indian plate and Eurasian landmass collision and resulting Himalayan Mountains.

▲ **8.43 Three types of orogenesis caused by plate convergence** (a) oceanic plate–continental plate collisions (example: Nazca plate–South American Plate collision and subduction); (b) oceanic plate–oceanic plate collisions (example: New Hebrides Trench near Vanuatu; and (c) continental plate–continental plate collision (example: Indian Plate and Eurasian landmass collision and resulting Himalayan Mountains).

geoQUIZ

1. Referring to Figure 8.43, summarize the process that forms fault-block mountains and their related valleys.
2. What process created the "Ring of Fire" orogenic region?
3. What type of orogenesis produces intensely folded mountains?

ENDOGENIC PROCESSES IMPACT HUMANS

- Endogenic processes cause natural hazards such as earthquakes and volcanic events that affect humans and ecosystems.
- Rocks provide materials for human use; geothermal power is a renewable resource.

HUMANS IMPACT ENDOGENIC PROCESSES

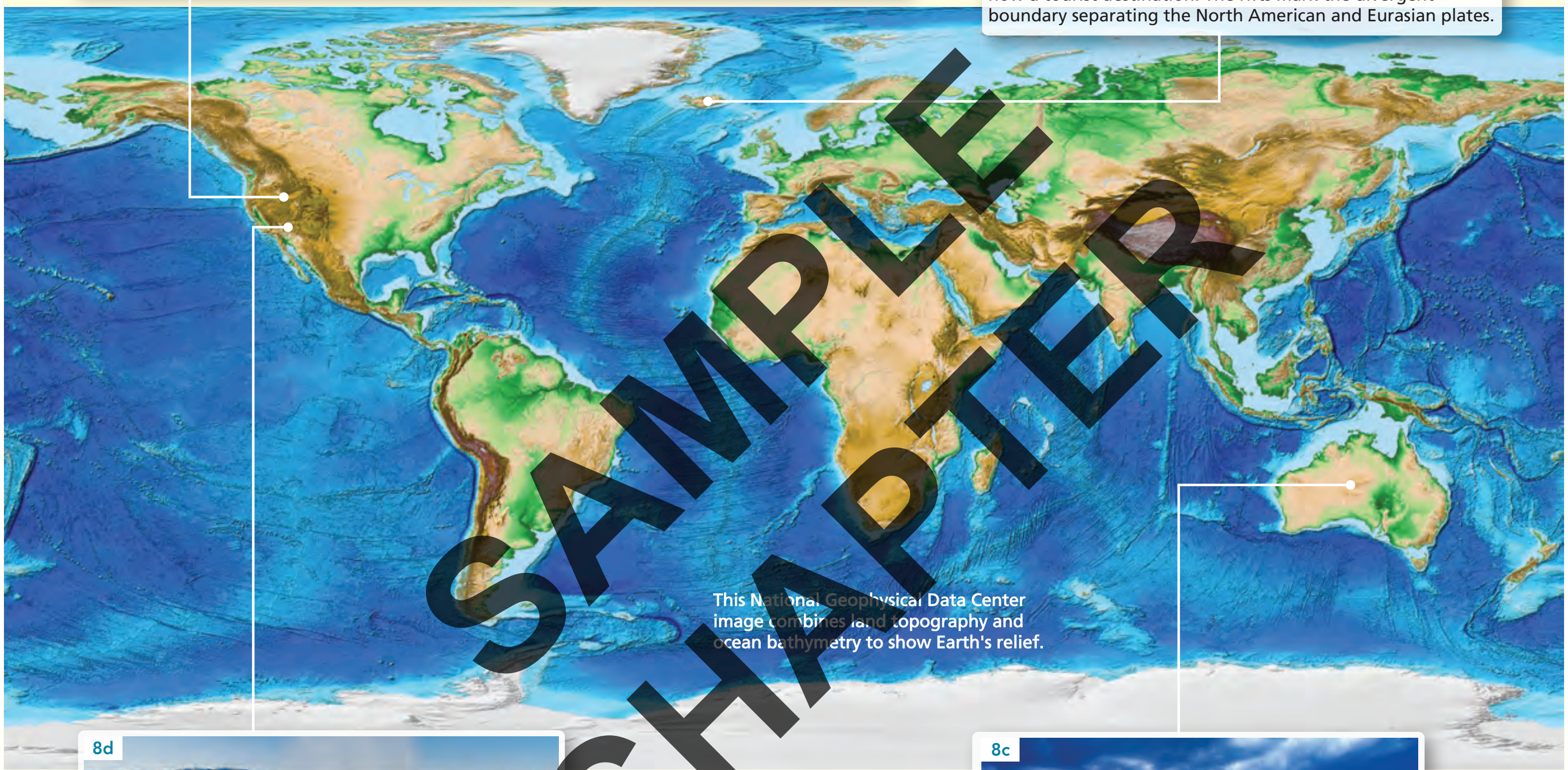
- Wells drilled into Earth's crust in association with oil and gas drilling or for enhanced geothermal systems may cause earthquakes.

