Even the height of these towering cliffs in the Andes Mountains of Peru represent only the top 0.01% of the Earth's radius.

CHAPTER 2

Journey to the Center of the Earth

The Earth is not a mere fragment of dead history, stratum upon stratum like the leaves of a book . . . but living poetry like the leaves of a tree.

—*Henry David Thoreau (1817–1862)*

LEARNING OBJECTIVES

By the end of this chapter, you should understand . . .

- that many objects besides the Sun and planets comprise the Solar System.
- that a magnetic field and an atmosphere surround our planet.
- that the Earth System includes many distinct, interacting realms.
- that the Earth has distinct internal layers (crust, mantle, and core).
- that the rigid lithosphere, Earth's outer shell, overlies a plastic asthenosphere.

2.1 Introduction

In 1961 a Russian cosmonaut, Yuri Gagarin, became the first human to orbit the Earth, and by the end of the decade two Americans, Neil Armstrong and Buzz Aldrin, became the first to walk on the Moon. These exploits were truly amazing: for the first time, humans saw their home planet from a distance and gained a true appreciation of its uniqueness and limits. Though people have not yet traveled farther than the Moon, we have sent spacecraft to other planets and beyond. In fact, in 2013 a spacecraft named *Voyager 1*, launched in 1977 to fly by Jupiter and Saturn, passed out of our Solar System. *Voyager 1* carries a message of greeting, inscribed on a copper disk, from humanity to whomever—or whatever—it might encounter tens of thousands of years in the future. Should *Voyager 1* ever reach one of the many exoplanets astronomers have found, the craft's instruments could provide interesting details about the body.

Let's turn the tables and speculate about what an imaginary spacecraft sent from exoplanet toward Earth would detect. In this chapter, we follow this "exoprobe" as it enters and traverses the Solar System and then explores the nature of Earth's immediate surroundings and finally, our planet's surface. Then we turn our attention downward, to characterize the interior of the Earth, from its surface to its center, as detected by measurements of the Earth's shape and gravitational pull and confirmed by instruments sent down to the surface. This high-speed fantasy tour provides a foundation from which we can develop geologic themes introduced through the remainder of this book.

2.2 Welcome to the Neighborhood

A Journey through the Solar System

For most of its journey toward our Solar System, the exoprobe travels through **interstellar space**, the region between stars. This region is a **vacuum** (an absence of matter) so profound that it contains less than one atom per liter—by comparison, air at sea level contains 27,000,000,000,000,000,000,000 (or, in scientific notation, 2.7×10^{22}) atoms per liter. The atoms in interstellar space are either parts of nebulae or are **cosmic rays**, high-energy atomic nuclei ejected into space at extreme velocity by supernova explosions. Eventually, the exoprobe begins to feel the ever-so-weak pull of the Sun's gravity—this happens at a distance of about 50,000 AU from the Sun. (An **AU**, or **astronomical unit**, is the distance between the Earth and the Sun—it equals about 150 million kilometers, or 93 million miles.) As it continues to move toward the Sun, the exoprobe detects specks, flakes, and balls of "ice" (frozen volatile materials such as water, carbon dioxide, ammonia, and methane), either leftovers of the nebulae from which our Solar System formed or fragments scattered into space soon after Solar System formation. Together, these objects make up the **Oort Cloud**, whose inner edge lies at a distance of about 3,500 AU from the Sun.

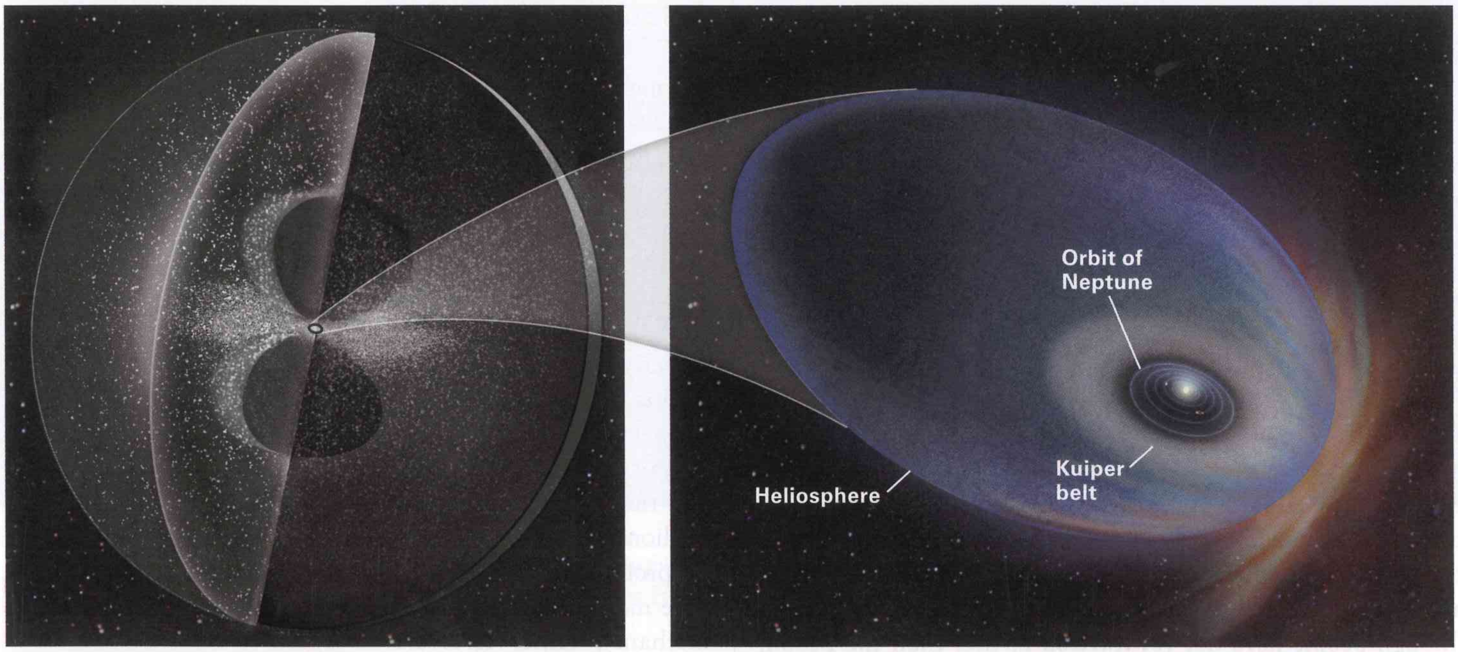
Did you ever wonder . . .

what defines the edge of our Solar System?

At a distance of about 200 AU, our spaceship crosses another invisible boundary and enters the bubble-like **heliosphere**, the inner edge of interstellar space. The region within the heliosphere contains predominantly solar-wind particles, electrons and protons ejected into space from our Sun, whereas the region outside contains predominantly cosmic rays ejected from other objects in space toward our Sun. It is the heliosphere, which technically defines the "edge" of the Solar System, that *Voyager 1* crossed. Then, at a distance of 30 to 55 AU, our spaceship traverses the **Kuiper Belt**, a diffuse ring of icy objects left over from the protoplanetary disk. About 100,000 of the objects in the Kuiper Belt have diameters over 100 km (**Fig. 2.1**), and some, such as Pluto and Eris, have diameters of over 1,200 km and are known as dwarf planets. *Comets* originate from the Kuiper Belt, and to a lesser extent, from the Oort Cloud (**Box 2.1**). All told, the Kuiper Belt and Oort Cloud could contain a trillion objects with a combined mass that may approach that of Jupiter.

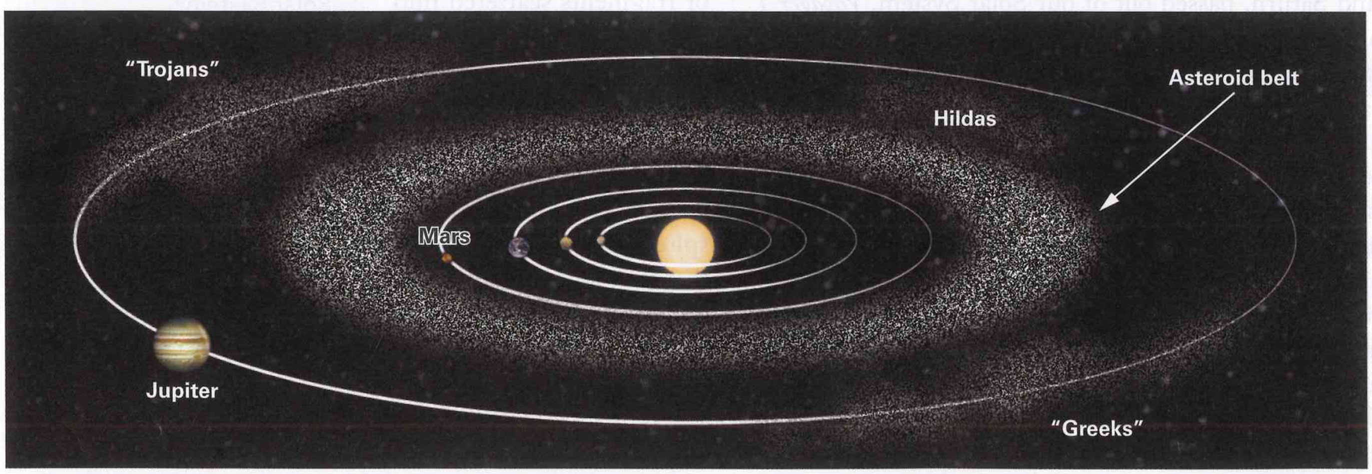
The orbit of Neptune, the outermost true planet, defines the inner edge of the Kuiper Belt—once we've passed this orbit, we're traversing **interplanetary space**. In interplanetary space, the concentration of atoms increases to between 5,000 and 100,000 per liter. Thus, while this region is still a profound vacuum, it is much denser than interstellar space. As our probe zooms across the *ecliptic*, the plane containing the orbits of all the planets, we pass Uranus, the other ice-giant planet), the two gas-giant planets (Saturn and Jupiter), and then the *asteroid belt*, a diffuse band about 2.5 AU across that contains about 10 million small solid objects (see Box 2.1). In the inner part of the Solar System we find the four terrestrial planets—reddish Mars, bluish Earth (with its large Moon), greenish cloud-enshrouded Venus, and heavily cratered Mercury (**Fig. 2.2**). Even from the distance of space, Earth looks special, so the exoprobe's computer picks it out to approach and study more closely.

FIGURE 2.1 What a spacecraft would see if it traversed the Solar System and its surroundings.



(a) The Oort Cloud is a diffuse cloud of icy particles held in by the Sun's gravity.

(b) The heliosphere, which is very tiny compared to the Oort Cloud, technically delimits the edge of the Solar System. The Kuiper Belt and planets lie within it.



(c) The asteroid belt lies outside of the orbit of Mars. Some asteroids (known as the Trojans and the Greeks) have been locked into Jupiter's orbit.

BOX 2.1 CONSIDER THIS . . .

Comets and Asteroids–The Other Stuff of the Solar System

Comets and asteroids are of growing concern to humanity because some of them have orbits that may cross the orbit of the Earth and thus could collide with our planet. What are comets and asteroids, and how do they differ from each other?

A **comet** is an icy planetesimal whose highly elliptical orbit brings it so close to the Sun that during part of its journey it evaporates and releases glowing gas and dust that forms a tail pointing away from the Sun (**Fig. Bx2.1a, b**). Comets that take less than 200 years to orbit the Sun originate from the Kuiper Belt, whereas those with longer orbits originate from the Oort Cloud. Objects become comets when gravity from planets tugs on them and sends them on a trajectory to the inner Solar System.

In recent decades, researchers have sent spacecraft to observe comets close-up. During an approach to Halley's Comet in 1986, *Giotto* photographed jets of gas and dust spurting from the comet's surface. *Stardust* visited a comet in 2004 and returned to Earth with samples, and in 2005 *Deep Impact* dropped a copper ball on a comet to analyze the debris ejected by the impact. Such studies confirm that comets consist primarily of frozen water (H_2O), carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), and other volatile compounds, along with a variety of organic chemicals and dust (tiny rocky or metallic particles). Considering these components, astronomers often refer to comets as "dirty snowballs." Some geologists have speculated that abundant impacts of comets with the Earth, early in Solar System history, might have brought water and even molecules from which life evolved.

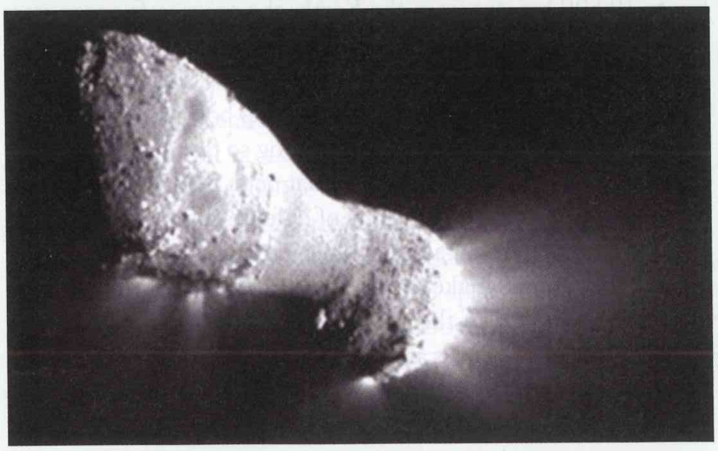
An **asteroid** is a small body of solid rock and/or metal that orbits the Sun. Most reside in the asteroid belt between the orbits of Mars and Jupiter. Some asteroids are small rocky planetesimals that were never incorporated into larger bodies, whereas others are fragments of once-large planetesimals that had differentiated into a metal core surrounded by rocky mantle before being shattered into fragments by collisions early in the history of the Solar System. While most asteroids are very small—from dust to basketball sized—astronomers have found 1,000 asteroids with diameters greater than 30 km and estimate that there may be about 2 million more with diameters greater than 1 km.

Though asteroids are numerous, their combined mass equals only about 4% that of the Earth's Moon. Notably, half of the mass of the asteroid belt resides in the four largest asteroids. Of these, the most massive, Ceres, is spherical and has a diameter of 950 km; its rocky/metallic center is surrounded by water and ice. The second most massive asteroid, Vesta, differentiated into a mantle and core and is somewhat spherical. Other asteroids do not have differentiated interiors and are too small for their own gravity to reshape them into spheres, so they are irregular, pockmarked masses (**Fig. Bx2.1c**). The material in the asteroid belt never merged to form a planet because it is constantly churned by Jupiter's gravitational pull.

