CHAPTER

1

Introducing Geology, the Essentials of Plate Tectonics, and Other Important Concepts

Strategy for Using This Textbook

- As authors, we try to be thorough in our coverage of topics so the textbook can serve you as a resource. Your instructor may choose, however, to concentrate only on certain topics for *your* course. Find out which topics and chapters you should focus on in your studying and concentrate your energies there.
- Your instructor may present additional material that is not in the textbook. Take good notes in class.
- Do not get overwhelmed by terms. (Every discipline has its own language.) Don't just memorize each term and its definition. If you associate a term with a concept or mental picture, remembering the term comes naturally when you understand the concept. (You remember names of people you know because you associate personality and physical characteristics with a name.) You may find it helpful to learn the meanings of frequently used prefixes and suffixes for geological terms. These can be found in appendix G.
- **Boldfaced** terms are ones you are likely to need to understand because they are important to the entire course.
- *Italicized* terms are not as important but may be necessary to understand the material in a particular chapter.
- Pay particular attention to illustrations. Geology is a visually oriented science, and the photos and artwork are at least as important as the text. You should be able to sketch important concepts from memory.
- Find out to what extent your instructor expects you to learn the material in the boxes. They offer an interesting perspective on geology and how it is used, but much of the material might well be considered optional for an introductory course and not vital to your understanding of major topics. Many of the "In Greater Depth" boxes are meant to be challenging—do not be discouraged if you need your instructor's help in understanding them.
- Read through the appropriate chapter before going to class. Reread it after class, concentrating on the topics covered in the lecture or discussion. Especially concentrate on concepts that you do not fully understand. Return to previously covered chapters to refresh your memory on necessary background material.
- Use the end of chapter material for review. The Summary is just that, a summary. Don't expect to get through an exam by only reading the summary and not the rest of the chapter. Use the Terms to Remember to see if you can visually or verbally associate the appropriate concept with each term. Answer the Testing Your Knowledge questions in writing. Be honest with yourself. If you are fuzzy on an answer, return to that portion of the chapter and reread it. Remember that these are just a sampling of the kinds of questions that might be on an exam.
- Geology, like most science, builds on previously acquired knowledge. You must retain what you learn from chapter to chapter. If you forget or did not learn significant concepts covered early in your course, you will find it frustrating later in the course. (To verify this, turn to chapter 20 and you will probably find it intimidating; but if you build on your knowledge as you progress through your course, the chapter material will fall nicely into place.)
- Get acquainted with the book's website at www.mhhe.com/plummer14e. You will find the online quizzes, animations, web exercises, and interactive items useful for review and in-depth learning.
- Be curious. Geologists are motivated by a sense of discovery. We hope you will be, too.

WHO NEEDS GEOLOGY?

Geology, the scientific study of Earth, benefits you and everyone else on this planet. The clothes you wear, the radio you listen to, the food you eat, and the car you drive exist because of what geologists have discovered about Earth. Earth can also be a killer. You might have survived an earthquake, flood, or other natural disaster thanks to action taken based on what scientists have learned about these hazards. Before getting into important scientific concepts, we will look at some of the ways geology has benefited you and will continue to do so.

Supplying Things We Need

We depend on the Earth for energy resources and the raw materials we need for survival, comfort, and pleasure. Every manufactured object relies on Earth's resources—even a pencil (figure 1.1). The Earth, at work for billions of years, has localized material into concentrations that humans can mine or extract. By learning how the Earth works and how different kinds of substances are distributed and why, we can intelligently search for metals, sources of energy, and gems. Even maintaining a supply of sand and gravel for construction purposes depends on geology.

The economic systems of Western civilization currently depend on abundant and cheap energy sources. Nearly all our vehicles and machinery are powered by petroleum, coal, or nuclear power and depend on energy sources concentrated unevenly in the Earth. The U.S. economy in particular is geared to petroleum as a cheap source of energy. During the past few decades, Americans have used up most of their country's known petroleum reserves, which took nature hundreds of millions of years to store in the Earth. The United States, and most other industrialized nations, are now heavily dependent

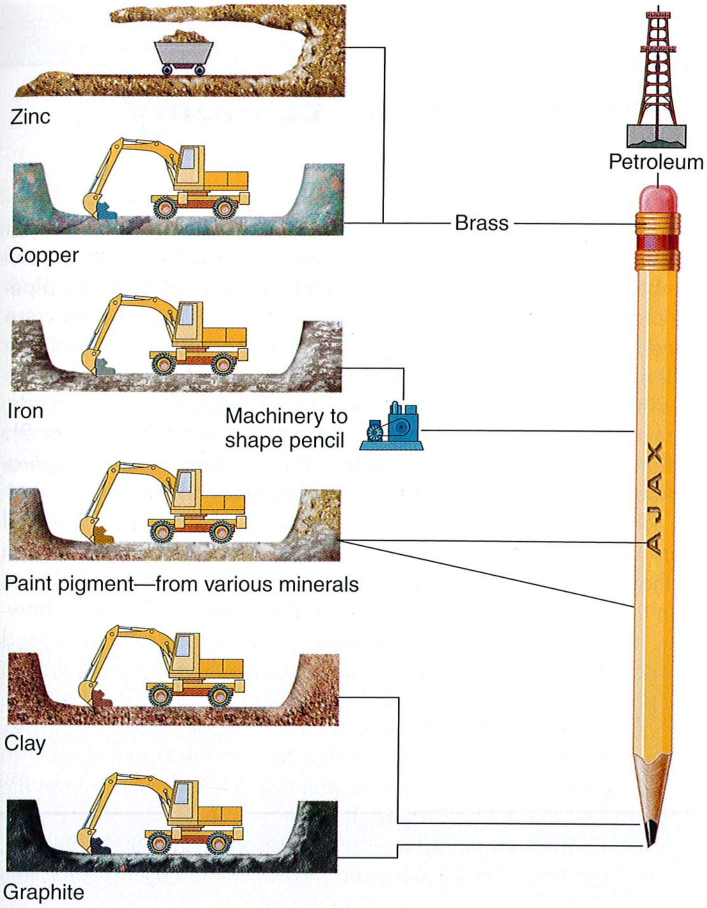


FIGURE 1.1
Earth's resources needed to make a wooden pencil.

on imported oil. When fuel prices jump, people who are not aware that petroleum is a nonrenewable resource become upset and are quick to blame oil companies, politicians, and oil-producing countries. (The Gulf Wars of 1991 and 2003 were at least partially fought because of the industrialized nations' petroleum requirements.) Finding more of this diminishing resource will require more money and increasingly sophisticated knowledge of geology. Although many people are not aware of it, we face similar problems with diminishing resources of other materials, notably metals such as iron, aluminum, copper, and tin, each of which has been concentrated in a particular environment by the action of the Earth's geologic forces.

Just how much of our resources do we use? According to the Mineral Information Institute, for every person living in the United States, approximately 17,260 kilograms (38,000 pounds; for metric conversions, go to appendix E) of resources, not including energy resources, are mined annually. The amount of each commodity mined per person per year is 3,860 kilograms stone, 2,539 kilograms sand and gravel, 213 kilograms limestone for cement, 75 kilograms clays, 190 kilograms salt, 265 kilograms other nonmetals, 162 kilograms iron, 30 kilograms aluminum, 5 kilograms copper, 5 kilograms lead and zinc, 2 kilograms manganese, and 11 kilograms other metals. Americans' yearly per capita consumption of energy resources includes 3,600 liters (951 gallons) of petroleum, 3,000 kilograms of coal, 2,300 cubic meters (80,000 cubic feet) of natural gas, and 0.1 kilograms of uranium.

Protecting the Environment

Our demands for more energy and metals have, in the past, led us to extract them with little regard for effects on the balance of nature within the Earth and therefore on us, Earth's residents. Mining of coal, if done carelessly, for example, can release acids into water supplies. Understanding geology can help us lessen or prevent damage to the environment—just as it can be used to find the resources in the first place.

The environment is further threatened because these are nonrenewable resources. Petroleum and metal deposits do not grow back after being harvested. As demands for these commodities increase, so does the pressure to disregard the ecological damage caused by the extraction of the remaining deposits. As the supply of resources decreases, we are forced to exploit them from harder-to-reach locations. The major oil spill in the Gulf of Mexico in 2010 was due in part to the very deep water in which drilling was taking place (see box 22.2).

Geology has a central role in these issues. Oil companies employ geologists to discover new oil fields, while the public and government depend on other geologists to assess the potential environmental impact of petroleum's removal from the ground, the transportation of petroleum (see box 1.1), and disposal of any toxic wastes from petroleum products.

The consumption of resources, in particular energy resources, is also affecting the Earth's climate. Chapter 21 covers the evidence for global climate change and its connection to greenhouse gases released by burning fossil fuels.

Avoiding Geologic Hazards

Almost everyone is, to some extent, at risk from natural hazards, such as earthquakes or hurricanes. Earthquakes, volcanic eruptions, landslides, floods, and tsunamis are the most dangerous *geologic hazards*. Each is discussed in detail in appropriate chapters. Here, we will give some examples to illustrate the role that geology can play in mitigating geologic hazards.

On Tuesday, January 12, 2010, a magnitude 7 earthquake struck close to Port-au-Prince, the capital city of Haiti. The city and other parts of Haiti were left in ruins (figure 1.2*A*). Responses to the emergency were severely hampered as roads were blocked by debris, hospitals were heavily damaged, the seaport in Port-au-Prince was rendered unusable, and the control tower at the airport was damaged. This made it difficult not only for Haitian emergency workers to rescue those trapped or injured, but also made it difficult for international relief to reach the country quickly. The Haitian government estimates that over 300,000 people were killed and a million were left

ENVIRONMENTAL GEOLOGY 1.1

Delivering Alaskan Oil—The Environment *versus* the Economy

In the 1960s, geologists discovered oil beneath the coast of the Arctic Ocean on Alaska's North Slope at Prudhoe Bay (box figure 1). It is now the United States' largest oil field. Thanks to the Trans-Alaska pipeline, completed in 1977, Alaska has supplied as much as 20% of the United States' domestic oil.

In the late 1970s before Alaskan oil began to flow, the United States was importing almost half its petroleum, at a loss of billions of dollars per year to the national economy. The drain on the country's economy and the increasing cost of energy can be major causes of inflation, lower industrial productivity, unemployment, and the erosion of standards of living. At its peak, over 2 million barrels of oil a day flowed from the Arctic oil fields.This means that over $10 billion a year that would have been spent importing foreign oil is kept in the American economy.

Despite its important role in the American economy, some considered the Alaska pipeline and the use of oil tankers to be unacceptable threats to the area's ecology.

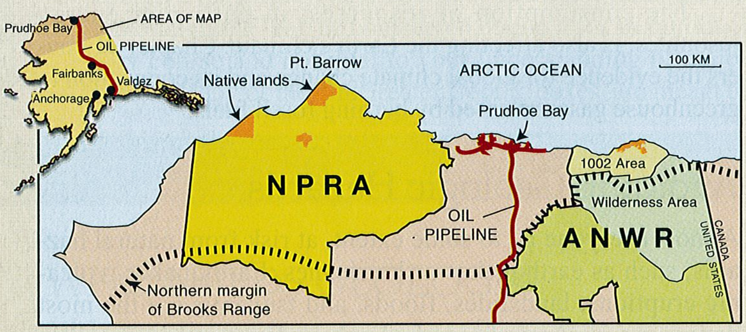
Geologists with the U.S. Geological Survey conducted the official environmental impact investigation of the proposed pipeline route in 1972. After an exhaustive study, they recommended against its construction, partly because of the hazards to oil tankers and partly because of the geologic hazards of the pipeline route. Their report was overruled. The Congress and the president of the United States exempted the pipeline from laws that require a favorable environmental impact statement before a major project can begin.