8a

Hydrothermal activity produces hot springs and associated travertine deposits in Yellowstone National Park, Wyoming, which sits above a stationary hot spot in Earth's crust. Grand Prismatic Spring, pictured here, is the largest hot spring in the United States. The geysers and thermal features of this area draw over 3 million visitors each year.

8b

The Mid-Atlantic Ridge system surfaces at Thingvellir, Iceland, now a tourist destination. The rifts mark the divergent boundary separating the North American and Eurasian plates.



This National Geophysical Data Center image combines land topography and ocean bathymetry to show Earth's relief.

8d

In April 2013, the Nevada Desert Peak EGS became the first U.S. enhanced geothermal project to supply electricity to the power grid.

8c

Uluru, also known as Ayers Rock, is probably Australia's best-known landmark. This steep-sided isolated sandstone feature, about 3.5 km (2.2 mi) long and 1.9 km (1.2 mi) wide, was formed from endogenic and exogenic processes and has cultural significance for the Aboriginal people

ISSUES FOR THE 21ST CENTURY

- Geothermal capacity will continue to be explored as an alternative energy source to fossil fuels.
- Mapping of tectonically active regions will continue to inform policy actions with regard to seismic hazards.

Looking Ahead

In the next chapter, we investigate geomorphology—the science of surface landforms. These processes include the weathering and erosion of the uplifted landscapes that formed the subject of this chapter.

Chapter 8 Review

What are Earth's History, Interior Structure, & Materials?

8.1 The Vast Span of Geologic Time

Describe **the geologic time scale.**

Distinguish **between relative and absolute time.**

Explain **how the principle of uniformitarianism helps geologists interpret Earth's history.**

- The *geologic time scale* is a summary timeline of all Earth history. Earth is about 4.6 million years old. The time scale depicts this time period into various segments, which may be viewed in *absolute* time or *relative* time. Of these, relative time dating supports the principle of *superposition*. A guiding principle of Earth science is uniformitarianism, the idea that "the present is the key to the past."

1. How are fossils and the principle of superposition used to help determine the difference between absolute time and relative time?

8.2 Earth's History & Interior

Summarize **how and when Earth formed.**

Describe **Earth's layered structure.**

- Earth's interior is made up of layers, each one distinct in either chemical composition or temperature. Heat energy moves outward from the center by conduction and convection. Earth's layers include the inner core, outer core, mantle, and crust. Near the top of the mantle is the asthenosphere, a plastic-like layer that underlies the rigid lithosphere and outer crust.

2. What is the relationship between the asthenosphere, the Moho, and the crust?

8.3 Cycles in Earth Systems

Analyze **how Earth's geologic cycle relates the tectonic, rock, and hydrologic cycles.**

Explain **how rocks cycle through geologic time.** ***differentiate*** **the processes that create igneous, sedimentary and metamorphic rocks.**

- The geologic cycle is the endless tug-of-war between the endogenic (interior Earth) forces that build landforms and the exogenic ones that erode them. This cycle can be further subdivided into the rock, tectonic, and hydrologic cycles. This chapter emphasizes the rock cycle, which forms the three main classes of rocks: igneous, sedimentary, and metamorphic.

3. Identify the two broad subdivisions of igneous rocks, then describe how one of these rocks could transition into a sedimentary rock, and then again, how the sedimentary rock could transition into a metamorphic rock. Include the environments where these transitions occur, such as an ocean trench or river delta.

How Does Plate Tectonics Explain Changes in Earth's Surface?