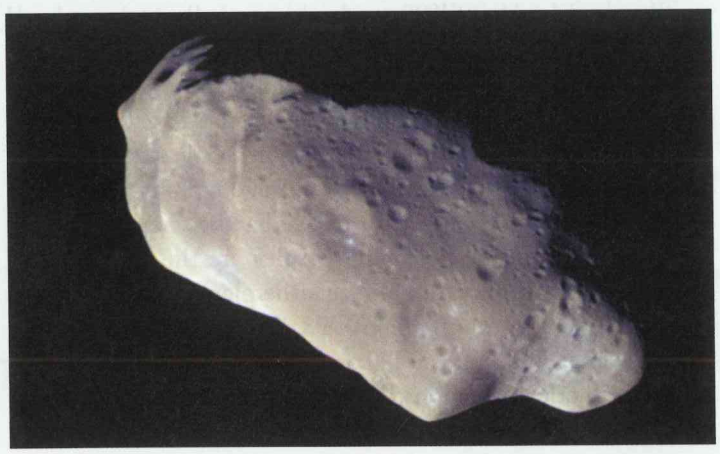
In recent decades, several space probes have visited asteroids. Some have flown by asteroids, and one, *Hayabusa* from Japan, landed on an asteroid, collected samples, and then returned to Earth. The *Dawn* spacecraft from the United States is currently mapping Ceres and Vesta in detail.

FIGURE Bx2.1 Images of asteroids and comets.

(a) Photograph of Comet Hale-Bopp, which approached the Earth in 1997. The head of this comet is about 40 km across.

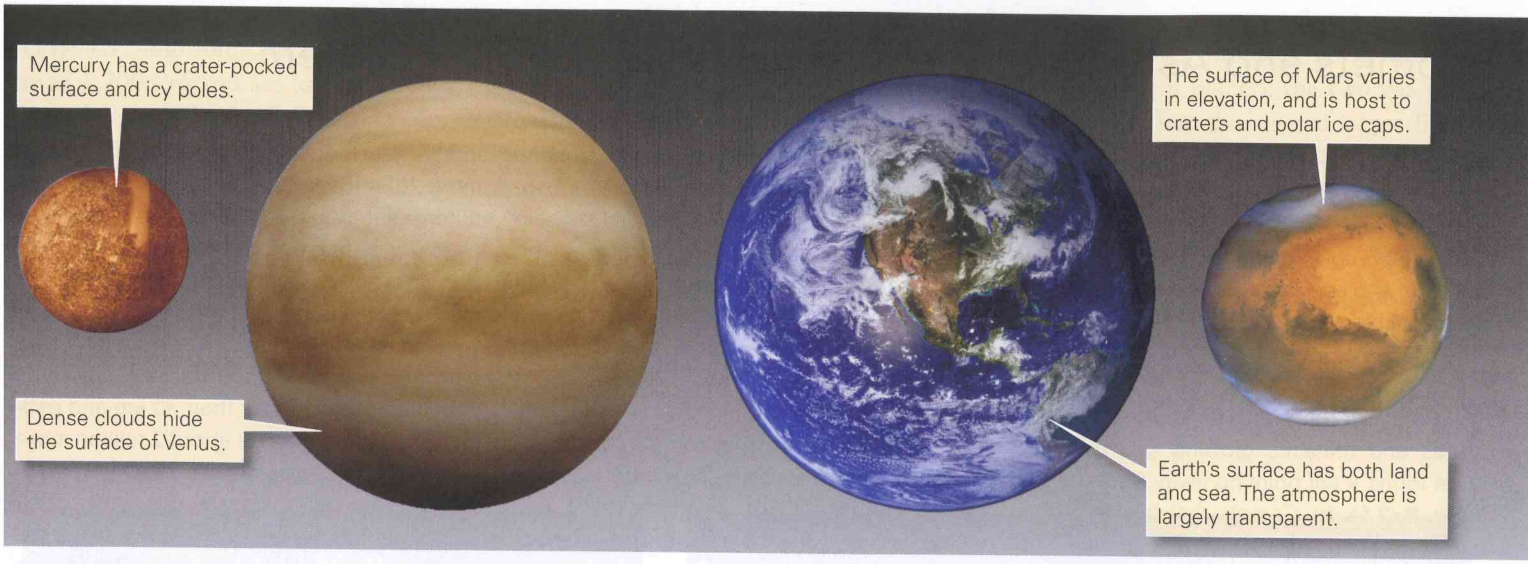


(b) Hartley 2, a comet viewed by the EPOXI spacecraft in 2010. The comet, which is about 1.5 km long, looks like a dirty snowball and emits jets of gas.



(c) Photograph of the asteroid Ida, a body that is about 56 km long.

FIGURE 2.2 An explorer from outer space would quickly realize that the four terrestrial planets look quite different from one another.



Earth's Magnetic Field

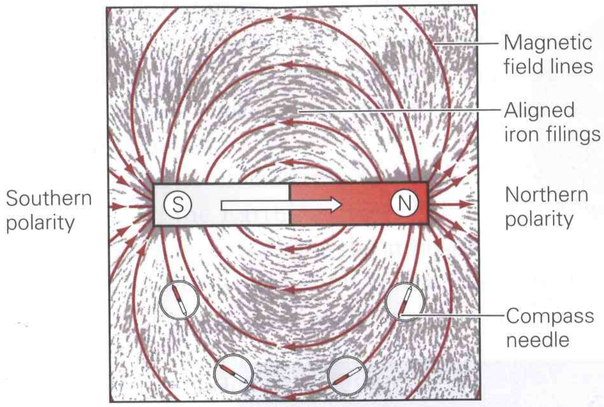
As the exoprobe nears the Earth, its instruments begin to detect the Earth's magnetic field, like a signpost shouting, "Approaching Earth!" A **magnetic field** is the region measurably affected by the force emanating from a magnet. This force, which grows progressively stronger as you approach the magnet, can attract or repel another magnet and can cause charged particles to move. Earth's magnetic field, like the familiar magnetic field around a bar magnet, is a **dipole**, meaning that it has two ends—a north pole and a south pole (**Fig. 2.3a, b**). If you bring two magnets close to each other, the unlike poles attract (pull toward each other), and the like poles repel (push away from each other). By convention, physicists represent the orientation of a magnetic dipole by an arrow that points from the south pole to the north pole, and they depict the magnetic field of a magnet by a set of invisible **magnetic field lines** that curve through the space around the magnet. Arrowheads along these lines point in a direction to complete a loop. Magnetized needles, such as iron filings or compass needles, when placed in a field, align with the magnetic field lines.

Because it is dipolar, we can simplistically represent the Earth's magnetic field as emanating from an imaginary bar magnet in the planet's interior. The north pole of this bar, as defined by physicists, lies near the south geographic pole of the Earth, whereas the south pole of the bar lies near the north geographic pole. (The **geographic poles** are the places where the spin axis of the Earth intersects the planet's surface. Presently, the spin axis tilts at angle of 23.4° relative to the ecliptic.) Nevertheless, geologists and geographers, by convention, refer to the magnetic pole closer to the north geographic pole as the *north magnetic pole*, and the magnetic pole closer to the south geographic pole as the *south magnetic pole*. This way, the north-seeking end of a compass points toward the north geographic pole. The magnetic poles move at an observable rate (currently 50 to 60 km per year), so at any given time the position of the magnetic poles is not exactly the same as that of the geographic poles, but they generally have not been more than 15° of latitude apart over the course of geologic time.

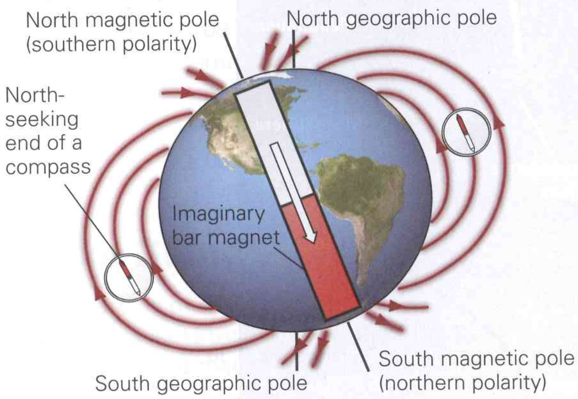
The solar wind interacts with Earth's magnetic field, distorting it into a huge teardrop pointing away from the Sun. Fortunately, the magnetic field deflects most (but not all) solar-wind particles, so that they do not reach Earth's surface. In other words, the magnetic field serves as a shield against solar-wind particles, which is important for life on Earth because the particles can be dangerous to life forms. Physicists refer to the region inside this magnetic shield as the **magnetosphere** (**Fig. 2.3c**).

Though it protects the Earth from most of the solar wind, the magnetic field does not stop the exoprobe. At distances of 3,000 km to 10,500 km out from the Earth, the spacecraft encounters the *Van Allen Radiation Belts*, named for the physicist who first recognized them in 1959. The Van Allen Belts, a region in which the magnetic field starts to strengthen, trap both cosmic rays and the solar-wind particles that were moving so fast they could penetrate the weaker outer part of the magnetic field. Thus, the Van Allen Belts serve as a second line of defense that protects life on Earth from dangerous radiation. But they don't trap all incoming particles. Some make it past the Van Allen Belts and follow magnetic field lines to the polar regions of Earth. When these particles interact with gas atoms nearer the Earth, they cause the gases to glow, like the gases in neon signs, creating spectacular

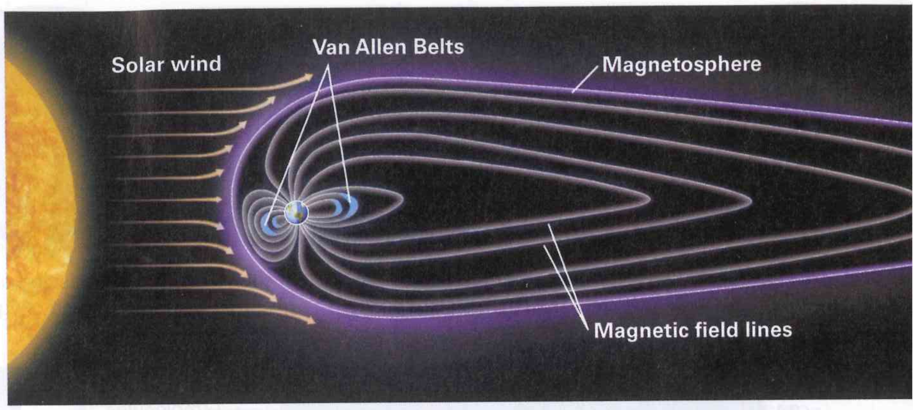
FIGURE 2.3 A magnetic field permeates the space around the Earth. It can be symbolized by a bar magnet.



(a) A bar magnet produces a magnetic field. Magnetic field lines point into the "south pole" and out from the "north pole."



(b) We can represent the Earth's field by an imaginary bar magnet inside.



(c) Earth behaves like a magnetic dipole, but the field lines are distorted by the solar wind. The Van Allen radiation belts trap charged particles.

(d) Charged particles flow toward Earth's magnetic poles and cause gases in the atmosphere to glow, forming colorful aurorae in polar skies.

aurorae (**Fig. 2.3d**). The *aurora borealis* occurs in high latitudes of the northern hemisphere, while the *aurora australis* occurs in high latitudes of the southern hemisphere.

A Plunge through the Atmosphere

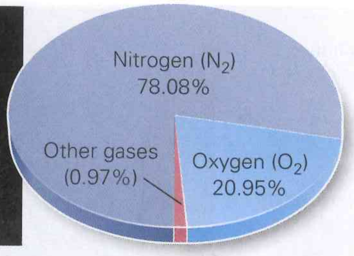
The exoprobe descends to an elevation of 600 km (370 miles) and goes into orbit around the planet, circling the globe once every 96 minutes. At this elevation, the spacecraft skims through the outer reaches of the Earth's **atmosphere**, the gaseous cloak that envelops the planet. This atmosphere contains a mixture of gases, which we refer to as *air*. The spacecraft's instruments determine that air consists of 78% nitrogen (N_2) and 21% oxygen (O_2), along with minor amounts (1% total) of other gases, including argon, carbon dioxide, neon, methane, ozone, carbon monoxide, and sulfur dioxide (**Fig. 2.4a, b**). Air also contains variable amounts of water (H_2O) gas, which, at lower elevations, locally condenses into whitish, translucent to opaque clouds that at any given time hide about 70% of the planet's surface; air without clouds is nearly transparent. Other terrestrial planets have atmospheres, but they are not like the Earth's—the atmospheres of Venus and Mars consists mostly of CO_2 gas, while that of Mercury consists of hydrogen and helium.

The density of the atmosphere progressively increases closer to the Earth, for the weight of overlying air squeezes on the air below, pushing gas molecules in the air closer together. At the Earth's surface, molecules are close enough together

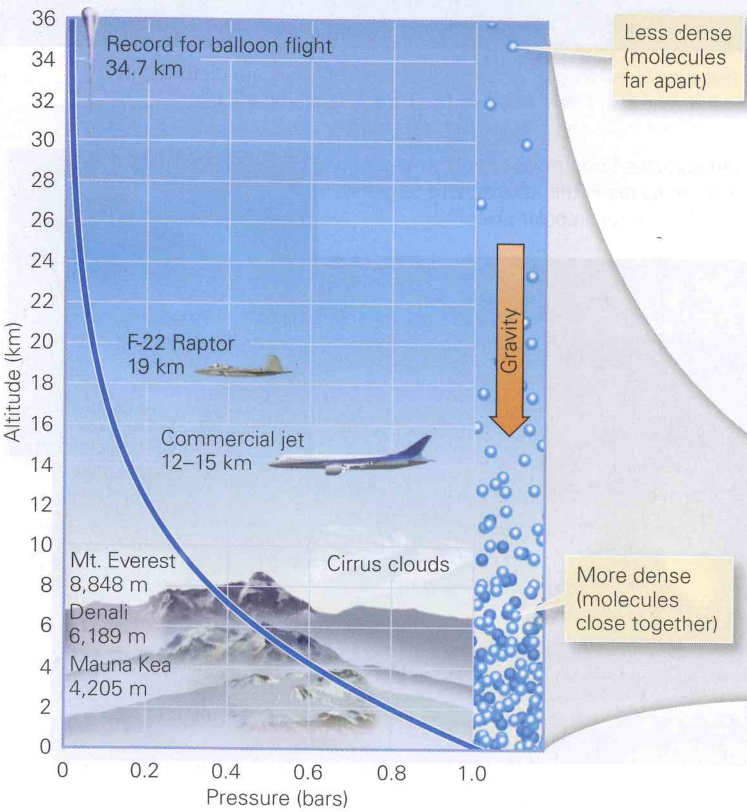
Did you ever wonder . . .
how thick our atmosphere is?

FIGURE 2.4 Characteristics of the atmosphere that envelops the Earth.