The 1,250-kilometer-long pipeline crosses regions of ice-saturated, frozen ground and major earthquake-prone mountain ranges that geologists regard as serious hazards to the structure.

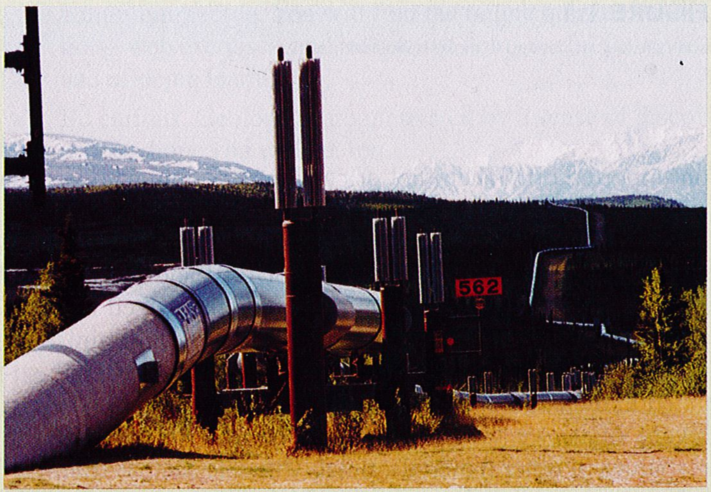
Building anything on frozen ground creates problems. The pipeline presented enormous engineering problems. If the pipeline were placed on the ground, the hot oil flowing through it could melt the frozen ground. On a slope, mud could easily slide and rupture the pipeline. Careful (and costly) engineering minimized these hazards. Much of the pipeline is elevated above the ground (box figure 2). Radiators conduct heat out of the structure. In some places, refrigeration equipment in the ground protects against melting.

Records indicate that a strong earthquake can be expected every few years in the earthquake belts crossed by the pipeline. An earthquake could rupture a pipeline—especially a conventional pipe as in the original design. When the Alaska pipeline was built, however, in several places sections were specially jointed and placed on slider beams to allow the pipe to shift as much as 6 meters without rupturing. In 2002, a major earthquake (magnitude 7.9—the same strength as the May 2008 earthquake in China, described in chapter 16, that killed over 87,000 people) caused the pipeline to shift several meters, resulting in minor damage to the structure, but the pipe did not rupture (box figure 3).

The original estimated cost of the pipeline was $900 million, but the final cost was $7.7 billion, making it the costliest privately



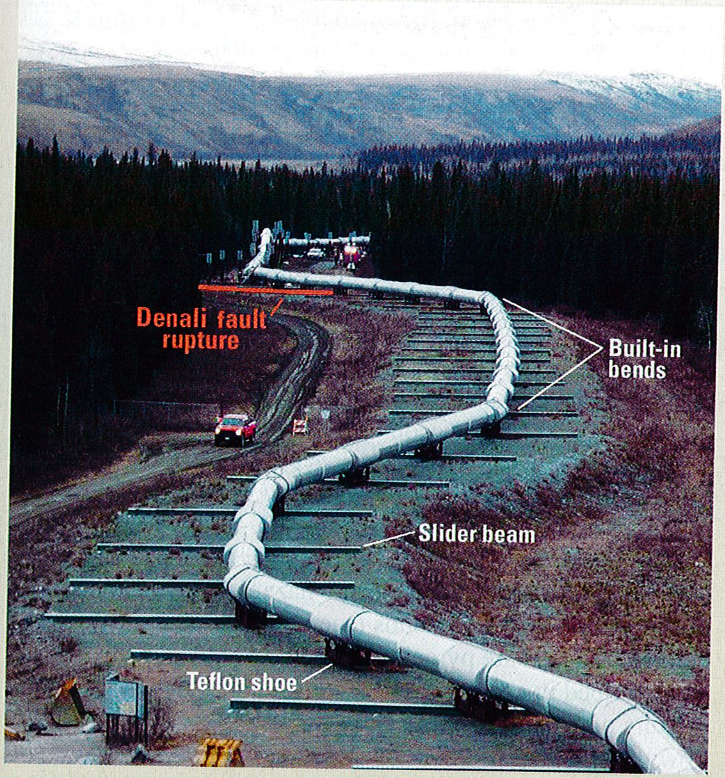
BOX 1.1 ■ FIGURE 1
Map of northern Alaska showing locations and relative sizes of the National Petroleum Reserve in Alaska (NPRA) and the Arctic National Wildlife Refuge (ANWR). "1002 Area" is the portion of ANWR being proposed for oil exploitation. Current oil production is taking place at Prudhoe Bay. *Source: U.S.G.S. Fact Sheet 045-02 and U.S.G.S. Fact Sheet 014-03*



BOX 1.1 ■ FIGURE 2
The Alaska pipeline. *Photo by David Applegate*

homeless. However, due to the immense damage and the difficulties involved in the response, the true impact in terms of casualties may never be known.

Just one month later, on February 10, a magnitude 8.8 earthquake hit off the coast of central Chile. The earthquake was the sixth largest ever recorded, releasing 500 times as much energy as the Haitian earthquake, and felt by 80% of the population. Movement of the sea floor due to the earthquake generated a tsunami that caused major damage to some coastal communities and prompted the issuance of a Pacific-wide tsufinanced construction project in history. The redesigning and construction that minimized the potential for an environmental disaster were among the reasons for the increased cost. Some spills from the pipeline have occurred. In January 1981, 5,000 barrels of oil were lost when a valve ruptured. In 2001, a man fired a rifle bullet into the pipeline, causing it to rupture and spill 7,000 barrels of oil into a forested area. In March 2006, a British Petroleum Company (BP) worker discovered a 201,000 gallon spill from that company's feeder pipes to the Trans-Alaska Pipeline. This was the largest oil spill on the North Slope to date. Subsequent inspection by BP of their feeder pipes revealed much more corrosion than they had expected.



BOX 1.1 ■ FIGURE 3

The Alaska pipeline where it was displaced along the Denali fault during the 2002 earthquake. The pipeline is fastened to teflon shoes, which are sitting on slider beams. Go to http://pubs.usgs.gov/fs/2003/fs014-03/pipeline.html for more information. *Alyeska Pipeline Service Company/U.S. Geologic Survey*

As a result they made a very costly scaling back of their oil production in order to replace pipes and make major repairs.

The Trans-Alaska pipeline was designed to last 30 years. Considerable work and money is going into upgrades that will keep it functioning beyond its projected lifetime.

When the tanker *Exxon Valdez* ran aground in 1989, over 240,000 barrels of crude oil were spilled into the waters of Alaska's Prince William Sound. It was the worst-ever oil spill in U.S. waters. The spill, with its devastating effects on wildlife and the fishing industry, dramatically highlighted the conflicts between maintaining the energy demands of the American economy and conservation of the environment. The 1972 environmental impact statement had singled out marine oil spills as being the greatest threat to the environment. Based on statistical studies of tanker accidents worldwide, it gave the frequency with which large oil spills could be expected. The *Exxon Valdez* spill should not have been a surprise.

As the Prudhoe Bay oil field production diminishes, the United States is becoming even more dependent on foreign oil than it was in the 1970s. Before the opening of North Slope production, the country was importing just under half of petroleum used. In 2010, Americans imported 61% of the oil they consumed. One of the "fixes" being proposed for becoming less dependent on foreign oil is to allow exploitation of oil in the Arctic National Wildlife Refuge on Alaska's North Slope. The rhetoric in the debate is more self-serving or emotional than scientific. At one extreme are those who feel that any significant, potential oil field should be developed without regard to environmental damage. At the other extreme are those who instinctively assume that any intrusion on an ecological environment is unacceptable. We can hope that the enormous amount of data from the Alaskan pipeline and the drilling of the Prudhoe Bay oil field (which has been producing decreasing amounts of oil with ongoing pumping) will be used to help transcend the politics. Perhaps an impartial environmental impact investigation should be done even though no longer required by law.

Additional Resources

The Alyeska pipeline company's site.

- www.alyeska-pipe.com/

U.S. Geological Survey fact sheet on the Arctic National Wildlife Refuge.

- http://pubs.usgs.gov/fs/2002/fs-045-02/

Geotimes article on the 2006 oil spill. Links at the end of this and other articles lead to older articles published by the magazine.

- www.geotimes.org/aug06/WebExtra080706.html

nami warning. It is estimated that 577 people were killed and 1.5 million people were displaced.

Although the impact on Chile was significant (figure 1.2*B*), this enormous earthquake killed far fewer people than the earthquake that struck Haiti. Why is this, and could the deaths in Haiti have been avoided? As described later in this chapter, geologists understand that the outer part of the Earth is broken into large slabs known as *tectonic plates* that are moving relative to each other. Most of the Earth's geologic activity, such as earthquakes and volcanic eruptions, occurs along

A

B

FIGURE 1.2

Damage caused by earthquakes in (A) Haiti and (B) Chile in 2010. Notice how many of the buildings in Haiti were reduced to rubble. Although many buildings were destroyed in Chile, strict building codes meant that many, such as the high-rise apartment building in the background of (B) survived the massive magnitude 8.8 earthquake. (A) *Photo by Tech Sgt. James L. Harper, Jr., U.S. Air Force.* (B) *Photo by Walter D. Mooney, U.S. Geological Survey.*

boundaries between tectonic plates. Both Chile and Haiti are located on plate boundaries, and both have experienced large earthquakes in the past. In fact, the largest earthquake ever recorded happened in Chile in 1960. The impact of earthquakes can be reduced, or *mitigated,* by engineering buildings to withstand shaking. Chile has strict building codes, which probably saved many lives. Haiti, however, is the poorest country in the Western Hemisphere and does not have the stringent building codes of Chile and other wealthy nations. Because of this, thousands of buildings collapsed and hundreds of thousands lost their lives.

Japan is seen as a world leader in earthquake engineering, but nothing could prepare the country for the events of March 11, 2011. At 2:46 P.M., a devastating magnitude 9.0 earthquake hit the east coast of Japan. The earthquake was the largest known to have hit Japan. Soon after the earthquake struck, tsunami waves as high as 38.9 meters (128 feet) inundated the coast. Entire towns were destroyed by waves that in some cases traveled up to 10 kilometers (6 miles) inland. The death toll from this disaster is expected to rise as high as 10,000, and almost half a million people were left homeless. Things could have been much worse. Due to the high building standards in Japan, the damage from the earthquake itself was not severe. Japan has an earthquake early warning system, and after the earthquake struck, a warning went out to millions of Japanese. In Tokyo, the warning arrived one minute before the earthquake was felt. This early warning is believed to have saved many lives. Japan also has a tsunami warning system, and coastal communities have clearly marked escape routes, and regular drills for their citizens. Concrete seawalls were built to protect the coast. Unfortunately, the walls were not high enough to hold back a wave of such great height, and some areas designated as safe areas were not on high enough ground. Still, without the safety precautions in place, many more thousands of people could have lost their lives. In some communities, lives were saved by the actions of their ancestors. Ancient stone markers along the coastline, some more than 600 years old, warn people of the dangers of tsunamis. In the hamlet of Aneyoshi one of these stone markers reads, "Remember the calamity of the great tsunamis. Do not build any homes below this point." The residents of Aneyoshi heeded the warning, locating their homes on higher ground, and the community escaped unscathed.