8.4 Plate Tectonics

Summarize **Wegener's hypothesis of continental drift, the formation and breakup of Pangaea, and why scientists at the time rejected the hypothesis.**

Describe **how the processes of plate tectonics transform Earth's surface over time.**

- Modern science has established that there is a cycle in which continents collide, forming supercontinents that then move apart and eventually re-form again. This process, called plate tectonics, includes the upwelling of magma; lithospheric plate movements; seafloor spreading and lithospheric subduction; earthquakes; volcanic activity; and lithospheric deformation such as warping, folding, and faulting.

4. How are earthquakes, volcanic eruptions, and faulting linked to plate tectonics?

8.5 Sea Floor Spreading & Subduction Zones

Describe **the roles of seafloor spreading and subduction in forming and destroying the ocean floor.**

Explain **how geomagnetism supports the concept of seafloor spreading.**

State **the relationship between subduction, earthquakes, and volcanoes.**

Identify **two mechanisms of plate motion.**

- On the seafloor, interconnected mid-ocean ridges occur at divergent plate boundaries, where plates move apart and pockets of magma form beneath the surface. Magma erupts through fractures and small volcanoes along the ridge, forming new seafloor. As the magma cools, bits of iron align with the magnetic North Pole, providing a record of seafloor age. Oceanic lithosphere is subducted beneath deep ocean trenches in subduction zones.

5. Why do some tectonic plates "subduct" underneath other plates?

8.6 Plate Boundaries

Describe **the types of plate boundaries and the movement associated with each.**

Explain **how earthquake and volcanic activity relate to plate boundaries.**

Identify **the cause and effect of hot spots.**

- At plate boundaries, plates meet and then either slide down into the asthenosphere or collide upward to form mountains. Plate motions—divergent, convergent, or transform—largely determine the landforms on Earth's surface. Plate boundaries are also the primary location of earthquake and volcanic activity. In the middle of some oceanic and continental plates, hot spots send upwelling magma to the surface.

6. How would the regional landforms of the Himalaya–Karakoram Mountains and the African Rift Zone be different if their respective plate motions suddenly reversed their directions?

How Do Plate Motions Affect Earth's Crust?

8.7 Deformation, Folding, & Faulting

Identify **the forces that deform the crust and the effects of deformation.**

Describe **folding and warping and their resulting landforms.**

Compare and contrast **the different types of faults.**

- All rocks undergo powerful stress by tectonic forces, gravity, and the weight of overlying rocks. Rocks respond to this strain by warping, folding, or faulting. These processes closely correlate with plate boundaries, and they are strong evidence for plate tectonics.

7. What is the difference between warping, folding, and faulting in a landscape?

8.8 Earthquakes

Explain **what happens during an earthquake.**

Distinguish **between earthquake intensity and magnitude.**

Discuss **why scientists cannot yet predict earthquakes.**

Give examples **of earthquake hazards in different parts of the world.**

- Earthquakes occur mostly along plate boundaries. Earthquakes occur when friction is overcome and the sides along plate boundaries or fault lines suddenly shift. Seismic waves then radiate outward from the focus and the epicenter, carrying energy throughout the planet. A worldwide network of seismographs record the transmitted waves.

8. Where and why are humans more likely to experience earthquakes and earthquake damage?

8.9 Volcanoes

Describe **the distribution of volcanic activity.**

Distinguish **between effusive eruptions and explosive eruptions and the volcanic landforms each produces.**

Identify **the structural features of a volcano, types of lava, and related volcanic landforms.**

Give examples **of volcano hazards in different parts of the world.**

- Volcanic activity occurs along subduction zones where continental and oceanic plates converge, in seafloor spreading zones, and at hot spots. The eruption type and the properties of the resulting lava are determined by the magma's chemistry. Volcanic activity appears in two main forms: effusive eruptions that produce shield volcanoes and explosive eruptions that produce composite cones and pyroclastic material.

9. Describe the three geologic settings where most volcanic activity occurs.

8.10 Mountain Building

Define **orogenesis.**

Explain **how mountains of different types support the plate tectonics model.**

- An *orogeny* is a mountain-building episode, occurring over millions of years as a large-scale deformation and uplift of the crust. The resulting volcanic or folded and faulted mountain chains are found either at the plate margins or as chains of parallel mountain ranges that form inland from two colliding or subducting plates. The precise type of mountain building depends upon the type of plate convergence.