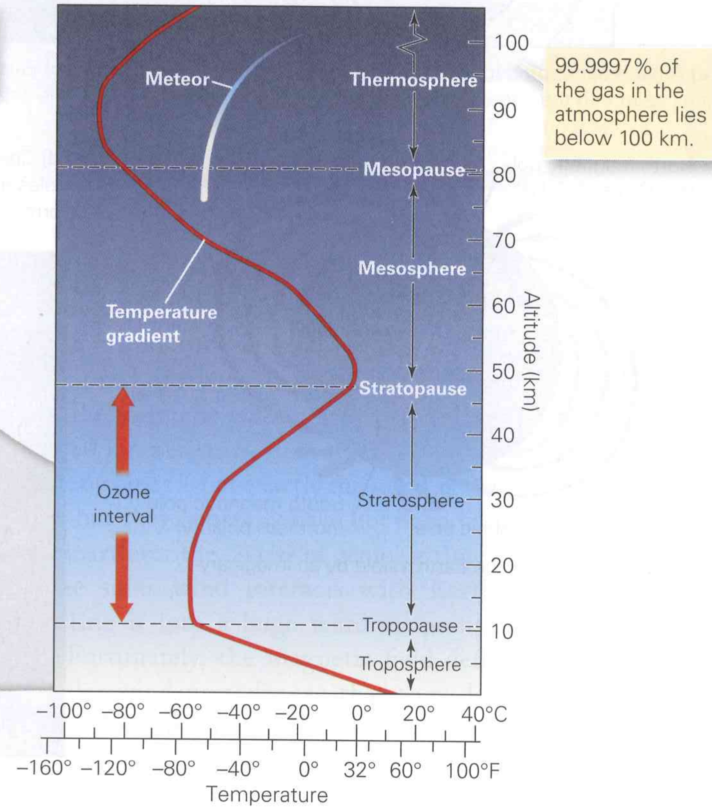
(a) An orbiting astronaut's photograph shows the haze of the atmosphere fading up into the blackness of space.



(b) Composition of atmosphere. Nitrogen and oxygen dominate.



(c) Molecules pack together more tightly at the base of the atmosphere, so atmospheric pressure changes with elevation.



(d) The atmosphere can be divided into several distinct layers. We live in the troposphere.

that the atmosphere has a density of 1.2 g/L. While vastly denser than interplanetary space, this is only 12% that of water. (Notably, the density of the Earth's atmosphere lies between that of Venus, which is 6.5 g/L, and Mars, which is 0.02 g/L.) *Air pressure*, the amount of push that the air exerts on material surrounding it, also increases closer to the surface because of the weight of the overlying atmosphere (**Fig. 2.4c**). Technically, we specify pressure in units of force (push) per unit area. For example, we could specify atmospheric pressure in pounds (a force) per square inch (an area), or kilograms per square centimeter. Air pressure at sea level averages 14.7 lb/in^2, or 1.04 kg/cm^2. Researchers generally use other units, such as atmospheres (abbreviated atm) and bars. In these units, air pressure at sea level is 1 atm. An atmosphere and a bar are almost the same: 1 atm = 1.01 bars.

Since air pressure decreases with increasing elevation, the air pressure at the peak of Mt. Everest, 8.85 km above sea level, is only 0.3 atm. People can't survive for long at elevations above about 5.5 km, where the air pressure is about 0.5 atm, 50% that of sea level, so since jet planes fly at altitudes above 5.5 km, their cabins must be pressurized by pumping air in.

The decrease in density with elevation means that 99% of atmospheric gas lies at elevations below 50 km, and the atmosphere is barely detectable at elevations above 120 km.

While molecules are still attracted to the Earth by gravity for half the distance to the Moon, there are so few molecules at elevations above about 600 km that the molecules no longer collide and interact like those of a gas. Thus, generally speaking, researchers consider the top of the atmosphere to lie at about 600 km.

The character of the atmosphere changes with increasing distance from the Earth's surface. Because of these changes, atmospheric scientists divide the atmosphere into layers. Most winds and clouds develop only in the lowest layer, the *troposphere*. The layers of the atmosphere that lie above the troposphere are named, in sequence from base to top: the stratosphere, the mesosphere, and the thermosphere (**Fig. 2.4d**). As described further in Chapter 20, the boundaries between layers are defined as elevations where temperature stops decreasing and starts increasing, or vice versa. Boundaries are named for the underlying layer. For example, the boundary between the troposphere and the overlying stratosphere is called the *tropopause*.

Take-Home Message

The Earth is one of eight planets and countless other, smaller objects that orbit the Sun. The Earth produces a magnetic field that deflects solar wind. An atmosphere composed mostly of N_2 and O_2 gas surrounds the planet; 99% of this atmosphere lies below an elevation of 50 km, so it is a thin envelope indeed.

QUICK QUESTION: What causes the aurorae?

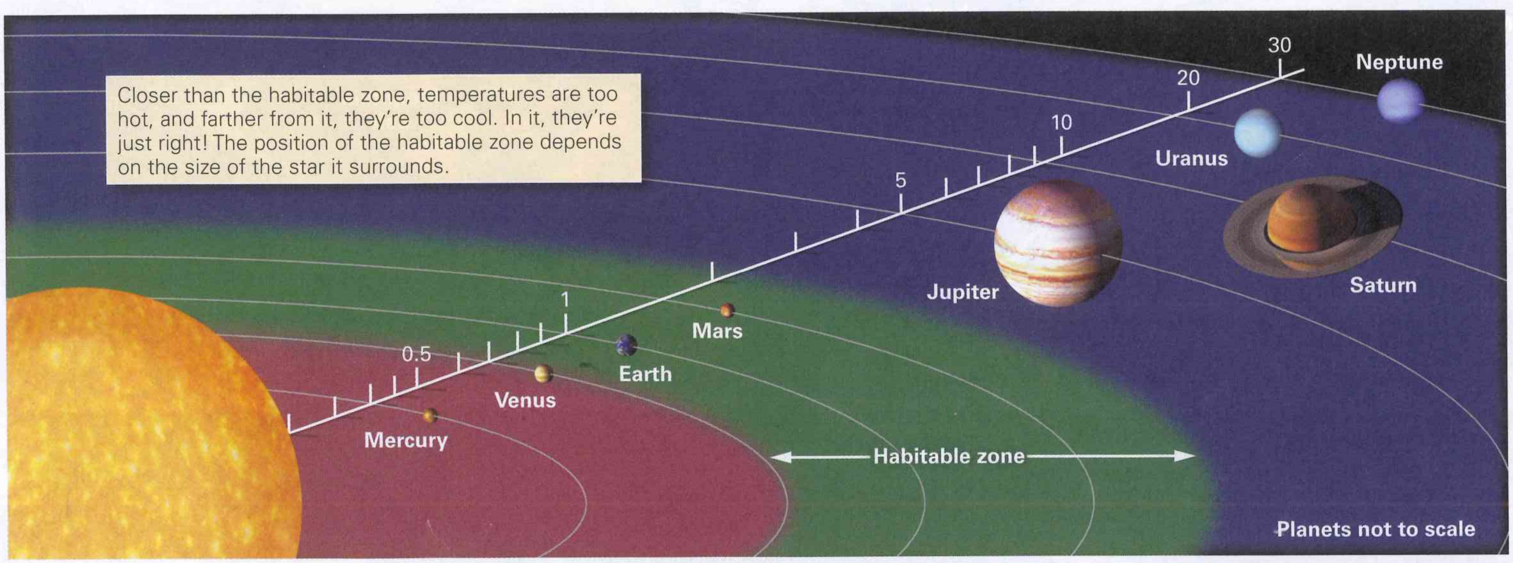
2.3 Basic Characteristics of the Earth

The Earth System

Once in orbit, the exoprobe surveys the Earth's surface and detects several distinct components. Beneath the *atmosphere* (the gaseous envelope that we've just discussed) lie the *hydrosphere* (surface and near-surface liquid water), the *cryosphere* (surface and near-surface ice and snow), the *biosphere* (the great variety of living organisms), and the *solid Earth*. Geologists refer to the combination of these components, and the complex interactions among them, as the **Earth System**. Of all the planets in the Solar System, only Earth currently has liquid water. Earth lies within the **habitable zone**, the distance from the Sun in which temperatures are in the range that liquid water can exist (**Fig. 2.5**); on planets closer to the Sun than the habitable zone, all water will be hot enough to evaporate, and on planets farther away water can exist only as solid ice. Astronomers estimate that the habitable zone in our Solar System extends between about 0.8 and 2.5 AU. This region includes the orbits of Venus, Earth, and Mars and some of the asteroid belt. The fact that surface temperatures on Venus are too hot for life (460°C) and on Mars are too cold (−55°C) has to do with the respective abilities of their atmospheres to trap heat. Venus has a dense atmosphere that traps a lot of heat, and Mars has a very thin atmosphere that doesn't.

As we'll see throughout this book, the Earth System is a dynamic place. Its surface and the objects on it move, and its

FIGURE 2.5 In our Solar System, only Earth lies within the relatively narrow habitable zone. The scale is in astronomical units (AU).



The Whole Earth

LATITUDE
49°18′51.35″N

LONGITUDE
36°48′46.13″W

Zoom to an elevation of 20,000 km (12,400 mi) and look straight down.

A view of the whole Earth, showing land, sea, and ice. Green areas are vegetated, tan areas are not.

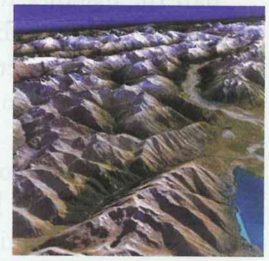
atmosphere and oceans circulate; materials from its interior spill out on the surface, and materials from the surface sink into the interior. The energy driving all this activity ultimately comes from heat inside the Earth, from gravity, and from the Sun's heat and light.

Land and Sea

As the exoprobe continues in orbit, it makes a basic map of the surface by collecting information about spatial variations in composition of the Earth's surface and determines that *dry land* (continents and islands) covers about 30% of the surface, whereas **surface water** covers the remaining 70% of the Earth (**Fig. 2.6**). Most surface water is salty and makes up the oceans (or sea), but some is fresh and fills lakes and rivers. Our instruments also detect **groundwater**, the water that fills cracks and holes (pores) beneath the land surface. Finally, we find that ice covers significant areas of land and sea in polar regions and at high elevations, and that living organisms populate the land, sea, air, and even the upper few kilometers of the subsurface.

To finish off its map of the Earth's surface, the spacecraft detects that the planet's land surface has **topography**, variations in the elevation of the land surface, and distinguishes plains, mountains, and valleys. Notably, the highest point on land, the peak of Mt. Everest, lies about 8.9 km above sea level, while the lowest point, the Dead Sea, lies about 0.4 km below sea level. The exoprobe's instruments also measure **bathymetry**, the variation in elevation of the ocean floor. The sea's surface looks much the same everywhere, because by definition it lies on average at sea level (changing temporarily by centimeters to tens of meters as waves and/or tides pass by). However, the sea floor hidden below displays distinct bathymetric realms. Most of the sea floor comprises broad **abyssal plains**, where the flat seafloor

SEE FOR YOURSELF . . .



The Southern Alps

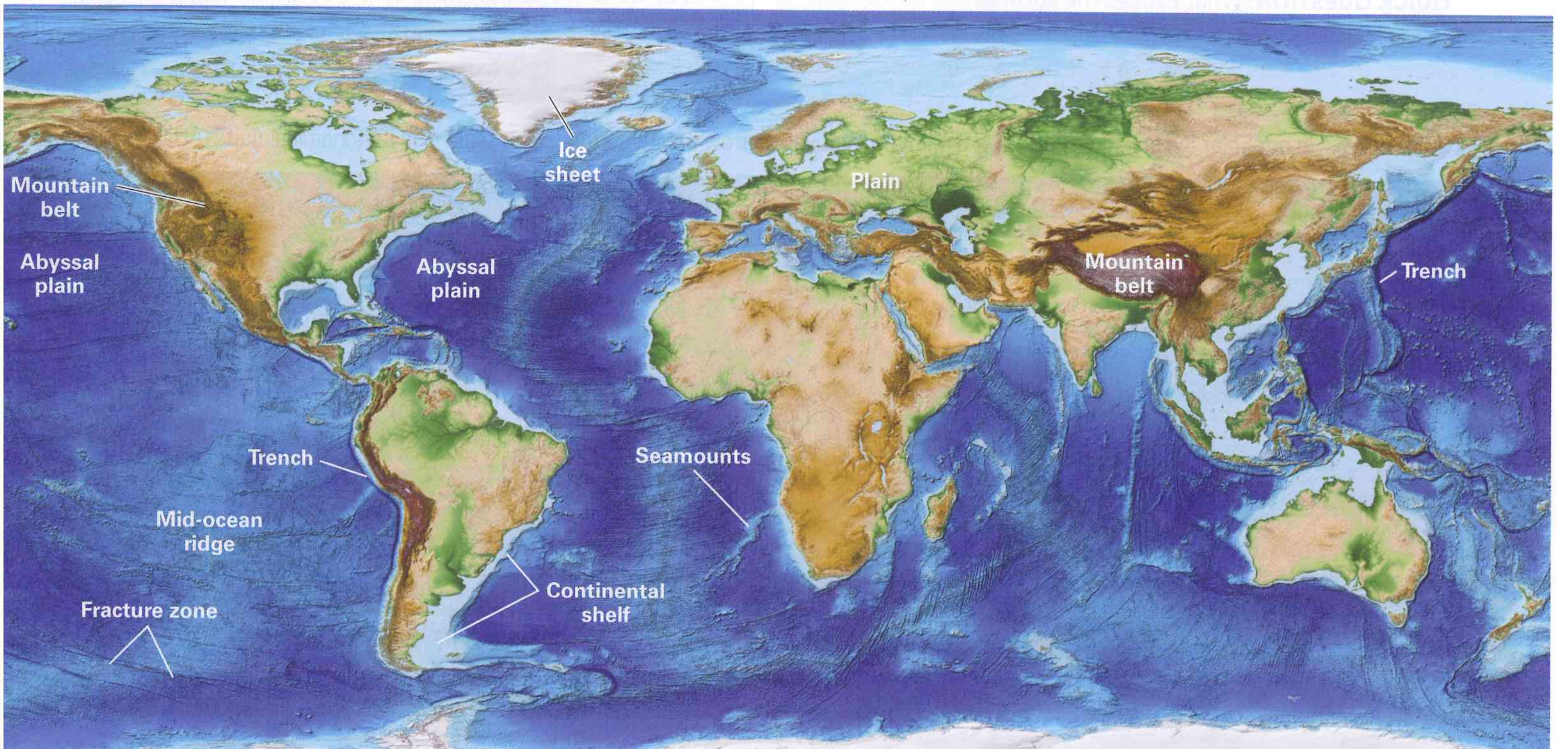
LATITUDE
44° 9′31.68″S

LONGITUDE
169°46′9.60″E

Zoom to an elevation of 25 km (15 mi) and tilt to look north.