Volcanic eruptions, like earthquakes and tsunamis, are products of Earth's sudden release of energy. Unlike earthquakes and tsunamis, however, volcanic eruptions can last for extended periods of time. Volcanic hazards include lava flows, falling debris, and ash clouds (see box 1.2). The most deadly volcanic hazards are pyroclastic flows and volcanic mudflows. As described in chapter 4, a *pyroclastic flow* is a hot, turbulent mixture of expanding gases and volcanic ash that flows rapidly down the side of a volcano. Pyroclastic flows often reach speeds of over 100 kilometers per hour and are extremely destructive. A *mudflow* is a slurry of water and rock debris that flows down a stream channel.

Mount Pinatubo's eruption in 1991 was the second largest volcanic eruption of the twentieth century. Geologists successfully predicted the climactic eruption (figure 1.3) in time for Philippine officials to evacuate people living near the moutain. Tens of thousands of lives were saved from pyroclastic flows and mudflows.

By contrast, one of the worst volcanic disasters of the 1900s took place after a relatively small eruption of Nevado del Ruiz in Colombia in 1985. Hot volcanic debris blasted out of the volcano and caused part of the ice and snow capping the peak to melt. The water and loose debris turned into a mudflow.

ENVIRONMENTAL GEOLOGY 1.2

A Volcanic Eruption in Iceland Shuts Down European Air Space for Over a Week

The hazards associated with volcanic eruptions are not necessarily localized. Volcanic ash spewed into the atmosphere presents a hazard to air traffic. Particles of ash can sandblast the windows, and clog a plane's sensors. When fine particles of ash are sucked into the jet engines, they melt and fuse onto the blades, causing the engines to fail. In 1985, a British Airways flight from London, England, to Auckland, New Zealand, flew into a cloud of ash flung up from Mount Galunggung in Indonesia. All four engines failed, and the plane dropped 14,000 feet before the engines could be restarted. This and other incidents have shown aviation authorities that extreme caution must be taken during a volcanic eruption.

In March 2010, Eyjafjallajökull (pronounced ay-uh-fyat-luh-yoe-kuutl-ul), a relatively small volcano in Icleand, began erupting lava from fissures on the side of the moutain. On the morning of April 14, the eruption shifted to new vents buried under the ice cap that covers the summit of the volcano and increased in intensity. The ice melted, adding cold water to the hot lava, causing it to cool rapidly and to fragment into ash particles. The ash was carried up into the atmosphere by an eruption plume where it encountered the jet stream, a band of high-speed winds that blow from west to east (box figure 1). The jet stream carried the ash cloud over much of northern Europe. Because of the hazard to air traffic, much of Europe's airspace was closed from April 15 to April 23, the largest disruption to air traffic since World War II. Flights into and out of Europe were canceled, leaving millions of passengers stranded around the world.

The cost to the airline industry is estimated to have been around $200 million a day. Total losses are estimated at $1.7 billion. The industry complained that the restrictions were too tight and that ash levels were low enough for safe flight.

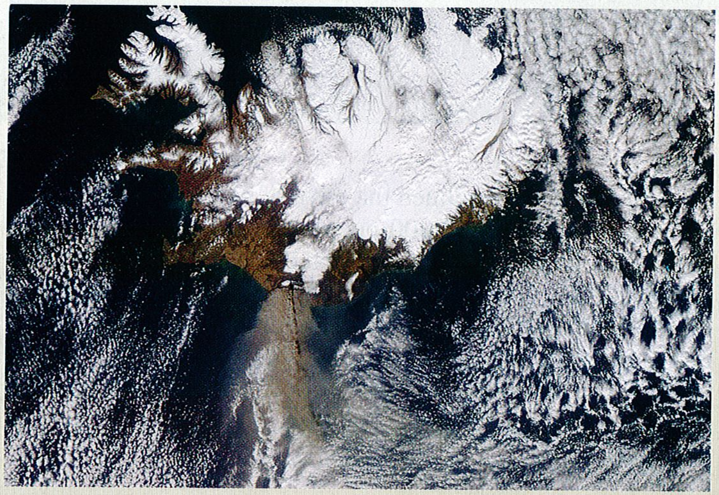
Additional Resources

Amazing images of the eruption can be found at

- http://www.boston.com/bigpicture/2010/04/more_from_eyjafjallajokull.html

The Institute of Earth Sciences Nordic Volcanological Center, University of Iceland—lots of great information about the eruptions

- http://www.earthquake.hi.is/page/ies_Eyjafjallajokull_eruption



BOX 1.2 ■ FIGURE 1

An ash plume from Iceland's Eyjafjallajökull Volcano spreads south toward Europe. Notice that the southern end of the plume is being blown eastward by the polar jet stream. *Image by Jeff Schmaltz, MODIS Rapid Response Team, NASA*

FIGURE 1.3

The major eruption of Mount Pinatubo on June 15, 1991, as seen from Clark Air Force Base, Philippines. *Photo by Robert Lapointe, U.S. Air Force*

FIGURE 1.4
Most of the town of Armero, Colombia, and its residents are buried beneath up to 8 meters of mud from the 1985 mudflow. *Photo © Jacques Langevin/Corbis*

The mudflow overwhelmed the town of Armero at the base of the volcano, killing 23,000 people (figure 1.4). Colombian geologists had previously predicted such a mudflow could occur, and they published maps showing the location and extent of expected mudflows. The actual mudflow that wiped out the town matched that shown on the geologists' map almost exactly. Unfortunately, government officials ignored the map and the geologists' report; otherwise, the tragedy could have been averted.

Understanding Our Surroundings

It is a uniquely human trait to want to understand the world around us. Most of us get satisfaction from understanding our cultural and family histories, how governments work or do not work. Music and art help link our feelings to that which we have discovered through our life. The natural sciences involve understanding the physical and biological universe in which we live. Most scientists get great satisfaction from their work because, besides gaining greater knowledge from what has been discovered by scientists before them, they can find new truths about the world around them. Even after a basic geology course, you can use what you learn to explain and be able to appreciate what you see around you, especially when you travel. If, for instance, you were traveling through the Canadian Rockies, you might see the scene in this chapter's opening photo and wonder how the landscape came to be.

You might wonder: (1) why there are layers in the rock exposed in the cliffs; (2) why the peaks are so jagged; (3) why there is a glacier in a valley carved into the mountain; (4) why this is part of a mountain belt that extends northward and southward for thousands of kilometers; (5) why there are mountain ranges here and not in the central part of the continent. After completing a course in physical geology, you should be able to answer these questions as well as understand how other kinds of landscapes formed.

EARTH SYSTEMS

The awesome energy released by an earthquake or volcano is a product of forces within the Earth that move firm rock. Earthquakes and volcanoes are only two consequences of the ongoing changing of Earth. Ocean basins open and close. Mountain ranges rise and are worn down to plains through slow, but very effective, processes. Studying how Earth works can be as exciting as watching a great theatrical performance. The purpose of this book is to help you understand how and why those changes take place. More precisely, we concentrate on *physical geology,* which is the division of geology concerned with Earth materials, changes in the surface and interior of the Earth, and the dynamic forces that cause those changes. Put another way, physical geology is about how Earth works.

But to understand geology, we must also understand how the solid Earth interacts with water, air, and living organisms. For this reason, it is useful to think of Earth as being part of a system. A *system* is an arbitrarily isolated portion of the universe that can be analyzed to see how its components interrelate. The *solar system* is a part of the much larger universe. The solar system includes the Sun, planets, the moons orbiting planets, and asteroids (see chapter 23).

The **Earth system** is a small part of the larger solar system, but it is, of course, very important to us. The Earth system has its components, which can be thought of as its subsystems. We refer to these as *Earth systems* (plural). These systems, or *"spheres,"* are the atmosphere, the hydrosphere, the biosphere, and the geosphere. You, of course, are familiar with the **atmosphere,** the gases that envelop Earth. The **hydrosphere** is the water on or near Earth's surface. The hydrosphere includes the oceans, rivers, lakes, and glaciers of the world. Earth is unique among the planets in that two-thirds of its surface is covered by oceans. The **biosphere** is all of the living or once-living material on Earth. The **geosphere,** or **solid Earth system,** is the rock and other inorganic Earth material that make up the bulk of the planet. This book mostly concentrates on the geosphere; to understand geology, however, we must understand the interaction between the solid Earth and the other systems (spheres).

The Japanese tsunami involved the interaction of the geosphere and the hydrosphere. The earthquake took place in the geosphere. Energy was transferred into giant waves in the hydrosphere. The hydrosphere and geosphere again interacted when waves inundated the shores.

All four of the Earth systems interact with each other to produce soil, such as we find in farms, gardens, and forests. The solid "dirt" is a mixture of decomposed and disintegrated rock and organic matter. The organic matter is from decayed plants—from the biosphere. The geosphere contributes the rock that has broken down while exposed to air (the atmosphere) and water (the hydrosphere). Air and water also occupy pore space between the solid particles.

IN GREATER DEPTH 1.3

Geology as a Career

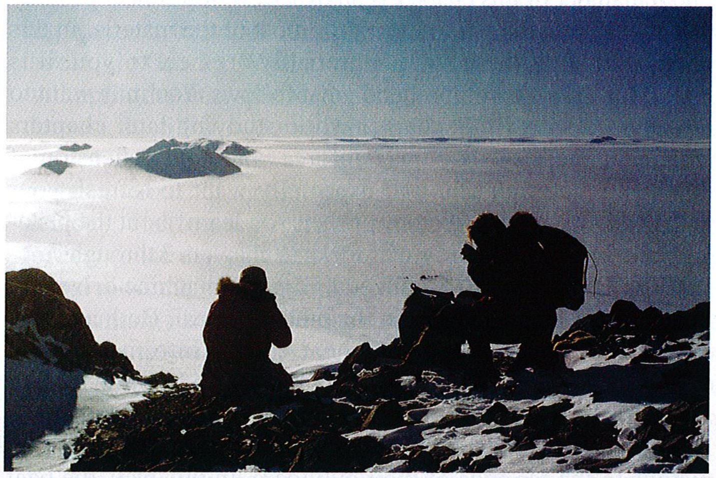
If someone says that she or he is a geologist, that information tells you almost nothing about what he or she does. This is because geology encompasses a broad spectrum of disciplines. Perhaps what most geologists have in common is that they were attracted to the outdoors. Most of us enjoyed hiking, skiing, climbing, or other outdoor activities before getting interested in geology. We like having one of our laboratories being Earth itself.

Geology is a collection of disciplines. When someone decides to become a geologist, she or he is selecting one of those disciplines. The choice is very large. Some are financially lucrative; others may be less so but might be more satisfying. Following are a few of the areas in which geologists work.