10. Describe how two colliding continental plates produce an orogenic landscape different from that produced at an oceanic hot spot.

Critical Thinking

1. Draw a simple sketch of the Earth's interior, label each layer, and list the physical characteristics, temperature, composition, and depth of each layer on your drawing.

2. Describe how an intrusive igneous rock forms. How would this same rock transition into a sedimentary rock? How could your new sedimentary rock then become a metamorphic rock?

3. Explain how different types of plate boundaries produce different types of landforms and landscapes.

4. Diagram a simple folded landscape in cross section, and identify two features created by the folded strata.

5. Where do you expect to find areas of volcanic activity in the world? Explain your answer.

Visual Analysis

Figure R8.1 looks into the inner gorge of the Grand Canyon. The Unkar Rapids of the Colorado River are visible in the lower center.

1. What does the principle of superposition tell us about where the oldest rocks, and the youngest rocks, are found in this photograph?

2. What likely tectonic forces mentioned in the text caused the rock layers in the middle of the photograph to tilt from left (higher) to right (lower)?

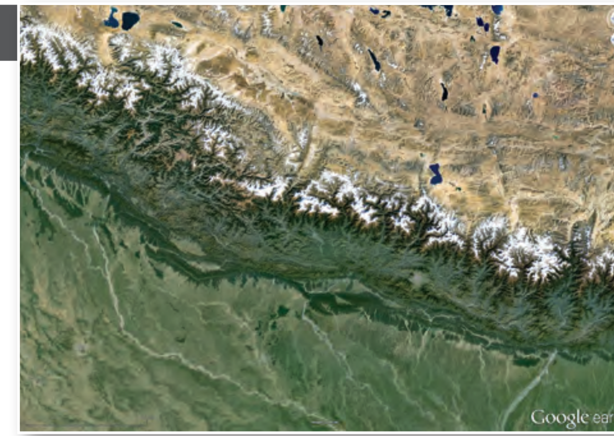
3. What suggests that the rocks just above the river might be a different type of rock (metamorphic, igneous, or sedimentary), from the rocks that lie on top of them?

▲ R8.1

Explore | Use **Google Earth** to explore the **Himalayas**.

Viewing Earth from space allows us to visualize tectonic plates on a continental/oceanic scale. In Google Earth, make sure that the "*Borders and Labels*" are checked, but leave other categories unchecked. Fly to *Nepal* and locate the capital, *Kathmandu*, from which you can view the Ganges River Plain to the south, the Himalaya in the middle, and the Tibetan Plateau to the north. Locate the city of *Musahri* on the Ganges Plain at the bottom of the image. While watching the elevation change (displayed at the bottom of the Google Earth screen), slide the cursor northward to Kathmandu, then east-northeast to Mt. Everest, marked with a green mountain symbol. From Mt. Everest, slide the cursor north across the Himalaya to the Tibetan Plateau.

1. How do topography and elevation change between India and Tibet?
2. How does plate tectonics explain these changes?



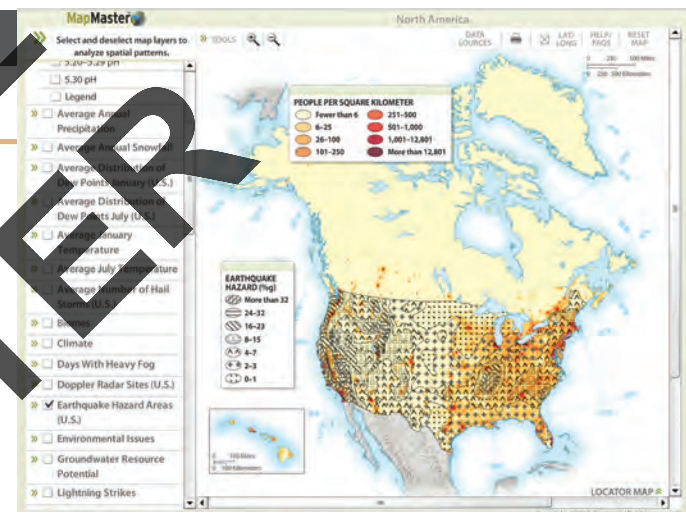
▲ R8.2

Interactive Mapping | Login to the **MasteringGeography** Study Area to access **MapMaster**.