Rugged topography of the Southern Alps of New Zealand.

FIGURE 2.6 This map of the Earth shows variations in elevation on both the land surface and the sea floor. Darker blues are deeper water in the ocean. Greens are lower elevation on land.



SEE FOR YOURSELF . . .

Bathymetry

LATITUDE
20° 8'31.57"N

LONGITUDE
92°51'12.35"W

Zoom to an elevation of 5,000 km (3,000 mi) and look straight down.

The bathymetry of the Gulf of Mexico, the eastern Pacific, and the Caribbean. Lighter blues are shallower.

lies at a depth of 4 to 5 km below sea level. The sea floor rises to shallower depths along **mid-ocean ridges**, elongate submarine mountains that rise as much as 2.5 km above the abyssal plains, and descends to greater depths in the **deep-ocean trenches**, elongate troughs in which the sea floor reaches a depth of as much as 10.9 km below sea level. Note that Earth's total relief, from the floor of the deepest trench to the peak of the highest mountain, is 19.8 km, only 0.3% of Earth's radius (6,371 km). In fact, if the Earth were the size of a billiard ball, it would actually be smoother than a billiard ball.

A graph, called a **hypsometric curve**, plotting surface elevation on the vertical axis and the percentage of the Earth's surface on the horizontal axis, shows that a relatively small proportion of the Earth's surface occurs at very high elevations (mountains) or at great depths (deep trenches). In fact, most of the land surface lies just within a kilometer of sea level, and most of the sea floor lies between 4 and 5 km deep (Fig. 2.7). Thus, changes in sea level of tens to a couple of hundred meters would dramatically change the amount of dry land.

Did you ever wonder . . .

what the average elevation of the land is?

What Is the Solid Earth Made Of?

To complete its initial exploration of the Earth, the exoprobe sends robot landers down to the surface to sample and analyze the **Earth materials** that make up the solid planet. Of the 92 naturally occurring elements (produced by fusion reactions in stars and supernova explosions) that make up the Earth, 91.2% of the Earth's mass consists of only 4—iron, oxygen, silicon, and magnesium (Fig. 2.8). The elements of the Earth bond together to form a great variety of materials that can be classified into several basic categories, which we introduce here. (All will be discussed in more depth later in this book.)

- *Organic chemicals:* Carbon-containing compounds that either occur in living organisms or have characteristics that resemble compounds in living organisms are called organic chemicals.
- *Minerals:* A solid, natural substance in which atoms are arranged in an orderly pattern is a mineral. A coherent sample of a mineral that grew to its present shape is a **crystal**. Most minerals are *inorganic* chemicals.
- *Glasses:* A solid in which atoms are not arranged in an orderly pattern is called glass.
- *Rocks:* An aggregate of mineral crystals or grains, or a mass of natural glass, is called a rock. Geologists recognize three main groups of rocks: *Igneous rocks* develop when hot molten (liquid) rock cools and freezes solid. *Sedimentary rocks* form either from fragments that break off pre-existing rock and become cemented together or from minerals that precipitate out of a water solution at or near the Earth's surface. *Metamorphic rocks* form when

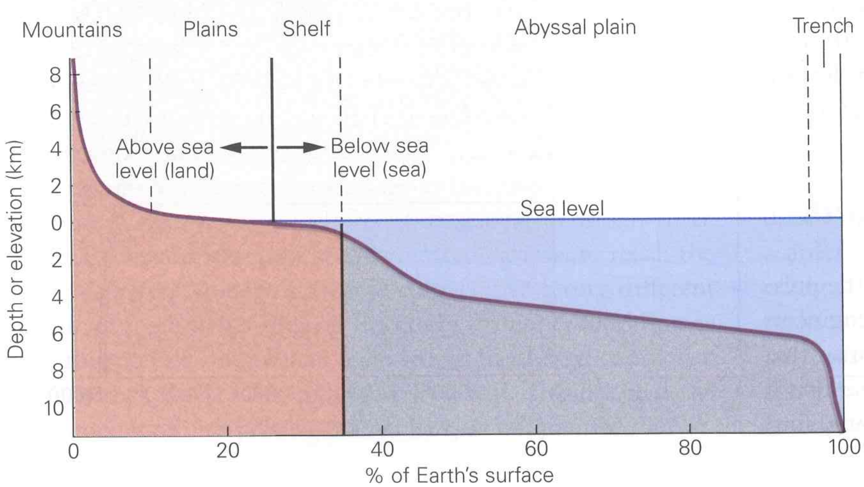


FIGURE 2.7 This graph shows a hypsometric curve, indicating the proportions of the Earth's solid surface at different elevations. Two principal zones—the continents and adjacent continental shelf areas (the submerged margins of continents), and the ocean floor—account for most of Earth's area. Mountains and deep trenches cover relatively little area.

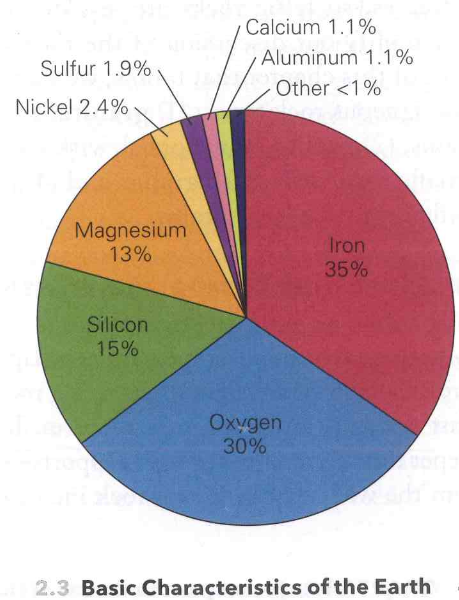


FIGURE 2.8 The proportions of major elements making up the mass of the whole Earth. Note that iron and oxygen account for most of the mass.

pre-existing rocks undergo changes in response to heat and pressure.

- *Grain:* The term *grain* is used either for individual crystals embedded within an igneous or metamorphic rock or for an individual fragment derived from a once-larger mineral sample or rock body. Grains derived from the fragmentation of rock can be composed of a single mineral, many minerals, and/or glass.
- *Sediment:* An accumulation of loose (unconsolidated) grains, meaning grains that have not been cemented together, is a *sediment*. Gravel and sand are types of sediment.
- *Metals:* Solids composed entirely of metal atoms (such as iron, aluminum, copper, and tin) are called *metals*. Metals can be stretched into wires or flattened into sheets; they tend to be shiny and can conduct electricity. An *alloy* is a mixture containing more than one type of metal.
- *Melts: Melts* form when solid materials become hot and transform into liquid. *Molten rock* is a type of melt. Geologists distinguish between *magma*, molten rock beneath the Earth's surface, and *lava*, molten rock that has flowed out onto the Earth's surface.
- *Volatiles:* As noted in Chapter 1, materials that can transform into gas at the relatively low temperatures found at the Earth's surface are called *volatiles*.

Most of the Earth consists of *silicate minerals*, which are minerals containing silica (SiO_2), either alone or bonded to other elements. Not surprisingly, rocks composed of silicate minerals are known as **silicate rocks**. Geologists distinguish among four classes of igneous silicate rocks based on a characteristic of their chemical composition, specifically, the proportion of silica to iron and magnesium that they contain. In order, from greatest to least proportion of silica to iron and magnesium, the names of these classes are: *felsic* (or silicic), *intermediate*, *mafic*, and *ultramafic*. (Chapter 6 provides further discussion of these classes.) Significantly, as the proportion of silica in a rock increases, the density decreases, so felsic rocks are less dense than mafic rocks. To simplify our discussion of the Earth's layers in the sections of this chapter that follow, we introduce the four common igneous rock types: (1) **granite**, a felsic rock with large grains; (2) **gabbro**, a mafic rock with large grains; (3) **basalt**, a mafic rock with small grains; and (4) **peridotite**, an ultramafic rock with large grains.

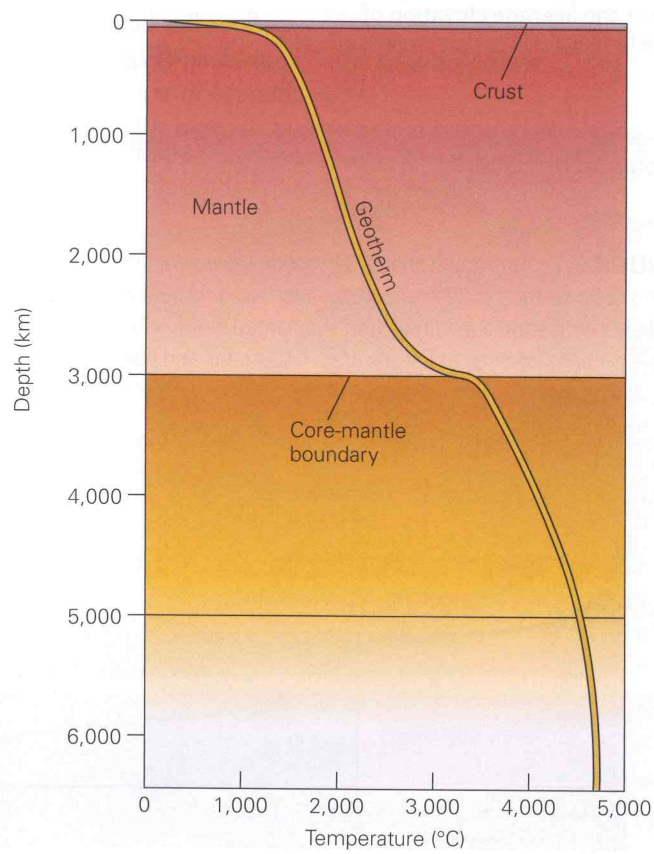
Pressure and Temperature inside the Earth

To keep underground tunnels from collapsing under the pressure created by the weight of overlying rock, mining engineers must design sturdy support structures. It is no surprise that deeper tunnels require stronger supports—the downward push from the weight of overlying rock increases with depth, simply because the mass of the overlying rock layer increases with depth. At the Earth's center, pressure probably reaches about 3,600,000 atm.

Temperature also increases with depth in the Earth. Even on a cool winter's day, miners who chisel away at gold veins exposed in tunnels 3.5 km below the surface swelter in temperatures of about 53°C (127°F). We refer to the rate of change in temperature with depth as the **geothermal gradient**. In the upper part of the crust, the geothermal gradient averages between 15° and 30°C per km. At greater depths, the rate decreases to 10°C per km or less. Thus, 35 km below the surface of a continent, the temperature reaches 400° to 700°C and the mantle-core boundary is about 3,500°C. No one has ever directly measured the temperature at the Earth's center, but calculations suggest it may exceed 4,700°C, close to the Sun's surface temperature of 5,500°C (**Fig. 2.9**).

Did you ever wonder . . .
how hot it gets at the center of this planet?

FIGURE 2.9 The Earth's geotherm shows how temperature increases with depth.



Take-Home Message

Geologists use the term *Earth System* in reference to the variety of interacting realms in, on, and around the planet. Thirty percent of the surface is land, while 70% is sea. Both the land surface and seafloor display notable variations in elevation and depth, respectively, but the difference between the highest point and the lowest is only about 0.3% of Earth's radius. The solid Earth consists of many materials, the most common of which is silicate rock.

QUICK QUESTION: How do geologists distinguish among classes of silicate rocks?

2.4 How Do We Know that the Earth Has Layers?

The world's deepest mine shaft penetrates gold-bearing rock that lies about 3.5 km (2 miles) beneath South Africa. Though miners seeking this gold begin their workday by plummeting straight down a vertical shaft for almost ten minutes aboard the world's fastest elevator, the shaft represents little more than a pinprick on Earth's surface when compared with the planet's average radius of 6,371 km. In fact, even the deepest well ever drilled, a 12.3-km-deep hole, penetrates only the upper 0.2% of the Earth. We literally live on the thin skin of our planet, its interior forever inaccessible to our direct observation.

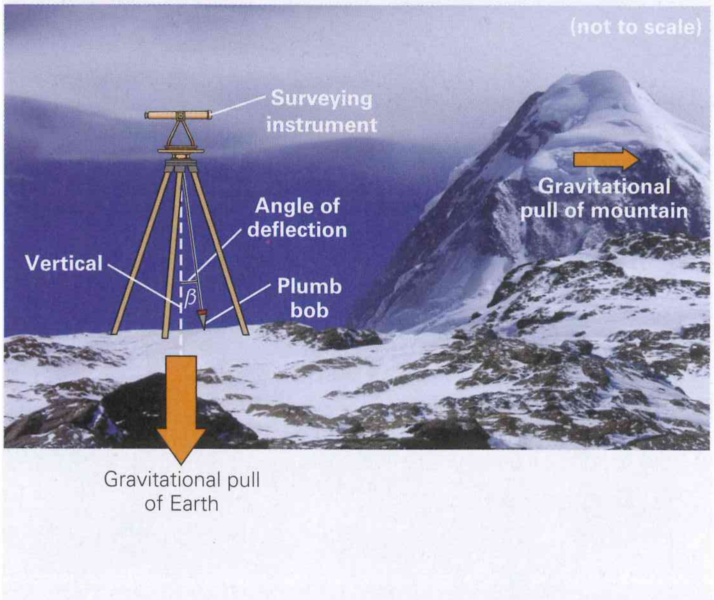
Lacking the ability to observe the Earth's interior firsthand, pre-20th-century writers and artists dreamed up fanciful images of it. For example, to the ancient Greeks the subsurface was Hades, the "underworld," which they pictured to be a realm of gloom populated by the dead. In Chinese lore, the underworld was a complex maze, and in Buddhist mythology it was a succession of caverns. The English poet John Milton (1608–74) described the subsurface realm as "a dungeon horrible, on all sides round, as one great furnace flamed; yet from those flames, no light" (**Fig. 2.10**). In the 18th and 19th centuries, some European writers thought the Earth's interior resembled a sponge, containing open caverns variously filled with molten rock, water, or air, an image that seemed to explain the source of volcanoes and water springs. The French science fiction writer, Jules Verne, used this image as the basis of his popular 1864 novel *Journey to the Center of the Earth*, in which three explorers wander through interconnected caverns to reach the Earth's center. Modern scientific studies give a very different picture of the Earth's interior. Except in the upper few kilometers, the interior contains no open spaces. Rather, it consists of distinct rock shells surrounding an iron ball. This image is the end product of interpreting many clues, as we now see.

FIGURE 2.10 An image of the Earth's interior, following a description from *Paradise Lost*, an epic poem published by John Milton in 1667, painted by John Martin (1789–1854).