Petroleum geologists work at trying to determine where existing oil fields might be expanded or where new oil fields might exist. A petroleum geologist can make over $90,000 a year working on wave-lashed drilling platforms in the North Sea off the coast of Norway. Mining geologists might be concerned with trying to determine where to extend an existing mine to get more ore or trying to find new concentrations of ore that are potentially commercially viable. Environmental geologists might work at mitigating pollution or preventing degradation of the environment. Marine geologists are concerned with understanding the sea floor. Some go down thousands of meters in submersibles to study geologic features on the sea floor. Hydrogeologists study surface and undergroundwater and assist in either increasing our supply of clean water or isolating or cleaning up polluted water. Glaciologists work in Antarctica studying the dynamics of glacier movement or collecting ice cores through drilling to determine climate changes that have taken place over the past 100,000 years or more. Other geologists who work in Antarctica might be deciphering the history of a mountain range, working on skis and living in tents (box figure 1). Volcanologists sometimes get killed or injured while trying to collect gases or samples of lava from a volcano. Some sedimentologists scuba dive in places like the Bahamas, skewering lobsters for lunch while they collect sediment samples. One geologist was the only scientist to work on the Moon. Geophysicists interpret earthquake waves or gravity measurements to determine the nature of Earth's interior. Seismologists are geophysicists who specialize in earthquakes.

Engineering geologists determine whether rock or soil upon which structures (dams, bridges, buildings) are built can safely support those structures. Paleontologists study fossils and learn about when extinct creatures lived and the environment in which they existed.

Teaching is an important field in which geologists work. Some teach at the college level and are usually involved in research as well. Demand is increasing for geologists to teach Earth science (which includes meteorology, oceanography, and astronomy as well as geology) in high schools. More and more secondary schools are adding Earth science to their curriculum and need qualified teachers.



BOX 1.3 ■ FIGURE 1
Geologists investigating the Latady Mountains, Antarctica. *Photo by C. C. Plummer*

Many geologists enjoy the challenge and adventure of field work, but some work comfortably behind computer screens or in laboratories with complex analytical equipment. Usually, a geologist engages in a combination of field work, lab work, and computer analysis.

Geologists tend to be happy with their jobs. In surveys of job satisfaction in a number of professions, geology rates near or at the top. A geologist is likely to be a generalist who solves problems by bringing in information from beyond his or her specialty. Chemistry, physics, and life sciences are often used to solve problems. Problems geologists work on tend to be ones in which there are few clues. So the geologist works like a detective, piecing together the available data to form a plausible solution. In fact, some geologists work at solving crimes—forensic geology is a branch of geology dedicated to criminal investigations.

Not all people who major in geology become professional geologists. Physicians, lawyers, and businesspeople who have majored in geology have felt that the training in how geologists solve problems has benefited their careers.

Additional Resource

For more information, go to the American Geological Institute's career site at

- www.earthscienceworld.org/careers/brochure.html

AN OVERVIEW OF PHYSICAL GEOLOGY—IMPORTANT CONCEPTS

The remainder of this chapter is an overview of physical geology that should provide a framework for most of the material in this book. Although the concepts probably are new to you, it is important that you comprehend what follows. You may want to reread portions of this chapter while studying later chapters when you need to expand or reinforce your comprehension of this basic material. You will especially want to refresh your understanding of plate tectonics when you learn about the plate-tectonic setting for the origin of rocks in chapters 3 through 7.

The Earth can be visualized as a giant machine driven by two engines, one internal and the other external. Both are *heat engines,* devices that convert heat energy into mechanical energy. Two simple heat engines are shown in figure 1.5. An automobile is powered by a heat engine. When gasoline is ignited in the cylinders, the resulting hot gases expand, driving pistons to the far ends of their cylinders. In this way, the heat energy of the expanding gas has been converted to the mechanical energy of the moving pistons, then transferred to the wheels, where the energy is put to work moving the car.

Earth's *internal* heat engine is driven by heat moving from the hot interior of the Earth toward the cooler exterior. Moving plates and earthquakes are products of this heat engine.

Earth's *external* heat engine is driven by solar power. Heat from the Sun provides the energy for circulating the atmosphere and oceans. Water, especially from the oceans, evaporates because of solar heating. When moist air cools, we get rain or snow.

Over long periods of time, moisture at the Earth's surface helps rock disintegrate. Water washing down hillsides and flowing in streams loosens and carries away the rock particles. In this way, mountains originally raised by Earth's internal forces are worn away by processes driven by the external heat engine.

We will look at how the Earth's heat engines work and show how some of the major topics of physical geology are related to the *internal* and *surficial* (on the Earth's surface) processes powered by the heat engines.

Internal Processes: How the Earth's Internal Heat Engine Works

The Earth's internal heat engine works because hot, buoyant material deep within the Earth moves slowly upward toward the cool surface and cold, denser material moves downward. Visualize a vat of hot wax, heated from below (figure 1.6). As the wax immediately above the fire gets hotter, it expands, becomes less dense (that is, a given volume of the material will weigh less), and rises. Wax at the top of the vat loses heat to the air, cools, contracts, becomes denser, and sinks. A similar process takes place in the Earth's interior. Rock that is deep within the Earth and is very hot rises slowly toward the surface, while rock that has cooled near the surface is denser and sinks downward. Instinctively, we don't want to believe that rock can flow like hot wax. However, experiments have shown that under the right conditions, rocks are capable of being molded (like wax or putty). Deeply buried rock that is hot and under high pressure can deform, like taffy or putty. But the deformation takes place very slowly. If we were somehow able to strike a rapid blow to the deeply buried rock with a hammer, it would fracture, just as rock at Earth's surface would.

Earth's Interior

As described in more detail in chapter 17, the **mantle** is the most voluminous of Earth's three major concentric zones (see figure 1.7). Although the mantle is solid rock, parts of it flow slowly, generally upward or downward, depending on whether it is hotter or colder than adjacent mantle.

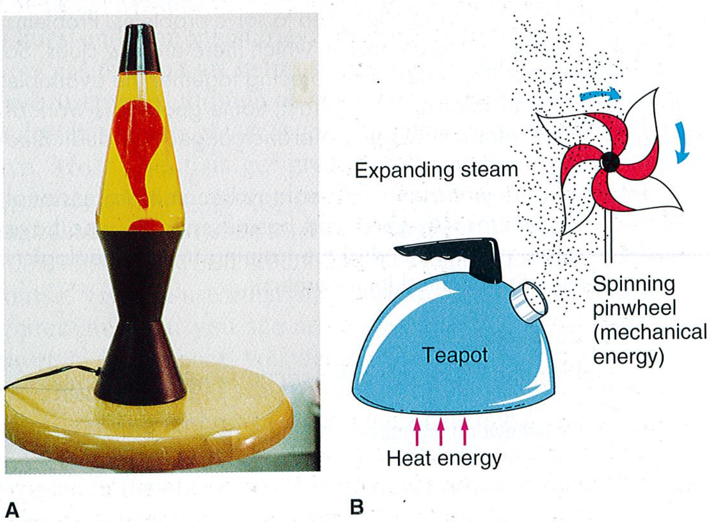


FIGURE 1.5
Two examples of simple heat engines. (*A*) A "lava lamp." Blobs are heated from below and rise. Blobs cool off at the top of the lamp and sink. (*B*) A pinwheel held over steam. Heat energy is converted to mechanical energy. *Photo by C. C. Plummer*

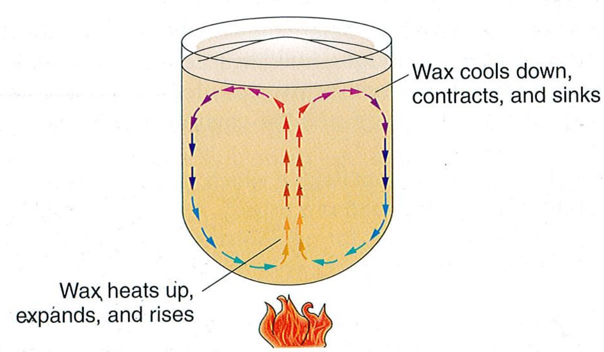


FIGURE 1.6
Movement of wax due to density differences caused by heating and cooling (shown schematically).

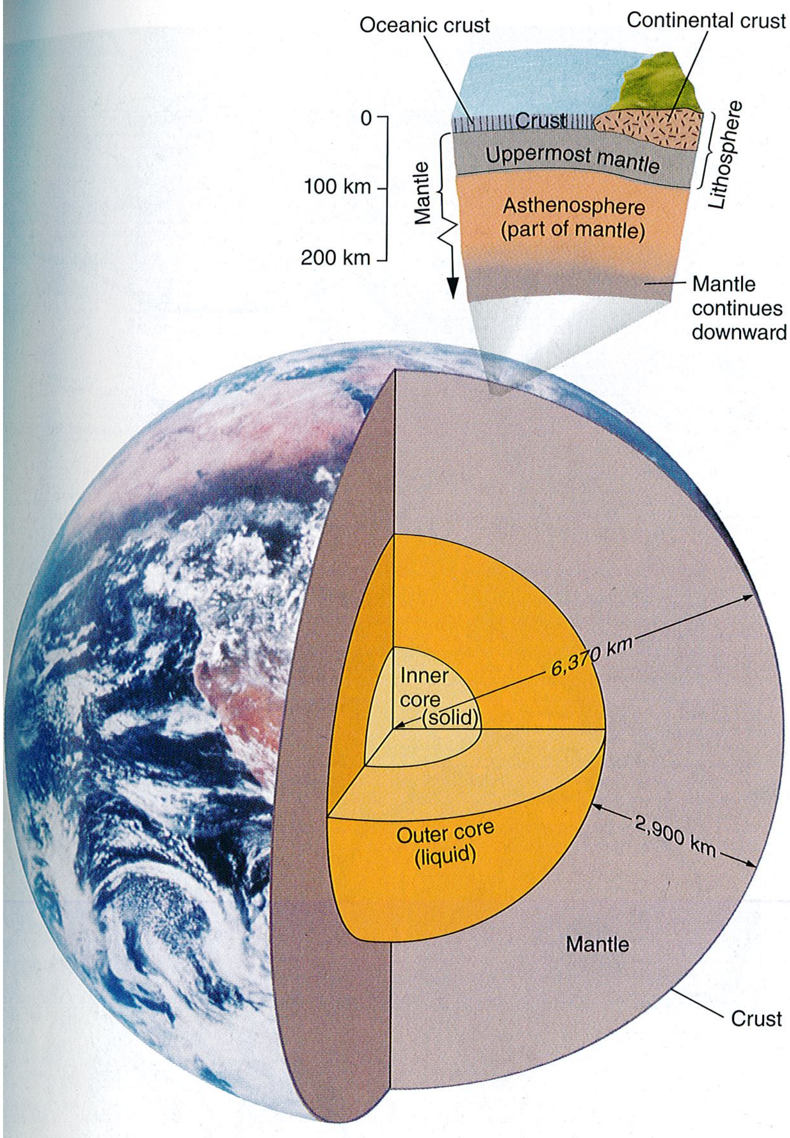


FIGURE 1.7

Cross section through the Earth. Expanded section shows the relationship between the two types of crust, the lithosphere and the asthenosphere, and the mantle. The crust ranges from 5 to 75 kilometers thick. *Photo by NASA*

The other two zones are the **crust** and the **core.** The crust of the Earth is analogous to the skin on an apple. The thickness of the crust is insignificant compared to the whole Earth. We have direct access to only the crust, and not much of the crust at that. We are like microbes crawling on an apple, without the ability to penetrate its skin. Because it is our home and we depend on it for resources, we are concerned more with the crust than with the inaccessible mantle and core.

Two major types of crust are *oceanic crust* and *continental crust.* The crust under the oceans is much thinner. It is made of rock that is somewhat denser than the rock that underlies the continents.