Comparing Earthquakes & Population Density in North America

- Open: MapMaster in MasteringGeography
- In the Physical Environment categories, Select: *Earthquake Hazard Areas* (U.S.). Next, turn on the *Population* categories, and select *Population Density*.

1. Compare the relationship between earthquake frequency and population density in the western and eastern United States. In which parts of the country are large numbers of people *most* at risk from earthquakes?
2. In which parts of the country are people *least* at risk from earthquakes?



▲ R8.3

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Key Terms

aa, p. 25
absolute time, p. 4
anticline, p. 18
batholith, p. 10
caldera, p. 25
cinder cone, p. 25
composite volcano p. 24
convection current, p. 6
crater p. 25
deep ocean trench, p. 15
earthquake, p. 19
effusive eruption, p. 24
explosive eruption, p. 24
extrusive igneous, p. 9
faulting, p. 19
folding, p. 18
geologic cycle p. 8
geologic time scale, p. 4
geomagnetism, p. 14
graben, p. 28
horst, p. 28
hot spot p. 17
igneous rock, p. 9
intrusive igneous, p. 9
lava, p. 10
lithospheric plates p. 12
magma p. 10
metamorphic rock p. 9
mid-ocean ridges, p. 14
mineral, p. 9
Mohorovičić discontinuity, p. 7
Moho, p. 7
moment magnitude scale p. 21
normal fault p. 19
orogenesis p. 28
Pangaea, p. 12
pahoehoe p. 12
pluton, p. 10
principle of superposition, p. 4
pyroclastic, p. 24
relative time, p. 4
reverse fault p. 19
Richter scale p. xxx
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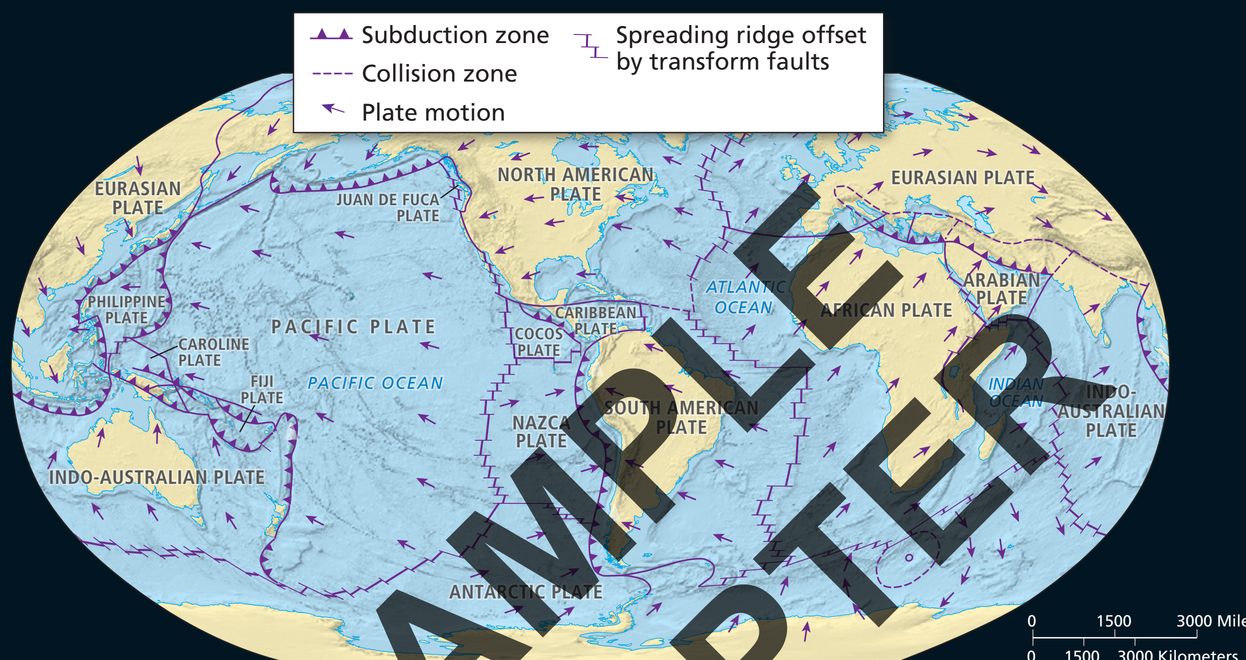
rock cycle p. 9
rock p. 9
seafloor spreading, p. 14
sedimentary rock, p. 9
seismic wave, p. 20
seismograph, p. 20
slab pulls p. 16
strike-slip p. 19
subduction zone, p. 15
syncline, p. 18
theory of plate tectonics, p. 12
thrust p. 19
uniformitarianism, p. 5
volcano p. 24