Early Clues to Characterize the Interior

The first key to understanding the Earth's interior came from studies that provided an estimate of this planet's average density (mass/volume). The volume of the Earth had been known since Eratosthenes first measured its dimensions, so all that was needed to determine the density was a measure of our planet's mass. In 1776, the British Royal Astronomer, Nevil Maskelyne, came up with the first realistic estimate of the mass. He obtained this estimate by observing the deflection, due to the gravitational attraction of a nearby mountain, of a lead ball (called a plumb bob) suspended from a wire. Maskelyne reasoned that if the mountain weren't there, the lead ball would be pulled straight down by the Earth's gravity. The mass of the mountain pulled the ball sideways, toward it, so the wire made a slight angle relative to vertical (**Fig. 2.11**). Since Newton's law of gravity states that the strength of gravitational pull depends on the amount of mass present, the amount of deflection represents the mass of the mountain relative to that of the whole Earth. From his measurements, Maskelyne calculated that the Earth had a density of 4.5 gm/cm^3. In 1798, another British scientist used a different method for measurement and came up with a value of about 5.5 gm/cm^3, the number we use today. Since average rocks at the Earth's surface have a density of only about 3.0 gm/cm^3, researchers immediately realized that the interior of the Earth must contain denser material than its outermost layer and couldn't possibly be full of caverns or other open spaces.

FIGURE 2.11 A surveyor noticed that the plumb line was deflected by an angle β, owing to the gravitational attraction of the mountain. The angle represents the ratio between the mass of the mountain and the mass of the whole Earth.



What could the denser material of the Earth's interior be? Researchers eventually concluded that this material must be a metal, for only metals can have sufficiently high density. (At the Earth's surface, the densest nonmetal, iodine, has a density of only 4.9 gm/cm^3, while iron at the Earth's surface has a density of 7.9 gm/cm^3). With this idea in mind, they then addressed the question of where the metal of the Earth's interior resides. They realized that, since the Earth is nearly a sphere, the metal must be concentrated near the center—otherwise, centrifugal force due to the spin of the Earth on its axis would pull the equator out, and the planet would become somewhat disk-shaped. (To picture why, consider that when you swing a hammer in a circle, your hand feels more force if you hold the end of the light wooden shaft rather than the heavy metal head.) Laboratory studies show that at the immense pressures occurring in the core, the metal comprising the core is almost twice as dense as it would be on the Earth's surface because the pressure squeezes molecules closer together.

Researchers then wondered about the state of the materials in the Earth—are they solid or liquid (molten)? Eventually, they concluded that even though molten rock occasionally oozes out of the interior of volcanoes, and thus must exist somewhere inside the Earth, most of the interior must be solid, because if it weren't, the land surface would rise and fall due to daily tides much more than it actually does. (The forces that produce tides, as discussed in Chapter 18, cause the liquid sea surface to rise and fall by as much as 14 m per day, but the land rises and falls by less than 0.5 m per day.)

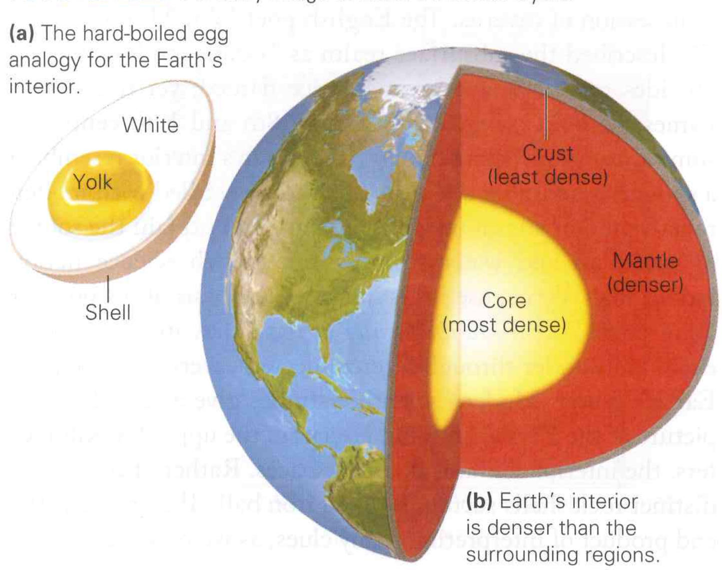
Taking into account all the above observations on the density, shape, and tidal behavior of the Earth, researchers realized by the end of the 19th century that the Earth resembled a hard-boiled egg in that it had three principal layers: a not-so-dense *crust* (like an eggshell) composed of rocks such as granite, basalt, and gabbro; a denser solid *mantle* in the middle (like an egg white), composed of a then-unknown material; and a very dense *core* (like an egg yolk), composed of an unknown metal (Fig. 2.12). Many questions remained: How thick are the layers? Are the boundaries between layers sharp or gradational? And what exactly are the layers composed of? Data available at the time could not provide answers, and it would take 20th-century studies of earthquakes to give us the detailed image of the interior that we have today.

Notably, studies by spacecraft sent to other terrestrial planets in the Solar System reveal, based on the same kind of evidence presented above, that all terrestrial planets share the same basic internal structure—with a crust, mantle, and core—though the relative thicknesses of the different layers on other planets are not the same as those of the Earth. Also, since the other terrestrial planets are smaller and have cooled more, their interiors are not as soft and plastic as that of the Earth and thus do not appear to flow (and convect) like the Earth's mantle does.

Clues from the Study of Earthquakes: Refining the Image of the Interior

To understand how earthquakes can provide information about the Earth's interior, we first need to understand what an earthquake is. When rock within the outer portion of the Earth suddenly breaks along a *fault* (a fracture on which slip occurs), it generates energy that travels through the surrounding rock outward from the break. You can simulate this process, on

FIGURE 2.12 An early image of Earth's internal layers.

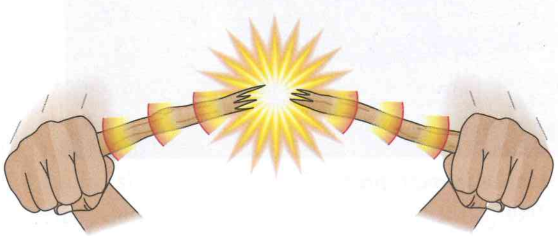


a small scale, by snapping a stick between your hands—the "shock" that you feel is energy that propagated along the stick from the break to your hands (**Fig. 2.13**). When energy reaches the Earth's surface and causes it to vibrate (move up and down or back and forth), it is called an **earthquake**, an episode of ground shaking.

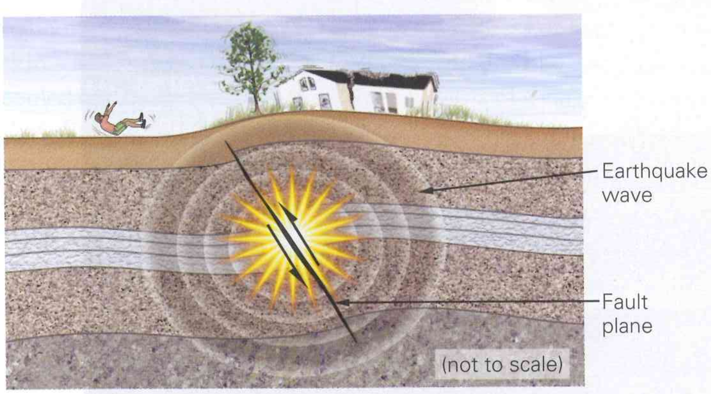
In 1889, a physicist in Germany noticed that the pendulum in his lab appeared to begin moving back and forth without having been touched. He reasoned that the pendulum was actually standing still while the Earth vibrated under it. A few days later, he read in a newspaper that a large earthquake had taken place in Japan minutes before the movement of his pendulum began. The physicist deduced that the energy generated by the earthquake had traveled all the way through the Earth from Japan and had shaken his laboratory in Germany; the shaking was so gentle that humans couldn't feel it, but it was enough to make the pendulum appear to sway relative to the room. Earthquake energy moves through rock or along the Earth's surface in the form of waves, called either *seismic waves* or earthquake waves. You can get a sense of what such waves look like by pushing suddenly on a spring or by jerking the end of a rope. (Chapter 10 provides further detail about earthquakes and seismic waves.)

Geoscientists immediately realized that the study of seismic waves traveling through the Earth might provide a tool for exploring the Earth's interior, much as ultrasound today helps doctors study a patient's insides. Specifically, laboratory measurements demonstrated that seismic waves travel at different velocities (speeds) through different materials. Thus, by detecting depths at which seismic-wave velocities suddenly change, geoscientists pinpointed the boundaries between layers and even recognized subtler boundaries within the main layers, as we now see. (Interlude D shows how the study of earthquake waves defines the Earth's layers.)

FIGURE 2.13 Faulting and earthquakes.



(a) Snapping a stick generates vibrations that pass through the stick to your hands.



(b) Similarly, when the rock inside the Earth suddenly breaks and slips, forming a fracture called a fault, it generates shock waves that pass through the Earth and shake the surface.

Take-Home Message

Measurements of the Earth's mass, shape, and tidal response led to the conclusion that the Earth has three principal internal layers—the crust, the mantle, and the core. Study of earthquake waves passing through the interior has refined this image.

QUICK QUESTION: What observation led 19th-century researchers to conclude that the Earth has a metal core?

2.5 What Are the Layers Made of?

We've concluded that the material composing the Earth's insides must be much denser than familiar surface rocks such as granite and basalt. How can we determine what it consists of? Geoscientists have used several approaches to provide insight into the composition of the Earth's interior, including (1) examination of meteorite composition, for some meteorites are fragments that came from the interiors of planetesimals and thus may resemble materials deep inside the Earth (**Box 2.2**); (2) studies to characterize materials that could be the sources of the igneous rocks found in the crust; (3) analysis of mantle fragments that were carried up into the crust with igneous melts; and (4) measurement of the densities of known materials under high pressures and temperatures to see how these compare with estimated densities of the planet's interior.

As a result of this work, we now have a pretty clear sense of what the layers inside the Earth are made of, though this picture is constantly being adjusted as new findings become available. Let's now look at the properties of individual layers, starting with the outermost layer, the crust (**Fig. 2.14**).

The Crust

When you stand on the surface of the Earth, you are standing on top of its outermost layer, the **crust**. The crust is our home and the source of all our resources. Chemically, it is distinctly

BOX 2.2 CONSIDER THIS . . .

Meteorites: Clues to What's Inside

During the early days of the Solar System, the Earth collided with and incorporated countless planetesimals and smaller fragments of solid material lying in its path. Intense bombardment ceased about 3.9 Ga (billion years ago), but even today collisions with space objects continue, and over 1,000 tons of material (rock, metal, dust, and ice) fall to Earth, on average, every year. The vast majority of this material consists of fragments derived from comets and asteroids sent careening into the path of the Earth after billiard-ball-like collisions with each other out in space or because of the gravitational pull of a passing planet. Some of the material, however, consists of chips of the Moon or Mars, ejected into space when large objects collided with those bodies.

Astronomers refer to any object from space that enters the Earth's atmosphere as a *meteoroid*. Meteoroids move at speeds of 20 to 75 km/s (over 45,000 mph), so fast that when they reach an altitude of about 150 km, friction with the atmosphere causes them to heat up and evaporate, leaving a streak of bright, glowing gas. The glowing streak, an atmospheric phenomenon, is a *meteor*, also known colloquially, though incorrectly, as a falling star (**Fig. Bx2.2a**). Most visible meteors completely evaporate by an altitude of about 30 km. But dust-sized ones may slow down sufficiently to float to Earth, and larger ones (fist-sized or bigger) can survive the heat of entry to reach the surface of the planet. In some cases, meteoroids explode as brilliant fireballs in midair.

Objects that strike the Earth are called **meteorites**. Almost all meteorites that have struck the Earth are small and have not caused notable damage on Earth. In fact, during human history, only a few have smashed through houses, dented cars, or bruised people. But two huge fireballs have caused significant damage. Specifically, a small comet exploded above

FIGURE Bx2.2 Meteors and meteorites.

(a) A shower of meteors over Hong Kong in 2001.

(b) The Barringer meteor crater in Arizona. It formed about 50,000 years ago and is 1.1 km in diameter.

(c) Examples of stony meteorites (left) and iron meteorites (right).

(d) In February 2013, a meteor exploded in the atmosphere above the Russian city of Chelyabinsk. The shock wave blew out windows and knocked people over.

Tunguska, Siberia, in 1908, flattening trees over an area of 2,150 square kilometers. More recently, in 2013, a small asteroid blew up 23 km above Chelyabinsk, Russia (**Fig. Bx2.2b**). This explosion was about 25 times larger than that of the atomic bomb over Hiroshima, and its shock waves blasted out windows and knocked down walls, injuring about 1,500 people. Huge impacts have been observed elsewhere in the Solar System. For example, in 1994, astronomers observed four huge impacts when a fragmented comet struck Jupiter. One of the impacts resulted in a 6-million-megaton explosion—this would be equivalent to blowing up 600 times the entire nuclear arsenal on Earth all at once! Even larger, catastrophic impacts in the geologic past may have been responsible for disrupting life on Earth, as we discuss later in this book. Some of these events have left huge craters that we can see today (**Fig. Bx2.2c**).

Most meteorites are asteroidal or planetary fragments, for the icy material of small cometary bodies is too fragile to survive the fall. Researchers recognize three basic classes of meteorites: *iron* (made of iron-nickel alloy), *stony* (made of rock), and *stony iron* (rock embedded in a matrix of metal). Of all known meteorites, about 93% are stony and 6% are iron (**Fig. Bx2.2d**). From their composition, researchers have concluded that some meteors (a special subcategory of stony meteorites called *chondrites*, because they contain small spherical nodules called chondrules) are asteroids derived from planetesimals that never underwent differentiation into a core and mantle. All other stony meteorites and all iron meteorites are asteroids derived from planetesimals that had differentiated into a metallic core and a rocky mantle early in Solar System history but later shattered into fragments during collisions with other planetesimals. Most meteorites appear to be about 4.54 Ga, but some chondrites as old as 4.57 Ga, are the oldest Solar System materials ever measured.

Since meteorites represent fragments of undifferentiated and differentiated planetesimals, geologists consider the average composition of meteorites to be representative of the average composition of the whole Earth. In other words, the estimates that geologists use for the proportions of different elements in the Earth are based largely on studying meteorites. Stony meteorites are probably similar in composition to the mantle, and iron meteorites are probably similar in composition to the core.

different from the whole Earth (**Fig. 2.15**). How thick is this all-important layer? Or, in other words, what is the depth to the crust-mantle boundary? An answer came from the work of Andrija Mohorovičić, a researcher working in Zagreb, Croatia. In 1909, Mohorovičić discovered that the velocity of seismic waves suddenly increased at a depth of a few tens of kilometers beneath the surface of continents, and he suggested that this increase was caused by an abrupt change in the properties of rock. He proposed that this change in seismic velocity represents the crust-mantle boundary. Today we refer to this boundary as the **Moho** in Mohorovičić's honor.