The lower parts of the crust and the entire mantle are inaccessible to direct observation. No mine or oil well has penetrated through the crust, so our concept of the Earth's interior is based on indirect evidence.

The crust and the uppermost part of the mantle are relatively rigid. Collectively, they make up the **lithosphere.** (To help you remember terms, the meanings of commonly used prefixes and suffixes are given in appendix G. For example, *lith* means "rock" in Greek. You will find *lith* to be part of many geologic terms.) The uppermost mantle underlying the lithosphere, called the **asthenosphere,** is soft and therefore flows more readily than the underlying mantle. It provides a "lubricating" layer over which the lithosphere moves (*asthenos* means "weak" in Greek). Where hot mantle material wells upward, it will uplift the lithosphere. Where the lithosphere is coldest and densest, it will sink down through the asthenosphere and into the deeper mantle, just as the wax does in figure 1.6. The effect of this internal heat engine on the crust is of great significance to geology. The forces generated inside the Earth, called **tectonic forces,** cause deformation of rock as well as vertical and horizontal movement of portions of the Earth's crust. The existence of mountain ranges indicates that tectonic forces are stronger than gravitational forces. (Mount Everest, the world's highest peak, is made of rock that formed beneath an ancient sea.) Mountain ranges are built over extended periods, as portions of the Earth's crust are squeezed, stretched, and raised.

Most tectonic forces are mechanical forces. Some of the energy from these forces is put to work deforming rock, bending and breaking it, and raising mountain ranges. The mechanical energy may be stored (an earthquake is a sudden release of stored mechanical energy) or converted to heat energy (rock may melt, resulting in volcanic eruptions). The working of the machinery of the Earth is elegantly demonstrated by plate tectonics.

The Theory of Plate Tectonics

From time to time a theory emerges within a science that revolutionizes that field. (As explained in box 1.4, a *theory* in science is a concept that has been highly tested and in all likelihood is true. In common usage, the word *theory* is used for what scientists call a *hypothesis*—that is, a tentative answer to a question or solution to a problem.) The theory of plate tectonics is as important to geology as the theory of relativity is to physics, the atomic theory to chemistry, or evolution to biology. The plate tectonic theory, currently accepted by virtually all geologists, is a unifying theory that accounts for many seemingly unrelated geologic phenomena. Some of the disparate phenomena that plate tectonics explains are where and why we get earthquakes, volcanoes, mountain belts, deep ocean trenches, and mid-oceanic ridges.

Plate tectonics was seriously proposed as a hypothesis in the early 1960s, though the idea was based on earlier work—notably, the hypothesis of *continental drift.* In the chapters on igneous, sedimentary, and metamorphic rocks, as in the chapter on earthquakes, we will expand on what you learn about the theory here to explain the origin of some rocks and why volcanoes and earthquakes occur. Chapter 19 is devoted to plate tectonics and will show that what you learned in many previous chapters is interrelated and explained by plate tectonic theory.

Plate tectonics regards the lithosphere as broken into *plates* that are in motion (see figure 1.8). The plates, which are much like segments of the cracked shell on a boiled egg, move

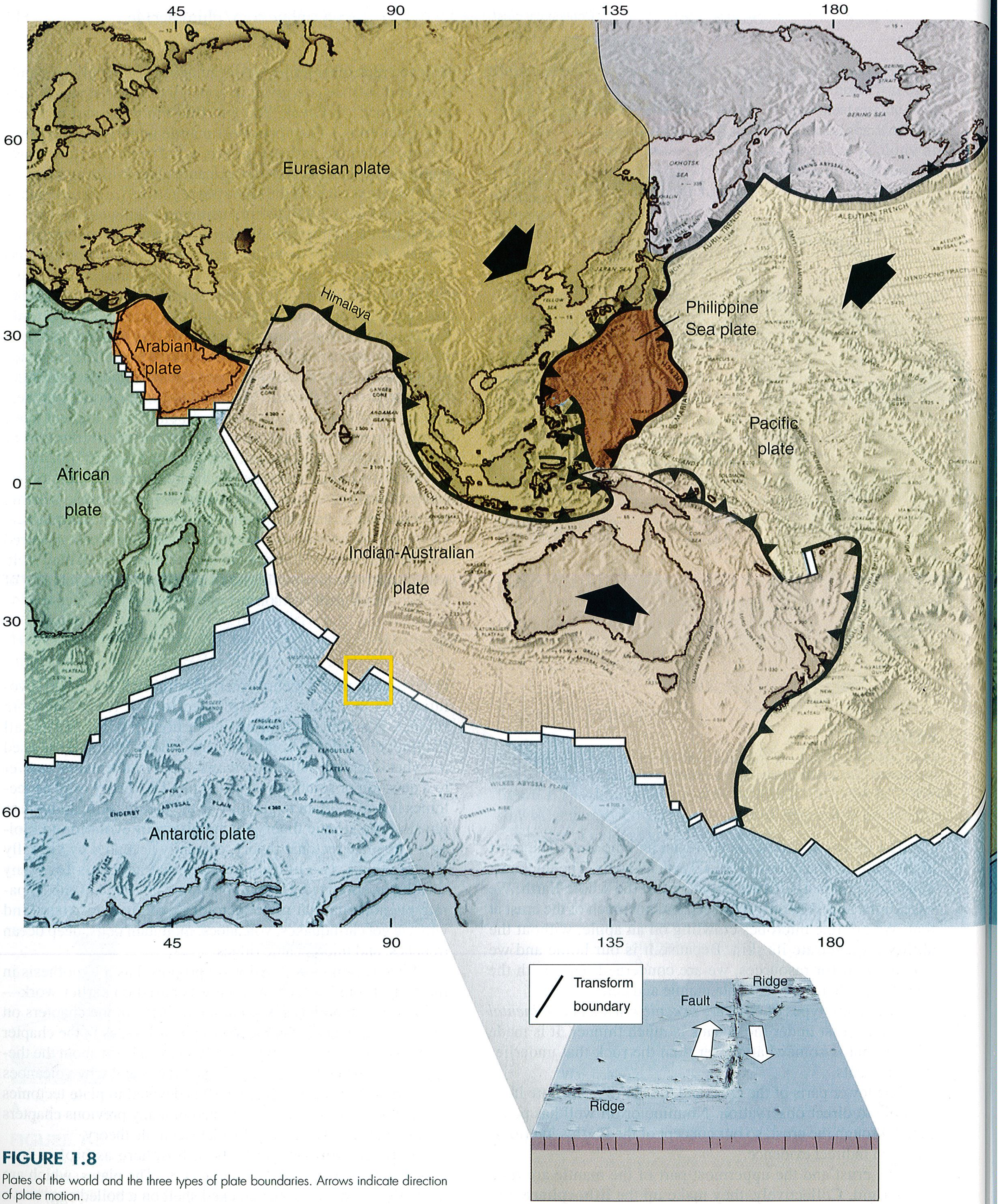


FIGURE 1.8

Plates of the world and the three types of plate boundaries. Arrows indicate direction of plate motion.

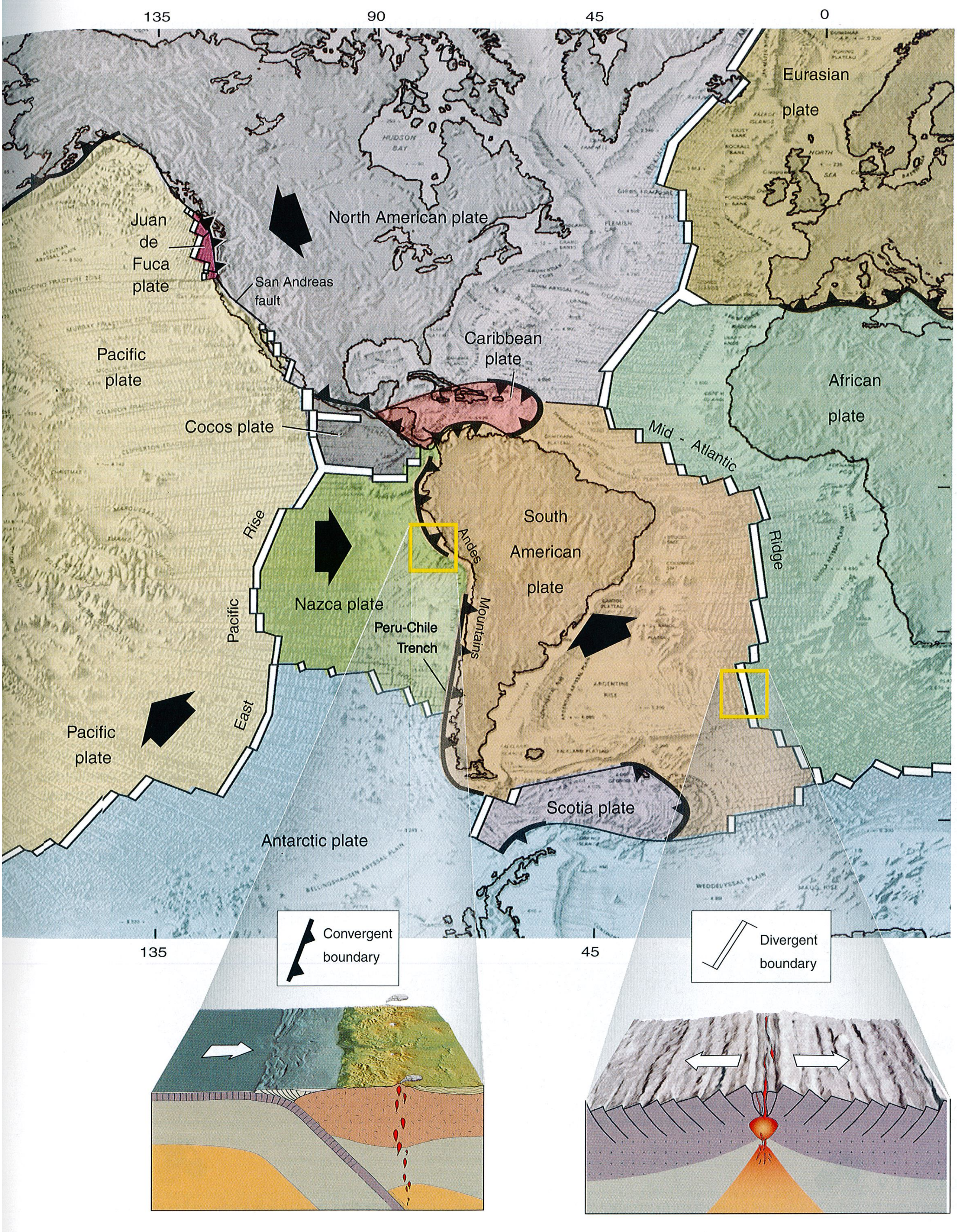

135
90
45
0
60
30
0
30
60
135
45
Eurasian plate
North American plate
Juan de Fuca plate
San Andreas fault
Pacific plate
Caribbean plate
African plate
Cocos plate
Mid - Atlantic Ridge
South American plate
Andes Mountains
Nazca plate
Peru-Chile Trench
East Pacific Rise
Pacific plate
Scotia plate
Antarctic plate
Convergent boundary
Divergent boundary

TABLE 1.1 Three Types of Plate Boundaries

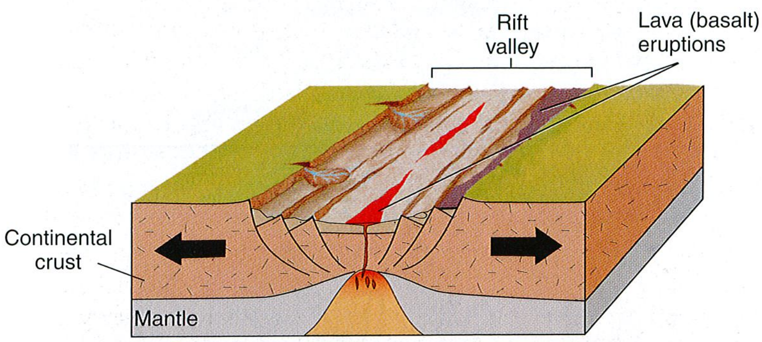
Boundary	What Takes Place	Result
Divergent	Plates move apart	Creation of new ocean floor with submarine volcanoes; mid-oceanic ridge; small to moderate earthquakes
Convergent	Plates move toward each other	Destruction of ocean floor; creation and growth of mountain range with volcanoes; subduction zone; Earth's greatest earthquakes and tsunamis
Transform	Plates move sideways past each other	No creation or destruction of crust; small to large earthquakes

relative to one another along *plate boundaries,* sliding upon the underlying asthenosphere. Much of what we observe in the rock record can be explained by the type of motion that takes place along plate boundaries. Plate boundaries are classified into three types based on the type of motion occurring between the adjacent plates. These are summarized in table 1.1.