GeoLab8

Life on the Edge: How do plate boundaries put humans at risk?

GeoLab8 MG Pre-Lab Video
https://goo.gl/DOYwiS

Figure GL 8.1 shows tectonic features in the recent geologic time of the late Cenozoic Era. Note that in Figure GL 8.1, each arrow represents 20 million years of movement. Recall the specific types of plate boundaries: convergent (subduction); divergent (seafloor spreading); mid-ocean ridges; and transform (lateral motion between crests of spreading ridges producing transform, or strike-slip, faults).



▲GL8.1 The continents today: plate boundary interactions

Apply

In this lab you will first use the map of late Cenozoic Era tectonic movements to learn about the principal motions of plates and plate boundaries. The second section involves using a hazard map, photograph, and tectonic diagram to assess the varied risks of living close to a plate boundary.

Objectives

- Identify the major plates.
- Locate and analyze the three types of plate movement and their boundaries.
- Explain why humans living on a plate boundary are subjected to multiple hazards.

Procedure

Part I

1. Describe the following plate boundaries in terms of the three types of plate boundary interactions shown in Figure GL8.1.
   a. The Nazca and South American plates
   b. The Caribbean and Atlantic Ocean plates
   c. The Philippine and Eurasian plates
   d. The Indo-Australian and Eurasian plates
2. Which plates converge near Japan? What explains the existence along this boundary of the islands that make up Japan?
3. Which type of landform are the colliding Juan De Fuca and North American plates likely producing? Explain your answer.
4. Looking at Figure GL 8.2a and b, identify where sedimentary, igneous, and metamorphic rocks would most likely be located in the Pacific Northwest region.

Part II

Plate boundaries are active geologic zones where endogenic and exogenic processes occur. Taken together, they pose substantial risks for humans who live on the edge of plate boundaries.

Use Figure GL 8.2 and the Chapter 8 modules to answer the following questions:

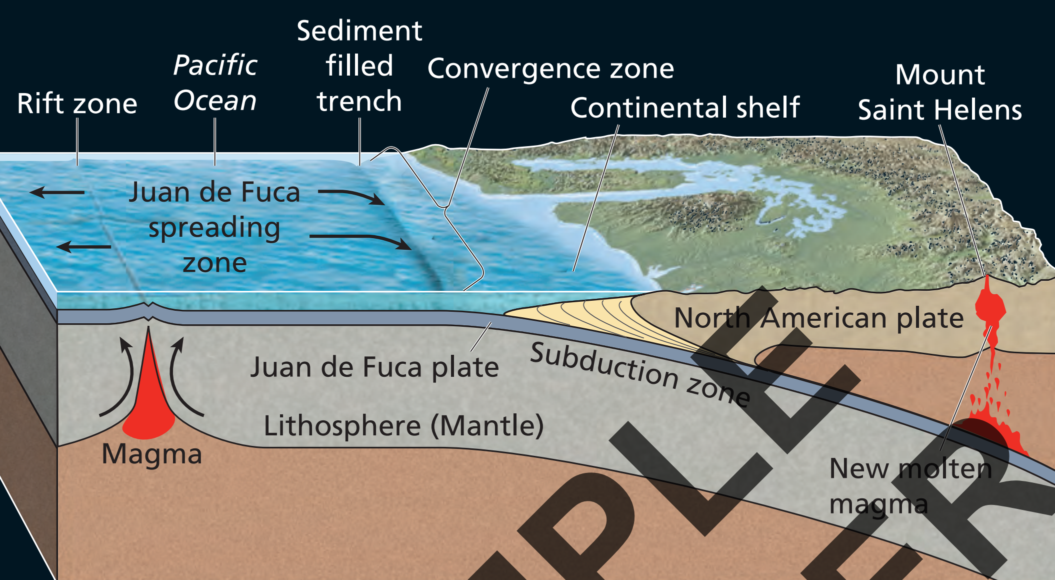
5. How does the type of plate boundary influence the number and type of natural hazards that threaten the Seattle area?