Studies since Mohorovičić's time show that the thickness of the crust, defined as the depth to the Moho, varies between 7 and 70 km, depending on location. Compared to the average radius of the Earth (6,371 km), the crust is only about 0.1% to 1.0% of the Earth's radius, so if the Earth were the size of a balloon, the crust would be about the thickness of the balloon's skin. The crust is not simply cooled mantle, like the skin on cooled chocolate pudding. Rather, it consists of a variety of rocks that differ in composition (chemical makeup) from underlying mantle rock. Geologists distinguish between two fundamentally different types of crust—**oceanic crust**, which underlies the seafloor, and **continental crust**, which underlies continents.

Oceanic crust is only 7 to 10 km thick. At highway speeds (100 km per hour), you could drive a distance equal to the thickness of the oceanic crust in only 5 minutes. The top portion of oceanic crust is a blanket of sediment, generally less than 1 km thick, that consists of clay and tiny shells that settled like snow out of sea water. Beneath this blanket, the oceanic crust consists of a layer of basalt and, below that, a layer of gabbro.

Continental crust, in contrast to oceanic crust, varies in thickness from 25 to 70 km. The thinnest crust lies beneath regions called rifts, where the crust is being stretched and pulled apart and therefore has been thinned. Very thick continental crust occurs beneath mountain belts forming where two continents are squeezing together, causing the crust to shorten horizontally and thicken vertically. The broad plains found in the interior of continents are generally 35 to 50 km thick, about four to six times the thickness of oceanic crust. Also, in contrast to oceanic crust, continental crust contains a great variety of rock types, ranging from mafic to felsic in composition. On average, upper continental crust is less mafic than oceanic crust—it has a felsic (granite-like) to intermediate composition—so continental crust overall is less dense than oceanic crust.

The Mantle

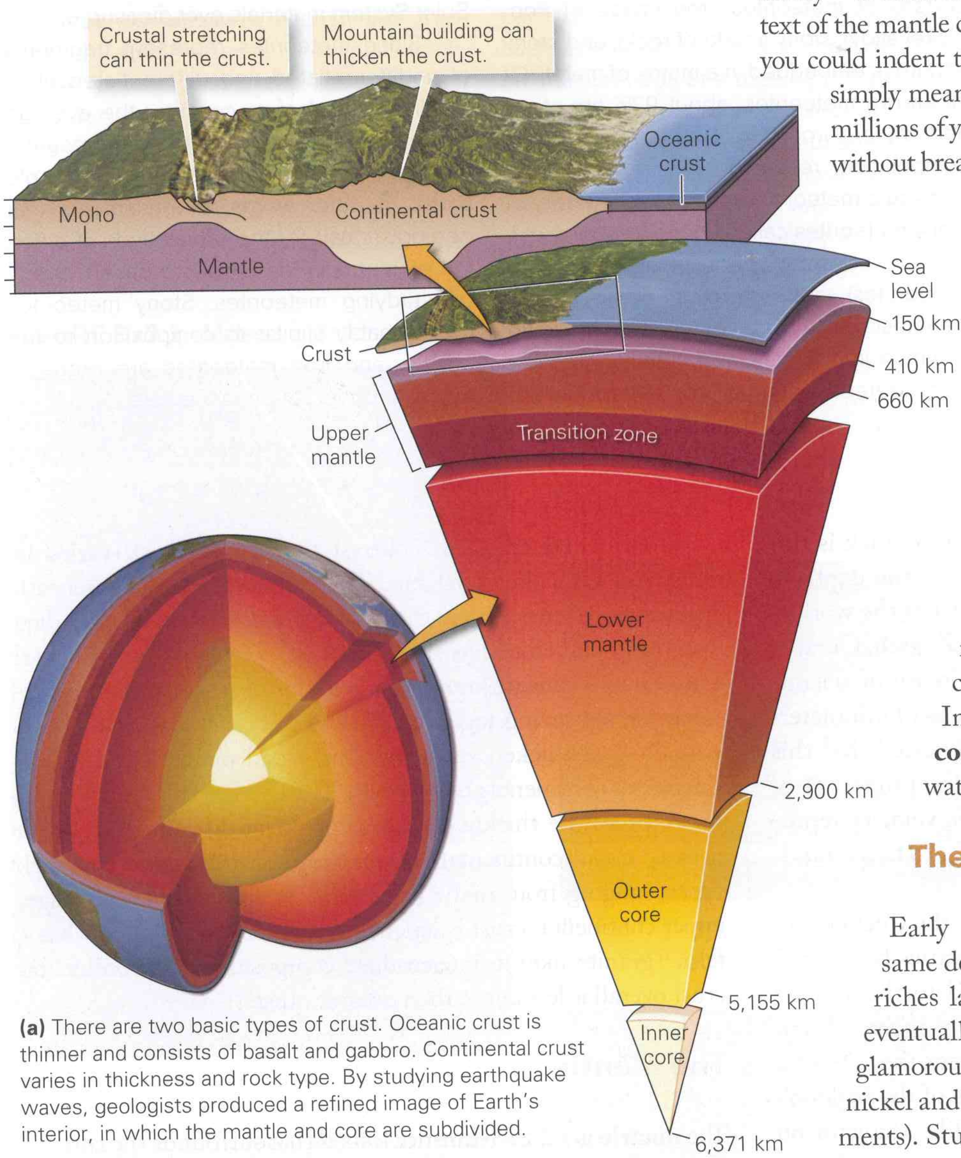
The **mantle** is a 2,885-km-thick shell that surrounds the core. In contrast to the crust, the mantle consists entirely of peridotite, a dark and dense ultramafic rock that's quite rare at the Earth's surface. Notably, the mantle accounts for most of the Earth's volume, and thus—perhaps surprisingly—peridotite, a rock that most people have never seen, is actually the most abundant rock in our planet!

Did you ever wonder . . .

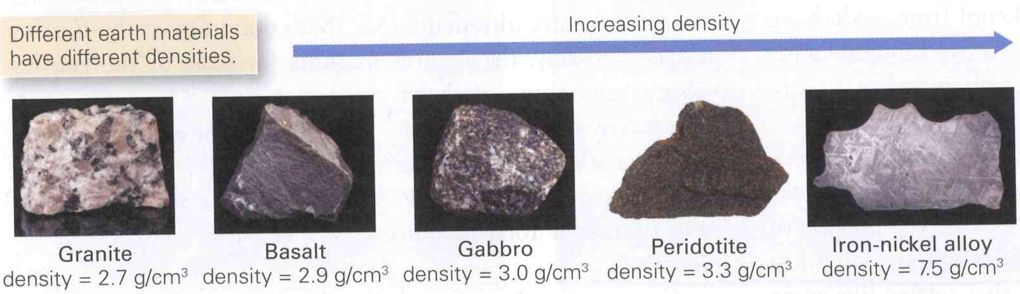
what the most abundant rock of the Earth is?

Geoscientists have found that the velocity of seismic waves changes markedly, in a step-like manner, in the portion of the mantle that lies between 410 and 660 km deep. Based on this observation, they divide the mantle into two sublayers—the **upper mantle**, down to a depth of 660 km, and the **lower mantle**, from 660 km down to 2,890 km. The portion of the upper mantle between 410 and 660 km, in which the steps in seismic velocity occur, is known as the **transition zone**. (Interlude D will explain why these steps exist.)

FIGURE 2.14 A modern view of Earth's interior layers.



(a) There are two basic types of crust. Oceanic crust is thinner and consists of basalt and gabbro. Continental crust varies in thickness and rock type. By studying earthquake waves, geologists produced a refined image of Earth's interior, in which the mantle and core are subdivided.



(b) These are examples of materials that characterize different layers inside the Earth. Continental crust has an average composition similar to granite, whereas oceanic crust consists of basalt and gabbro. The mantle consists of peridotite and the core of iron-nickel alloy.

Almost all of the mantle is solid rock. But even though it's solid, mantle rock below a depth of about 100 km beneath the ocean floor, and of about 150 km beneath continents, is so hot that it's soft enough to flow. This flow, however, takes place extremely slowly—at a rate of less than 15 cm a year. Thus, "soft" in the context of the mantle does not mean liquid, and it does not mean that you could indent the mantle by pushing on with your finger—it simply means that over long periods of time (thousands to millions of years) mantle rock can change shape significantly without breaking. Note that we stated earlier that almost all of the mantle is solid. We said this because at a depth of 100 to 300 km beneath most ocean floor (and at a few other localities), up to a few percent of the mantle has melted. This melt occurs in thin films or tiny drops between the solid grains in mantle rock.

Although, overall, the temperature of the mantle increases with depth, temperature can also vary significantly with location even at the same depth. Warmer regions of mantle are less dense than adjacent cooler regions, so warmer regions are buoyant relative to cooler regions. As a result, warmer regions tend to flow upward, or "upwell," while cooler regions flow downward, or "downwell." In other words, the mantle undergoes very slow **convection**. The process resembles the flow of water in a simmering pot on a stove (**Box 2.3**).

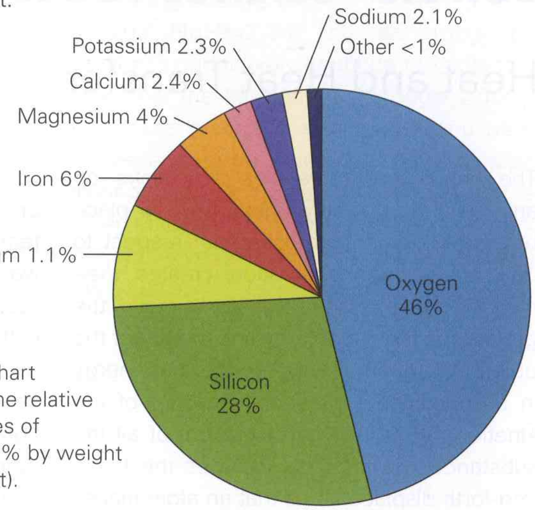
The Core

Early calculations suggested that the **core** had the same density as gold, so people once dreamed that vast riches lay at the heart of our planet. Alas, geologists eventually concluded that the core consists of a far less glamorous material, iron alloy (>80% iron mixed with nickel and lesser amounts of sulfur, oxygen, and other elements). Studies of seismic waves led geoscientists to divide the core into two parts, the *outer core* (between 2,900 and 5,155 km deep) and the *inner core* (from 5,155 km down to the Earth's center at 6,371 km). The outer core consists of liquid iron alloy. It can exist as a liquid because the temperature in the outer core is so high that even the great pressures squeezing the region cannot keep atoms locked into a solid framework. The iron alloy of the outer core can flow, and this flow generates the

FIGURE 2.15 A table and a graph illustrating the abundance of elements in the Earth's crust.

Element	Symbol	% by weight	% by volume	% by atoms
Oxygen	O	46.3	93.8	60.5
Silicon	Si	28.0	0.9	20.5
Aluminum	Al	8.1	0.8	6.2
Iron	Fe	5.5	0.5	1.9
Calcium	Ca	3.4	1.0	1.9
Magnesium	Mg	2.8	0.3	1.4
Sodium	Na	2.4	1.2	2.5
Potassium	K	2.3	1.5	1.8
All others	—	1.2	>0.1	3.3

(a) A chart of relative abundances. Oxygen (O) and silicon (Si) account for almost three-quarters of the weight. By far, oxygen is the most abundant type of atom.



(b) A pie chart showing the relative abundances of elements (% by weight in the crust).

Earth's magnetic field (**Geology at a Glance**, pp. 56–57). Computer models suggest that because the Earth spins on its axis the flow in the outer core follows spiral paths aligned with the axis.

The inner core, with a radius of about 1,220 km, is a solid iron alloy that may reach a temperature of over 4,700°C. Even though it is hotter than the outer core, the inner core is a solid because it is deeper and is subjected to even greater pressure. The pressure keeps atoms locked together tightly in very dense crystals. As the Earth slowly cools, the base of the outer core solidifies and becomes, by definition, part of the inner core. Researchers estimate that the diameter of the inner core is growing, as a result, by about 1 mm per year.

Take-Home Message

The outermost shell of the Earth, the crust, is very thin relative to other layers; its base is called the Moho. The mantle, which accounts for most of the Earth's volume, consists of very dense, mostly solid rock and can be divided into the upper mantle and lower mantle. A tiny amount of melt occurs between solid grains in part of the upper mantle. The mantle surrounds a core of iron alloy. The outer core exists in a liquid state and its flow generates the Earth's magnetic field. The inner core is solid.

QUICK QUESTION: Is the crust the same thickness everywhere?

2.6 The Lithosphere and the Asthenosphere

So far, we have identified three major layers (crust, mantle, and core) inside the Earth that differ compositionally from each other. Because of these differences, abrupt changes in seismic-wave velocity pinpoint the depths of these boundaries. An alternative way of thinking about Earth layers comes from studying the degree to which the material making up a layer can flow when subjected to pushes or pulls over a relatively short time period. In this context we distinguish between *rigid materials*, which can bend or break but do not flow, and *plastic materials*, which are relatively soft and can flow without breaking.

Let's apply this concept to the outer portion of the Earth. Geologists have determined that the outer 100 to 150 km of the Earth is relatively rigid. In other words, the Earth has an outer shell composed of rock that does not flow, overall, on a time scale of years to decades. This outer layer is called the **lithosphere**, and it consists of the crust plus the uppermost, and therefore cooler, part of the mantle. We refer to the portion of the mantle within the lithosphere as the **lithospheric mantle**. Note that the terms lithosphere and crust are not synonymous—the crust is just the upper part of the lithosphere; most of the lithosphere actually consists of mantle rock, specifically mantle rock that is cool enough to be rigid. (Cooler rock tends to be more rigid, while hotter rock tends to be more plastic. To picture this contrast, compare the behavior of a wax candle that you've just taken out of a freezer, to one that has been warmed by the summer Sun on a hot day.)

Geologists distinguish between two types of lithosphere (**Fig. 2.16**). Most *oceanic lithosphere*, meaning lithosphere topped by oceanic crust, has a thickness of about 100 km. (As we'll see later, oceanic lithosphere is thinner along mid-ocean ridges.) In contrast, *continental lithosphere*, topped by continental crust, generally has a thickness of 150 to 200 km.

The lithosphere overlies a region called the **asthenosphere**, the portion of the mantle that can flow and undergoes convection. The boundary between the lithosphere and asthenosphere occurs where the temperature reaches about 1,280°C. It is at this temperature that mantle rock (peridotite) becomes soft enough to flow, for rock gets softer as it gets hotter because

BOX 2.3 SCIENCE TOOLBOX . . .