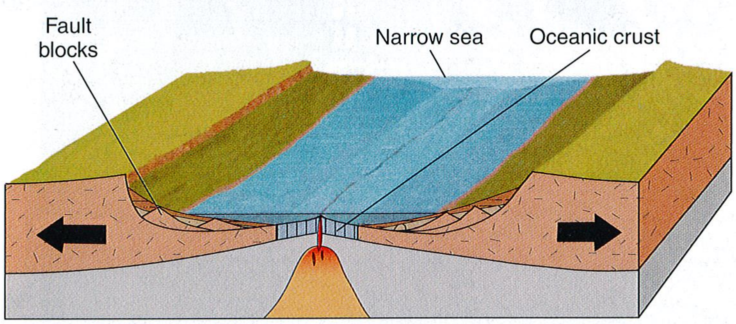
Divergent Boundaries

The first type of plate boundary, a **divergent boundary,** involves two plates that are moving apart from each other. Most divergent boundaries coincide with the crests of submarine mountain ranges, called **mid-oceanic ridges** (figure 1.8). The mid-Atlantic ridge is a classic, well-developed example. Motion along a mid-oceanic ridge causes small to moderate earthquakes.

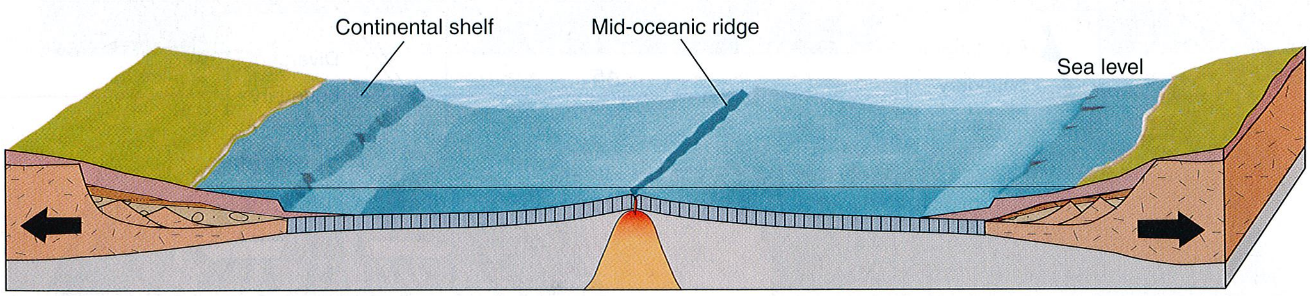
Although most divergent boundaries present today are located within oceanic plates, a divergent boundary typically initiates within a continent. It begins when a split, or *rift,* in the continent is caused either by extensional (stretching) forces within the continent or by the upwelling of hot asthenosphere from the mantle below (figure 1.9*A*). Either way, the continental plate pulls apart and thins. Initially, a narrow valley is formed. Fissures extend into a magma chamber. **Magma** (molten rock) flows into the fissures and may erupt onto the floor of the rift. With continued separation, the valley deepens, the crust beneath



A–Continent undergoes extension. The crust is thinned and a rift valley forms.



B–Continent tears in two. Continent edges are faulted and uplifted. Basalt eruptions form oceanic crust.



C–Continental sediments blanket the subsiding margins to form continental shelves. The ocean widens and a mid-oceanic ridge develops, as in the Atlantic Ocean.

FIGURE 1.9
A divergent boundary begins as a continent is pulled apart. As separation of continental crust proceeds, oceanic crust develops, and an initially narrow sea floor grows larger in time.

the valley sinks, and a narrow sea floor is formed (figure 1.9*B*). Underlying the new sea floor is rock that has been newly created by underwater eruptions and solidification of magma in fissures. Rock that forms when magma solidifies is **igneous rock.** The igneous rock that solidifies on the sea floor and in the fissures becomes *oceanic crust.* As the two sides of the split continent continue to move apart, new fissures develop, magma fills them, and more oceanic crust is formed. As the ocean basin widens, the central zone where new crust is created remains relatively high. This is the mid-oceanic ridge that will remain as the divergent boundary as the continents continue to move apart and the ocean basin widens (figure 1.9*C*).

A mid-oceanic ridge is higher than the deep ocean floor (figure 1.9*C*) because the rocks, being hotter at the ridge, are less dense. A *rift valley,* bounded by tensional cracks, runs along the crest of the ridge. The magma in the chamber below the ridge that squeezes into fissures comes from partial melting of the underlying asthenosphere. Continued pulling apart of the ridge crest develops new cracks, and the process of filling and cracking continues indefinitely. Thus, new oceanic crust is continuously created at a divergent boundary. Not all of the mantle material melts—a solid residue remains under the newly created crust. New crust and underlying solid mantle make up the lithosphere that moves away from the ridge crest, traveling like the top of a conveyor belt. The rate of motion is generally 1 to 18 centimeters per year (approximately the growth rate of a fingernail), slow in human terms but quite fast by geologic standards.

The top of a plate may be composed exclusively of oceanic crust or might include a continent or part of a continent. For example, if you live on the North American plate, you are riding westward relative to Europe because the plate's divergent boundary is along the mid-oceanic ridge in the North Atlantic Ocean (figure 1.8). The western half of the North Atlantic sea floor and North America are moving together in a westerly direction away from the mid-Atlantic ridge plate boundary.

Convergent Boundaries

The second type of boundary, one resulting in a wide range of geologic activities, is a **convergent boundary,** wherein plates move toward each other (figure 1.10). By accommodating the addition of new sea floor at divergent boundaries, the destruction of old sea floor at convergent boundaries ensures the Earth does not grow in size. Examples of convergent boundaries include the Andes mountain range, where the Nazca plate is subducting beneath the South American plate, and the Cascade Range of Washington, Oregon, and northern California, where the Juan de Fuca plate is subducting beneath the North American plate. Convergent boundaries, due to their geometry, are the sites of the largest earthquakes on Earth.

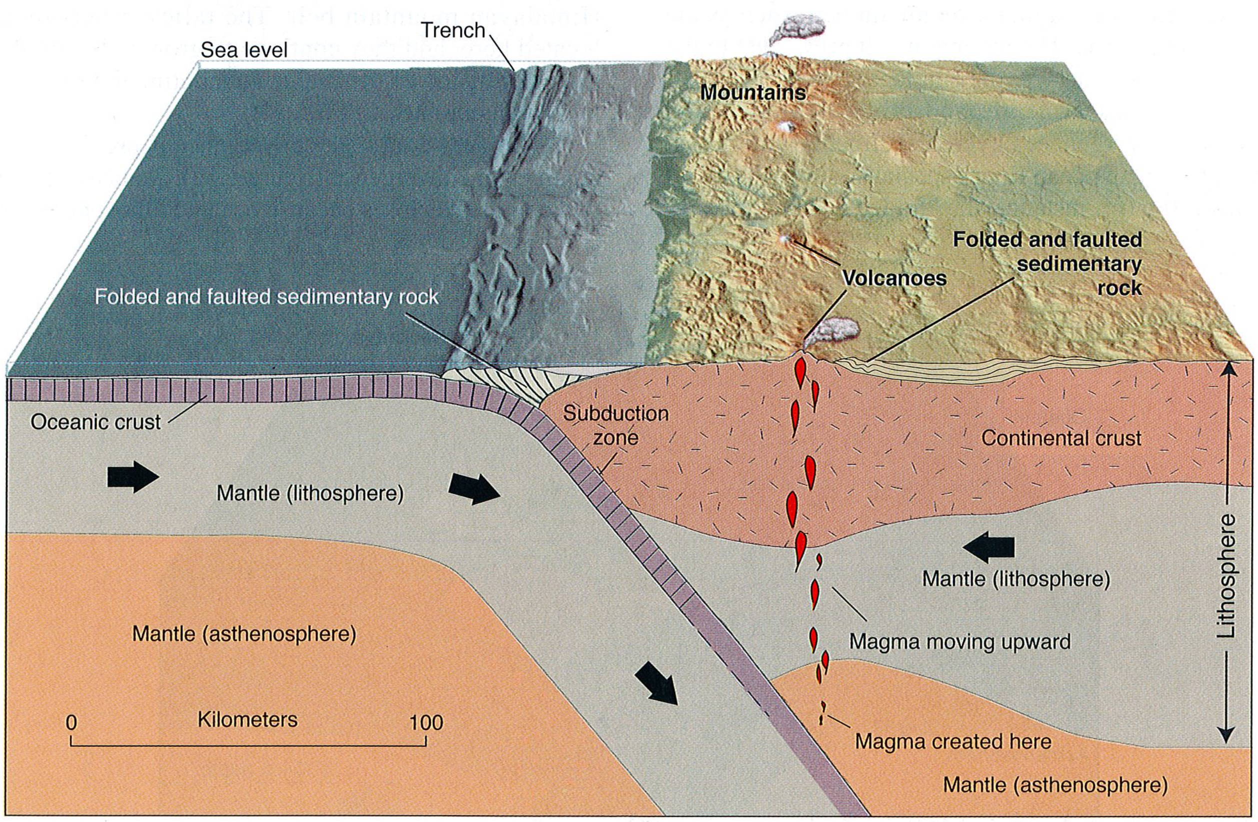


FIGURE 1.10

Block diagram of an ocean-continent convergent boundary. Oceanic lithosphere moves from left to right and is subducted beneath the overriding continental lithosphere. Magma is created by partial melting of the asthenosphere.

It is useful to describe convergent boundaries by the character of the plates that are involved: **ocean-continent, ocean-ocean,** and **continent-continent.** The difference in density of oceanic and continental rock explains the contrasting geological activities caused by their convergence.

Ocean-Continent Convergence

If one plate is capped by oceanic crust and the other by continental crust, the less-dense, more-buoyant continental plate will override the denser, oceanic plate (figure 1.10). The oceanic plate bends beneath the continental plate and sinks along what is known as a **subduction zone,** a zone where an oceanic plate descends into the mantle beneath an overriding plate. Deep *oceanic trenches* are found where oceanic lithosphere bends and begins its descent. These narrow, linear troughs are the deepest parts of the world's oceans.