6. Among the many natural hazards found in the Pacific Northwest, which one, usually triggered by earthquakes on the plate boundary, does not occur in inland locations?

7. If during the next million years, the North American, Pacific, and Juan de Fuca plates slowly shifted their direction relative to one another, would the Seattle region become a safer place for humans to live?

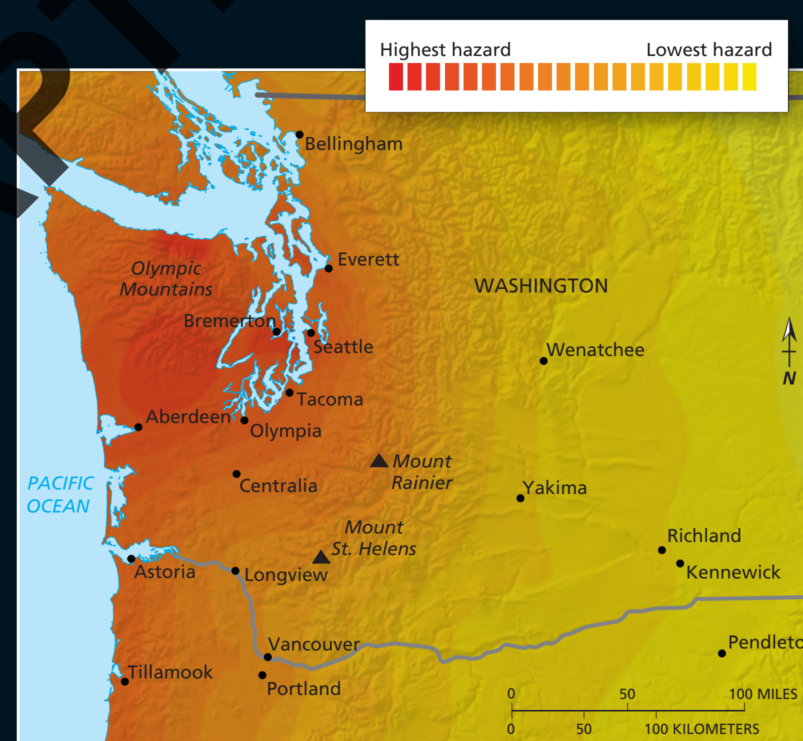
Analyze & Conclude

8. What are the advantages and disadvantages of living in the natural environment that results from this plate boundary?



(a)

(b)



(c)

▲GL8.2 **(a) Juan de Fuca plate and subduction zone (b) Downtown Seattle, in the shadow of Mt. Rainier (c) Pacific Northwest earthquake hazard.**

Log in MasteringGeography™ to complete the online portion of this lab, view the Pre-Lab Video, and complete the Post-Lab activity. www.masteringgeography.com

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Illustration and Text Credits

Figure 8.1: Geologic time scale, showing highlights of Earth's history. From R. Christopherson, Elemental Geosystems 7e, (c) 2013 Pearson Education, Inc. Data and update from Geological Society of America and Nature 429 (May 13, 2004): 124–125.

Figure 8.17 (a) Detail from ocean-floor map. (b) The mid-Atlantic rift surfaces through Iceland. Adapted from J. R. Heirtzler, S. Le Pichon, and J. G. Baron, Deep-Sea Research 13, © 1966, Pergamon Press, p. 247 and The Bedrock Geology of the World by R. L. Larson, et al., © 1985, W. H. Freeman and Company.

Table 8.2: Magnitude, Intensity, and Frequency of Earthquakes Source: USGS Earthquake Hazards Program.

Line Art: Movements of lithospheric plates. Source: U.S. Geodynamics, National Academy of Sciences and National Academy of Engineering

Map: Nepal,2015. www.thegatewaypundit.com/2015/04/massive-7-8-earthquake-hitsnepal-avalanche-on-mount-everest-800-dead/

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