Heat and Heat Transfer

The atoms and molecules that make up an object do not stay rigidly fixed in place but rather jiggle and jostle with respect to one another. This vibration creates *thermal energy*—the faster the atoms move, the greater the thermal energy and the hotter the object. Put another way, the thermal energy in a substance represents the sum of the kinetic energy (energy of motion) of all the substance's atoms. This includes the back-and-forth displacements that an atom makes as it vibrates, as well as the movement of an atom from one place to another.

When we say that one object is hotter or colder than another, we are describing its temperature. *Temperature* is a measure of warmth relative to some standard and represents the average kinetic energy of atoms in the material. In everyday life, we generally use the freezing or boiling point of water at sea level as the standard. In the Celsius (centigrade) scale, we arbitrarily set the freezing point of water (at sea level) as 0°C and the boiling point as 100°C, whereas in the Fahrenheit scale, we set the freezing point as 32°F and the boiling point as 212°F.

The coldest a substance can be is the temperature at which its atoms or molecules stand still. We call this temperature absolute zero, or 0K (pronounced "zero kay"), where K stands for Kelvin (after Lord Kelvin, 1824–1907, a British physicist), another unit of temperature; degrees in the Kelvin scale are the same increment as degrees in the Celsius scale. You simply can't get colder than absolute zero, meaning that you can't extract any thermal energy from a substance at 0K (−273.15°C).

Heat is the thermal energy transferred from one object to another. Heat can be measured in calories, defined so that 1,000 calories can heat 1 kilogram of water by 1°C. Heat can be transferred from one place or material to another. When heat is added to a substance, the substance warms in that its molecules start to vibrate or move more rapidly. When a substance cools, the motion of its molecules slows. There are four ways in which heat transfer takes place in the Earth System: radiation, conduction, convection, and advection.

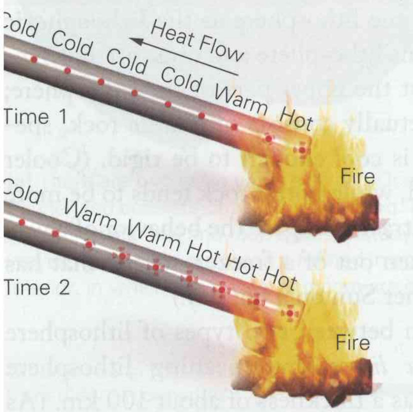
Radiation is the process by which electromagnetic waves transmit heat into a body or out of a body (**Fig. Bx2.3a**). For example, when the Sun heats the ground during the day, radiative heating takes place. Similarly, when heat rises from the ground at night, radiative heating is occurring—in the opposite direction.

Conduction takes place when you stick the end of an iron bar in a fire (**Fig. Bx2.3b**). The iron atoms at the fire-licked end of the bar start to vibrate more energetically; they gradually incite atoms farther up the bar to start jiggling, and these atoms in turn set atoms even farther along in motion. In this way, heat slowly flows along the bar until you feel it with your hand. Conduction does not involve actual movement of atoms from one place to another.

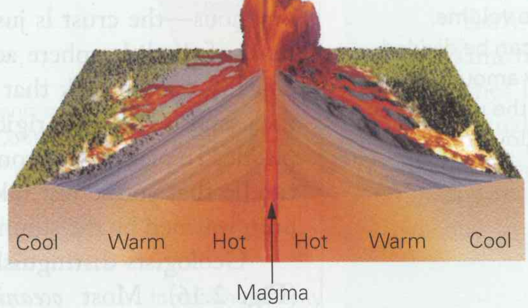
FIGURE Bx2.3 The four processes of heat transfer.

(a) Radiation from sunlight warms the Earth.

(c) Convection takes place when moving fluid carries heat with it. Hot fluid rises while cool fluid sinks, setting up a convective cell.



(b) Conduction occurs when you heat the end of an iron bar in a flame. Heat flows from the hot region toward the cold region as vibrating atoms cause their neighbors to vibrate.

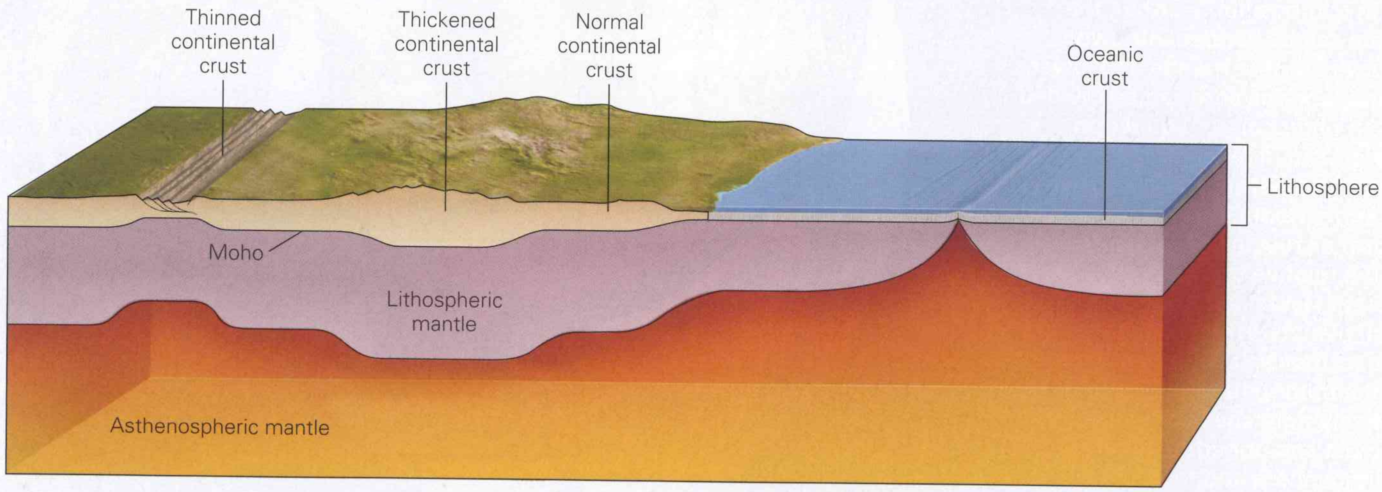


(d) During advection, a hot liquid (such as molten rock) rises into cooler material, and heat then conducts from the hot liquid into the cooler material.

Convection takes place when you set a pot of water on a stove (**Fig. Bx2.3c**). The heat from the stove warms the water at the base of the pot by making the molecules of water vibrate faster and move around more. As a consequence, the density of the water at the base of the pot decreases, for as you heat a liquid, the atoms move away from each other and the liquid expands. For a time, cold water remains at the top of the pot; but eventually the warm, less-dense water becomes buoyant relative to the cold, dense water. In a gravitational field, a buoyant material rises (like a Styrofoam ball in a pool of water) if the material above it is weak enough to flow out of the way. Since liquid water can flow easily, hot water rises. When this happens, cold water sinks to take its place. The new volume of cold water then heats up and rises itself. Thus, during convection, the actual flow of the material itself carries heat. The trajectory of flow defines *convective cells*.

Advection, a less-familiar process, happens when heat is carried by a fluid flowing through cracks and pores within a solid material (**Fig. Bx2.3d**). The heat brought by the fluid conductively heats up the adjacent solid that the fluid passes through. Advection takes place, for example, if you pass hot water through a metal pipe and the pipe itself gets hot. In the Earth, advection occurs where molten rock rises through the crust beneath a volcano and heats up the crust in the process.

FIGURE 2.16 A block diagram of the lithosphere emphasizing the difference between continental and oceanic lithosphere.



thermal energy causes bonds to break. Keep in mind that even though the asthenosphere flows, it is not molten overall. As we noted earlier, the mantle contains only tiny amounts of melt in films and drops between solid grains, and this zone of "partial melt" occurs only in the upper part of the asthenosphere (between depths of 100 and 300 km) beneath the ocean floor. In this interval, seismic waves travel more slowly, so this portion of the mantle has been called the *low-velocity zone*. While we can define the top of the asthenosphere as the base of the lithosphere (i.e., at a depth of about 100 km below oceanic abyssal plains and 150 to 200 km below the surface of continents), we can't really assign a specific depth to the base of the asthenosphere because all of the mantle has the ability flow. For purposes of discussion, however, some geologists place the base of the asthenosphere at the top of the lower mantle.

Take-Home Message

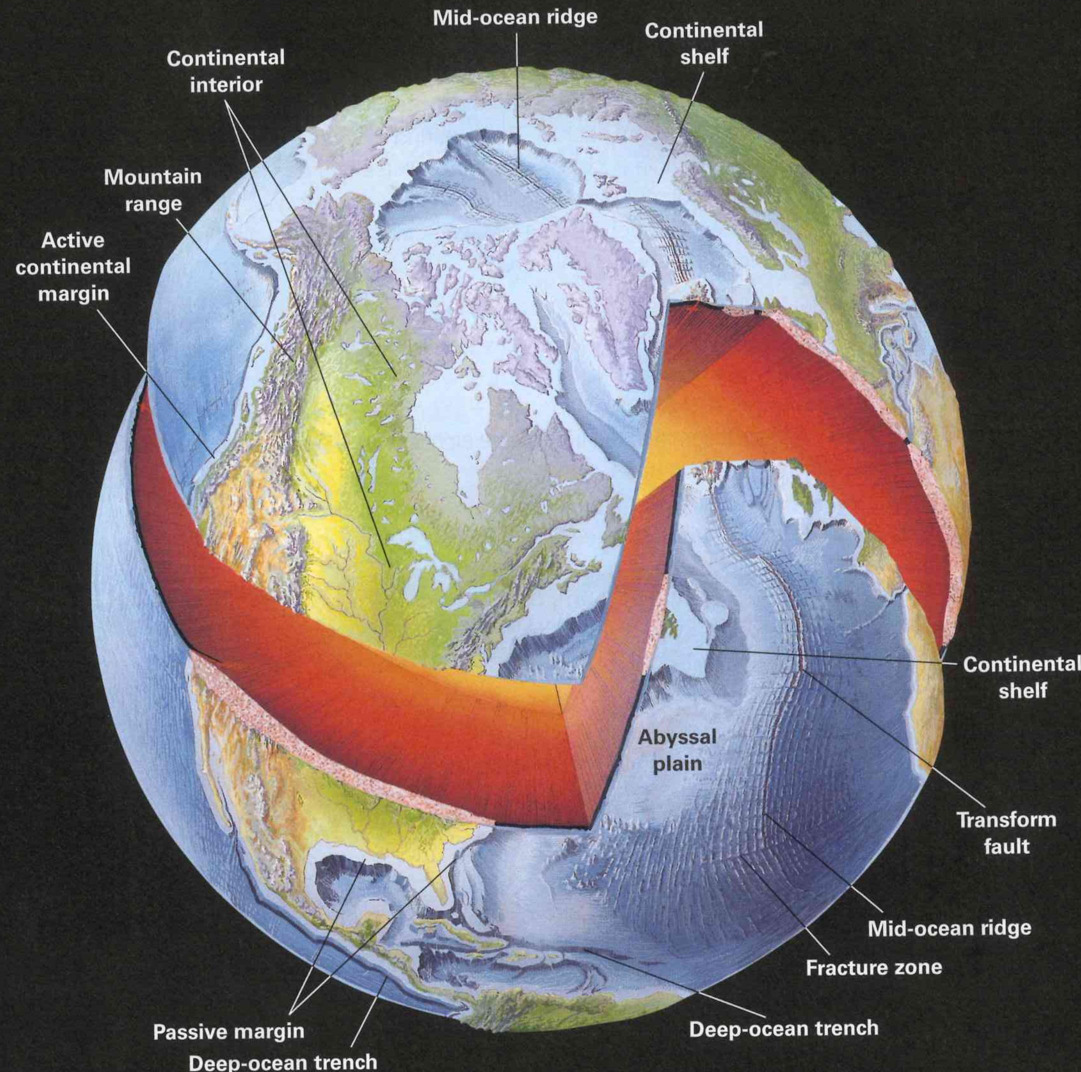
The crust and the outermost mantle together comprise the rigid lithosphere, a layer which overlies the softer, flowable asthenosphere. The behavior (rigid vs. plastic) of the mantle depends on the temperature.

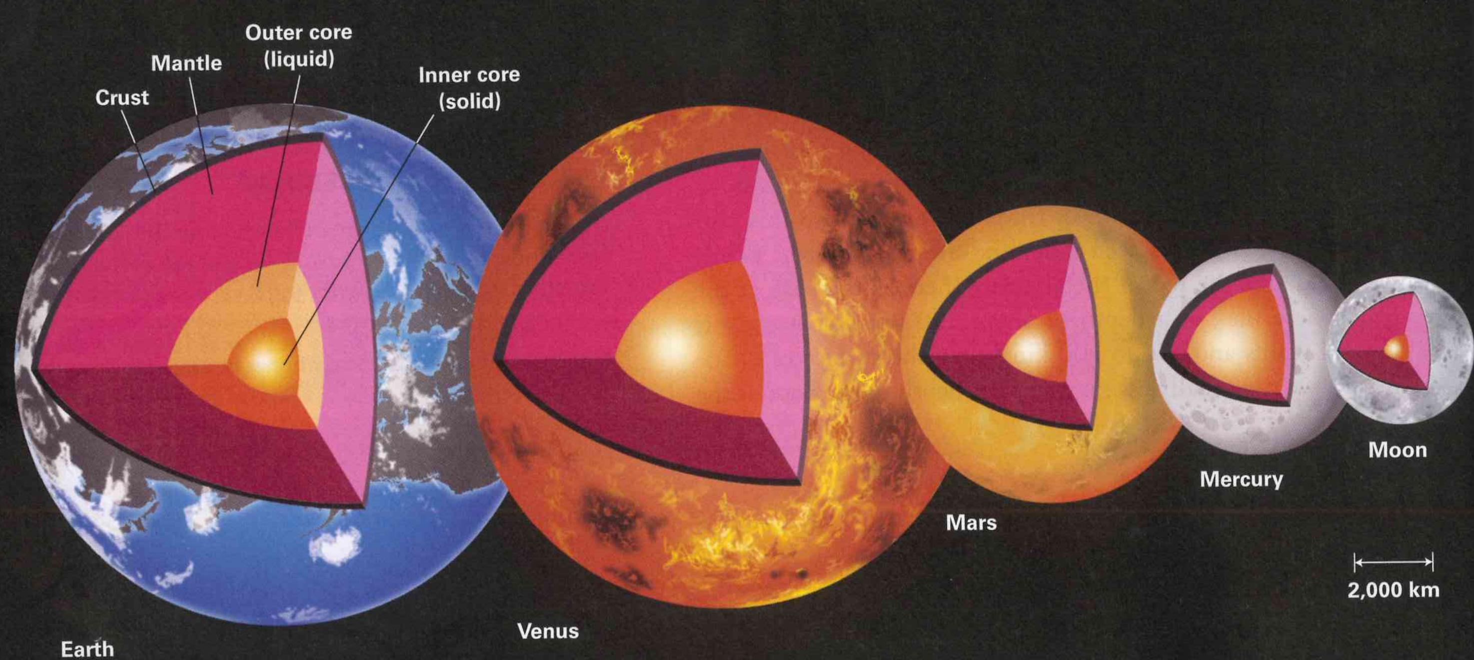
QUICK QUESTION: Is the asthenosphere entirely a liquid?