In the region where the top of the subducting plate slides beneath the asthenosphere, melting takes place and magma is created. Magma is less dense than the overlying solid rock. Therefore, the magma created along the subduction zone works its way upward and either erupts at volcanoes on the Earth's surface to solidify as *extrusive* igneous rock, or solidifies within the crust to become *intrusive* igneous rock. Hot rock, under high pressure, near the subduction zone that does not melt may change in the solid state to a new rock—**metamorphic rock.**

Near the edge of the continent, above the rising magma from the subduction zone, a major mountain belt, such as the Andes or Cascades, forms. The mountain belt grows due to the volcanic activity at the surface, the emplacement of bodies of intrusive igneous rock at depth, and intense compression caused by plate convergence. Layered sedimentary rock that may have formed on an ocean floor especially shows the effect of intense squeezing (for instance, the "folded and faulted sedimentary rocks" shown in figure 1.10). In this manner, rock that may have been below sea level might be squeezed upward to become part of a mountain range.

Ocean-Ocean Convergence

If both converging plates are oceanic, the denser plate will subduct beneath the less-dense plate (figure 1.11). A portion of a plate becomes colder and denser as it travels farther from the mid-oceanic ridge where it formed. After subduction begins, molten rock is produced just as it is in an ocean-continent subduction zone; however, in this case, the rising magma forms volcanoes that grow from an ocean floor rather than on a continent. The resulting mountain belt is called a *volcanic island arc.* Examples include the Aleutian Islands in Alaska and the islands that make up Japan, the site of the great earthquake and tsunami of 2011, described earlier.

Continent-Continent Convergence

If both converging plates are continental, a quite different geologic deformation process takes place at the plate boundary. Continental lithosphere is much less dense than the mantle below and, therefore, neither plate subducts. The buoyant nature of continental lithosphere causes the two colliding continental plates to buckle and deform with significant vertical uplift and thickening as well as lateral shortening. A spectacular example of continent-continent collision is the Himalayan mountain belt. The tallest peaks on Earth are located here, and they continue to grow in height due to continued collision of the Indian subcontinent with the continental Eurasian plate.

Continent-continent convergence is preceded by oceanic-continental convergence (figure 1.12). An ocean basin between two continents closes because oceanic lithosphere is subducted

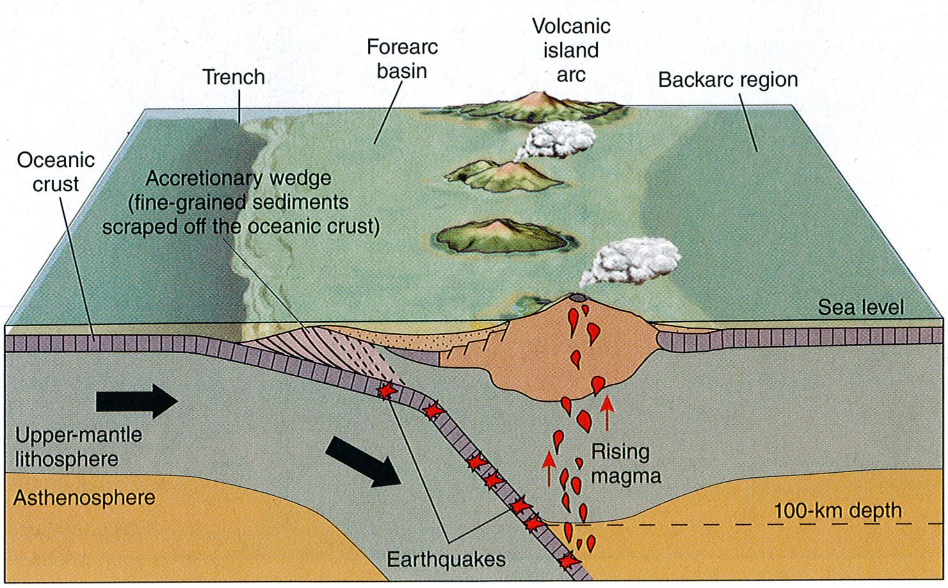


FIGURE 1.11
A volcanic island arc forms as a result of oceanic-oceanic plate convergence.

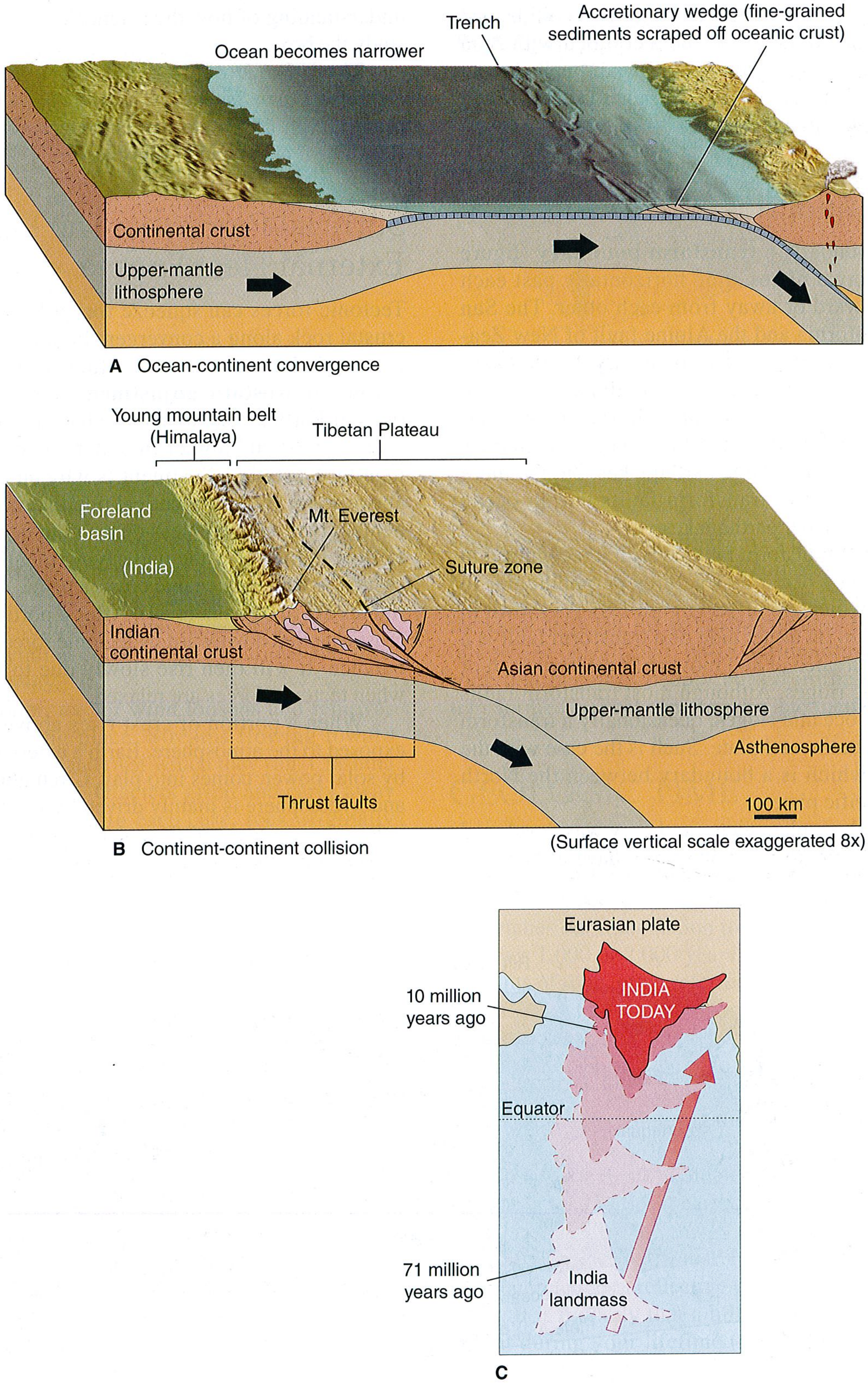


FIGURE 1.12

Continent-continent convergence is preceded by the closing of an ocean basin while ocean-continent convergence takes place. *C* shows the position of India relative to the Eurasian plate in time. The convergence of the two plates created the Himalaya. Some of the features shown, such as accretionary wedge and foreland basin, are described in chapters 6 and 19.

beneath one of the continents. When the continents collide, one becomes wedged beneath the other. India collided with Asia around 40 million years ago, yet the forces that propelled them together are still in effect. The rocks continue to be deformed and squeezed into higher mountains.

Transform Boundaries

The third type of boundary, a **transform boundary** (figure 1.13), occurs where two plates slide horizontally past each other, rather than toward or away from each other. The San Andreas fault in California and the Alpine fault of New Zealand are two examples of this type of boundary. Earthquakes resulting from motion along transform faults vary in size depending on whether the fault cuts through oceanic or continental crust and on the length of the fault. The San Andreas transform fault has generated large earthquakes, but the more numerous and much shorter transform faults within ocean basins generate much smaller earthquakes.

The significance of transform faults was first recognized in ocean basins. Here they occur as fractures perpendicular to mid-oceanic ridges, which are offset (figure 1.8). As shown in figure 1.13, the motion on either side of a transform fault is a result of rock that is created at and moving away from each of the displaced oceanic ridges. Although most transform faults are found along mid-oceanic ridges, occasionally a transform fault cuts through a continental plate. Such is the case with the San Andreas fault, which is a boundary between the North American and the Pacific plates.

Box 1.4 outlines how plate tectonic theory was developed through the *scientific method.* If you do not have a thorough understanding of how the scientific method works, be sure to study the box.

The U.S. Geological Survey's online publication, *This Dynamic Earth,* is an excellent supplement for learning about plate tectonics. Access it as described in "Exploring Web Resources" at the end of this chapter.

Surficial Processes: The Earth's External Heat Engine

Tectonic forces can squeeze formerly low-lying continental crustal rock along a convergent boundary and raise the upper part well above sea level. Portions of the crust also can rise because of **isostatic adjustment,** vertical movement of sections of Earth's crust to achieve balance. That is to say, lighter rock will "float" higher than denser rock on the underlying mantle. Isostatic adjustment is why an empty ship is higher above water than an identical one that is full of cargo. Continental crust, which is less dense than oceanic crust, will tend to float higher over the underlying mantle than oceanic crust (which is why the oceanic crust is below sea level and the continents are above sea level). After a portion of the continental crust is pulled downward by tectonic forces, it is out of isostatic balance. It will then rise slowly due to isostatic adjustment when tectonic forces are relaxed.