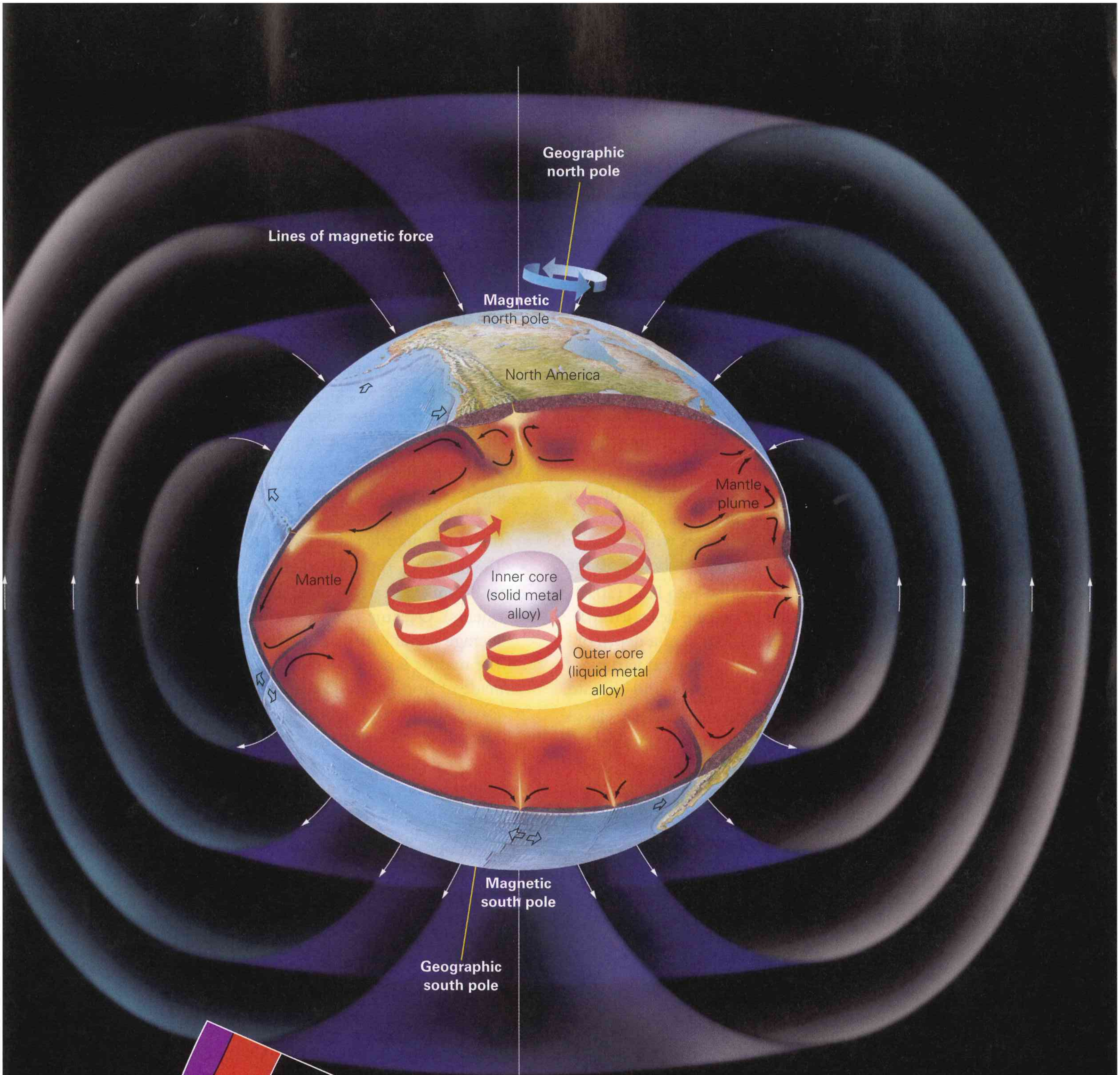
GEOLOGY AT A GLANCE

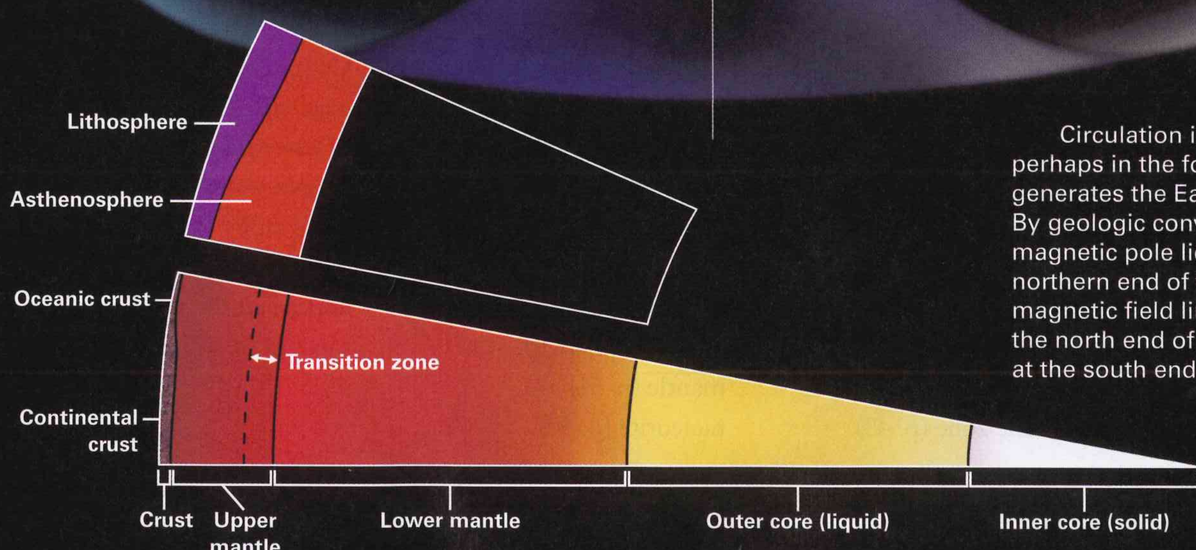
The Earth from Surface to Center

If we could remove all the clouds and water that hide much of the solid surface from view, we would see that both the land areas and the seafloor have plains and mountains. And if we could break open the Earth, we would see that its interior consists of a series of concentric layers (crust, mantle, and core) that differ from one another in terms of their composition and seismic velocity. Notably, oceanic crust differs from continental crust, both in thickness and in composition. Further, the mantle can be divided into two sublayers (upper mantle and lower mantle) and the core can be divided into an outer core of liquid iron alloy and an inner core of solid iron alloy. All terrestrial planets, as well as Earth's Moon, have differentiated to form a crust, mantle, and core. But the relative thicknesses of the different layers are not the same for all planets. When discussing plate tectonics, it is convenient to call the outer part of the Earth, a relatively rigid shell composed of the crust and uppermost mantle, the lithosphere and to refer to the underlying warmer, more plastic portion of the mantle as the asthenosphere.









Circulation in the outer core, perhaps in the form of spiral currents, generates the Earth's magnetic field. By geologic convention, the north magnetic pole lies near the geographic northern end of the Earth. Note that magnetic field lines point downward at the north end of the planet and outward at the south end of the planet.

CHAPTER SUMMARY

- A traverse through the Solar System crosses many features. The Solar System is surrounded by the Oort Cloud of icy particles, attracted by the Sun's gravitational field. The edge of the Solar System itself, a bubble-like surface called the heliosphere, marks the limit at which the pressure of solar wind is countered by that of cosmic rays. Inboard lie the Kuiper Belt of icy objects, the outer planets, the asteroid belt of rocky and metallic material, and the inner planets.
- A magnetic field surrounds the Earth. The field shields it from solar wind. Closer to Earth, the field creates the Van Allen Belts, which also trap cosmic rays.
- A layer of gas, the atmosphere, surrounds the Earth. Air in the atmosphere consists of 78% nitrogen, 21% oxygen, and 1% other gases. Air pressure decreases with elevation, so 99% of the gas in the atmosphere resides below 50 km.
- The surface of the Earth can be divided into land (30%) and ocean (70%). Most of the land surface lies within 1 km of sea level, and most of the seafloor is at a depth of 4 to 5 km. Earth's land surface displays a great variety of landscapes because of variations in elevation and climate.
- Earth materials include organic chemicals, minerals, glasses, rocks (igneous, metamorphic, and sedimentary), grains, sediment, metals, melts, and volatiles. Most rocks on Earth contain silica (SiO_2) and thus are called silicate rocks. We distinguish among felsic, intermediate, mafic, and ultramafic igneous rocks based on the proportion of silica.
- The Earth's interior can be divided into three compositionally distinct layers, named from surface to center: the crust, the mantle, and the core. The first recognition of this division came from studying the density and shape of the Earth. The image has been refined by studying how the speed of seismic waves changes with depth.
- Pressure and temperature both increase with depth in the Earth. At the center, pressure is 3.6 million times greater than at the surface, and the temperature reaches over 4,700°C. The increase in temperature as depth increases is the geothermal gradient.
- Studies of seismic waves reveal the existence of sublayers in the core (liquid outer core and solid inner core) and mantle (upper mantle and lower mantle). The lower part of the upper mantle is the transition zone.
- The crust is a thin skin that varies in thickness from 7 to 10 km (beneath oceans) to 25 to 70 km (beneath continents). Oceanic crust is mafic in composition, whereas average upper continental crust is felsic to intermediate. The mantle is composed of ultramafic rock. The core is made of iron alloy and consists of two parts—the outer core is liquid, and the inner core is solid. Flow in the outer core generates the magnetic field.
- The crust plus the upper part of the mantle constitutes the lithosphere, a relatively rigid shell up to 150 km thick. The lithosphere lies over the asthenosphere, mantle that is capable of flowing and, therefore, convecting.

GUIDE TERMS

abyssal plain (p. 45)
asteroid (p. 39)
asthenosphere (p. 53)
astronomical unit (AU) (p. 37)
atmosphere (p. 41)
aurorae (p. 41)
basalt (p. 46)
bathymetry (p. 44)
comet (p. 39)
continental crust (p. 51)
convection (p. 52)
core (p. 52)
cosmic rays (p. 37)
crust (p. 49)
crystal (p. 45)
deep-ocean trench (p. 45)
dipole (p. 40)
Earth materials (p. 45)
earthquake (p. 49)
Earth System (p. 43)
gabbro (p. 46)
geographic pole (p. 40)
geothermal gradient (p. 46)
granite (p. 46)
groundwater (p. 44)
habitable zone (p. 43)
heliosphere (p. 37)
hypsometric curve (p. 45)
interplanetary space (p. 38)
interstellar space (p. 37)
Kuiper Belt (p. 37)
lithosphere (p. 53)
lithospheric mantle (p. 53)
lower mantle (p. 52)
magnetic field (p. 40)
magnetic field lines (p. 40)
magnetosphere (p. 40)
mantle (p. 51)
meteorite (p. 50)
mid-ocean ridge (p. 45)
Moho (p. 51)
oceanic crust (p. 51)
Oort Cloud (p. 37)
peridotite (p. 46)
silicate rock (p. 46)
surface water (p. 44)
topography (p. 44)
transition zone (p. 52)
upper mantle (p. 52)
vacuum (p. 37)

REVIEW QUESTIONS

1. Why do astronomers consider the space between planets to be a vacuum in comparison with the atmosphere near sea level?
2. Name the features that a spacecraft traversing the Solar System and its surroundings would encounter.
3. What is the Earth's magnetic field? Draw a representation of the field on a piece of paper. Where are the magnetic poles in relation to the geographic poles?
4. How does the magnetic field interact with solar wind and cosmic rays? Be sure to consider the magnetosphere, the Van Allen radiation belts, and the aurorae.
5. What is Earth's atmosphere composed of? Why would you die of suffocation if you were to parachute from an airplane at an elevation of 12 km without taking an oxygen tank with you?
6. What is the proportion of land area to sea area on Earth? From studies of the hypsometric curve, approximately what proportion of the Earth's surface lies at elevations above 2 km?
7. What are the two most abundant elements in the Earth? Describe the major categories of materials constituting the Earth. Does the crust have the same composition as the whole Earth?
8. What are silicate rocks? Give four examples of such rocks, and explain how they differ from one another in terms of their chemical composition.
9. How did researchers first obtain a realistic estimate of Earth's average density? What observations led to the realization that the Earth is largely solid and that a particularly dense core lies at the center?
10. What are seismic waves? Does the velocity at which an earthquake wave travels change or stay constant as the wave passes through the Earth?
11. What are the principal layers of the Earth? What happens to earthquake waves when they reach the boundary between layers?
12. How do temperature and pressure change with increasing depth in the Earth? Be sure to explain the geothermal gradient.
13. What is the Moho? How was it first recognized? Describe the differences between continental crust and oceanic crust.
14. What is the mantle composed of? What are the three sublayers within the mantle? Is there any melt within the mantle?
15. What is the core composed of? How do the inner core and outer core differ from each other? We can't sample the core directly, but geologists have studied samples of materials that are probably very similar in composition to the core. Where do these samples come from?
16. What is the difference between a meteor and a meteorite? Are all meteorites composed of the same material? Explain your answer.
17. What is the difference between lithosphere and asthenosphere? Which layer is softer and flows easily? At what depth does the lithosphere-asthenosphere boundary occur? Is this above or below the Moho?

ON FURTHER THOUGHT

18. (a) Recent observations suggest that the Moon has a very small, solid core that is less than 3% of its mass. In comparison, Earth's core is about 33% of its mass. Explain why this difference might exist. (Hint: Recall the model for Moon formation that we presented in Chapter 1.) (b) The Moon has virtually no magnetosphere. Why? (Hint: Remember what causes Earth's magnetic field.)
19. Popular media sometimes imply that the crust floats on a "sea of magma." Is this a correct image of the mantle just below the Moho? Explain your answer.
20. The measured temperature at the bottom of the deepest drill hole is about 180°C (356°F). What is the geothermal gradient at the location of this hole?