When a portion of crust rises above sea level, rocks are exposed to the atmosphere. Earth's external heat engine, driven by solar power, comes into play. Circulation of the atmosphere and hydrosphere is mainly driven by solar power. Our weather is largely a product of the solar heat engine. For instance, hot air rises near the equator and sinks in cooler zones to the north

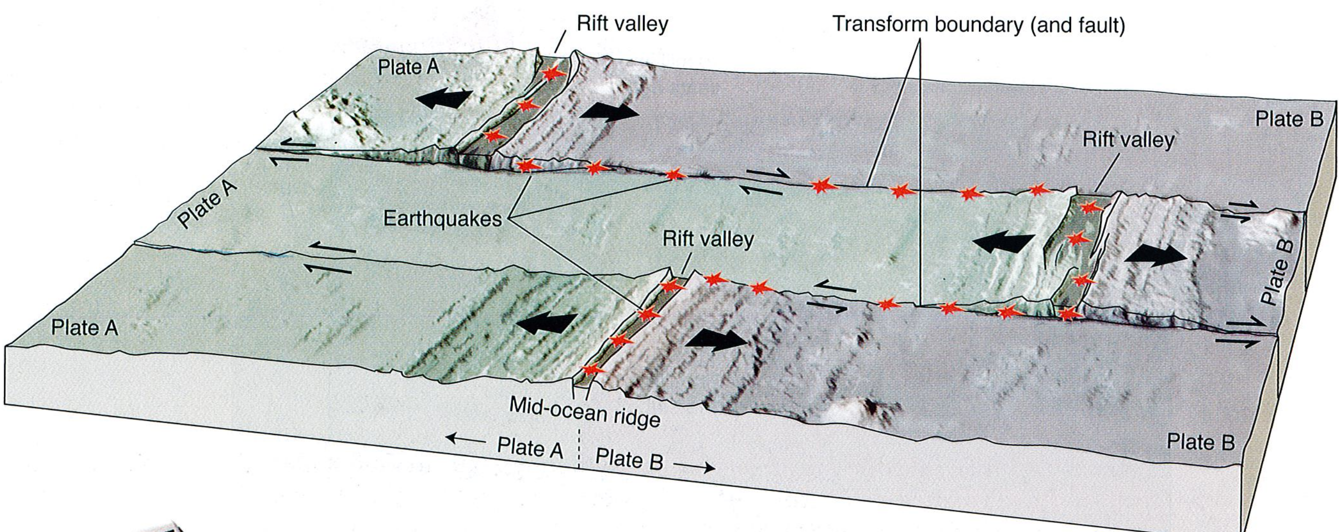


FIGURE 1.13

Transform faults (transform boundaries between plates) are the segments of the fractures between offset ridge crests. Oceanic crust is created at the ridge crests and moves away from the crest as indicated by the heavy arrows. The pairs of small arrows indicate motion on adjacent sides of fractures. Earthquakes take place along the transform fault because rocks are moving in opposite directions. The fractures extend beyond the ridges, but here the two segments of crust are moving in the same direction and rate and there are no earthquakes—these are not part of transform faults.

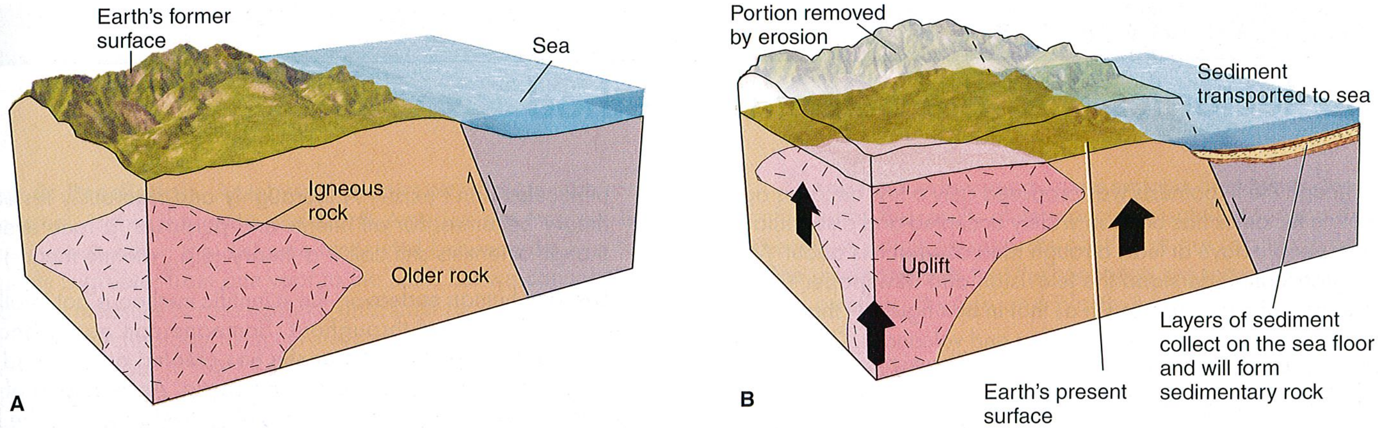


FIGURE 1.14
Erosion, deposition, and uplift. (*A*) Magma has solidified deep underground to become igneous rock. (*B*) As the surface erodes, sediment is transported to the sea to become sedimentary rock. Isostatic adjustment causes uplift of the continent. Erosion and uplift expose the igneous rock at the surface.

and south. Solar heating of air creates wind; ocean waves are, in turn, produced by wind. When moist air cools, it rains or snows. Rainfall on hillsides flows down slopes and into streams. Streams flow to lakes or seas. Glaciers grow where there is abundant snowfall at colder, high elevations and flow downhill because of gravity.

Where moving water, ice, or wind loosens and removes material, **erosion** is taking place. Streams flowing toward oceans remove some of the land over which they run. Crashing waves carve back a coastline. Glaciers grind and carry away underlying rock as they move. In each case, rock originally brought up by the Earth's internal processes is worn down by surficial processes (figure 1.14). As material is removed through erosion, isostasy works to move the landmass upward, just as part of the submerged portion of an iceberg floats upward as ice melts. Or, going back to our ship analogy, as cargo is unloaded, the ship rises in the water.

Rocks formed at high temperature and under high pressure deep within the Earth and pushed upward by isostatic and tectonic forces are unstable in their new environment. Air and water tend to cause the once deep-seated rocks to break down and form new materials. The new materials, stable under conditions at the Earth's surface, are said to be in **equilibrium**—that is, adjusted to the physical and chemical conditions of their environment so that they do not change or alter with time. For example, much of an igneous rock (such as granite) that formed at a high temperature tends to break down chemically to clay. Clay is in equilibrium—that is to say it is stable—at the Earth's surface.

The product of the breakdown of rock is **sediment,** loose material. Sediment may be transported by an agent of erosion, such as running water in a stream. Sediment is deposited when the transporting agent loses its carrying power. For example, when a river slows down as it meets the sea, the sand being transported by the stream is deposited as a layer of sediment.

In time, a layer of sediment deposited on the sea floor becomes buried under another layer. This process may continue, burying our original layer progressively deeper. The pressure from overlying layers compresses the sediment, helping to consolidate the loose material. With the cementation of the loose particles, the sediment becomes *lithified* (cemented or otherwise consolidated) into a **sedimentary rock.** Sedimentary rock that becomes deeply buried in the Earth may later be transformed by heat and pressure into metamorphic rock.

GEOLOGIC TIME

We have mentioned the great amount of time required for geologic processes. As humans, we think in units of time related to personal experience—seconds, hours, years, a human lifetime. It stretches our imagination to contemplate ancient history that involves 1,000 or 2,000 years. Geology involves vastly greater amounts of time, often referred to as *deep time.*

In order to try and comprehend the vastness of deep time, go to the section "Comprehending Geologic Time" at the end of chapter 8. There we relate a very slow and very long movie to Earth's history. Figure 8.25 compares deep time to a trip across the United States at the speed of 1 kilometer per 1 million years.

To be sure, some geologic processes occur quickly, such as a great landslide or an earthquake. These events occur when stored energy (like the energy stored in a stretched rubber band) is suddenly released. Most geologic processes, however, are slow but relentless, reflecting the pace at which the heat engines work. It is unlikely that a hill will visibly change in shape or height during your lifetime (unless through human activity). However, in a geologic time frame, the hill probably is eroding away quite rapidly. "Rapidly" to a geologist may mean that within a few million years, the hill will be reduced nearly to a plain. Similarly, in the geologically "recent" past of several million years ago, a sea may have existed where the hill is now. Some processes are regarded by geologists as "fast" if they are begun and completed within a million years.

IN GREATER DEPTH 1.4

Plate Tectonics and the Scientific Method

Although the hypothesis was proposed only a few decades ago, plate tectonics has been so widely accepted and disseminated that most people have at least a rough idea of what it is about. Most nonscientists can understand the television and newspaper reports (and occasional comic strip, such as that in box figure 1) that include plate tectonics in reports on earthquakes and volcanoes. Our description of plate tectonics implies little doubt about the existence of the process. The theory of plate tectonics has been accepted as scientifically verified by geologists. Plate tectonic theory, like all knowledge gained by science, has evolved through the processes of the **scientific method.** We will illustrate the scientific method by showing how plate tectonics has evolved from a vague idea into a theory that is so likely to be true that it can be regarded as "fact."

The basis for the scientific method is the belief that the universe is orderly and that by *objectively* analyzing phenomena, we can discover their workings. Science is a deeply human endeavor that involves creativity. A scientist's mind searches for connections and thinks of solutions to problems that might not have been considered by others. At the same time, a scientist must be aware of what work has been done by others, so that science can build on those works. Here, the scientific method is presented as a series of steps. A scientist is aware that his or her work must satisfy the requirements of the steps but does not ordinarily go through a formal checklist.

1. A question is raised or a problem is presented.
2. Available information pertinent to the question or problem is analyzed. Facts, which scientists call **data,** are gathered.
3. After the data have been analyzed, tentative explanations or solutions that are consistent with the observed data, called **hypotheses,** are proposed.
4. One predicts what would occur in given situations if a hypothesis were correct.
5. Predictions are tested. Incorrect hypotheses are discarded.
6. A hypothesis that passes the testing becomes a **theory,** which is regarded as having an excellent chance of being true. In science, however, nothing is considered proven absolutely. All scientifically derived knowledge is subject to being proven false. (Can you imagine what could prove that atoms and molecules don't exist?) A thoroughly and rigorously tested theory becomes, for all intents and purposes, a fact, even though scientists still call it a theory (e.g., atomic theory).

FRANK & ERNEST® by Bob Thaves

BOX 1.4 ■ FIGURE 1
Plate tectonics sometimes show up in comic strips. *FRANK & ERNEST: © Thaves/Dist. by Newspaper Enterprise Association, Inc.*

Like any human endeavor, the scientific method is not infallible. Objectivity is needed throughout. Someone can easily become attached to the hypothesis he or she has created and so tend subconsciously to find only supporting evidence. As in a court of law, every effort is made to have observers objectively examine the logic of both procedures and conclusions. Courts sometimes make wrong decisions; science, likewise, is not immune to error.

The following outline shows how the concept of plate tectonics evolved:

Step 1: A question asked or problem raised. Actually, a number of questions were being asked about seemingly unrelated geological phenomena.

What caused the submarine ridge that extends through most of the oceans of the world? Why are rocks in mountain belts intensely deformed? What sets off earthquakes? What causes rock to melt underground and erupt as volcanoes? Why are most of the active volcanoes of the world located in a ring around the Pacific Ocean?

Step 2: Gathering of data. Early in the twentieth century, the amount of data was limited. But through the decades, the information gathered increased enormously. New data, most notably information gained from exploration of the sea floor in the mid-1900s, forced scientists to discard old hypotheses and come up with new ideas.

Step 3: Hypotheses proposed. Most of the questions being asked were treated as separate problems wanting separate hypotheses. Some appeared interrelated. One hypothesis, **continental drift,** did address several questions. It was advocated by Alfred Wegener, a German scientist, in a book published in the early 1900s.

Wegener postulated that the continents were all once part of a single supercontinent called Pangaea. The hypothesis explained why the coastlines of Africa and South America look like separated parts of a jigsaw puzzle. Some 200 million years ago, this supercontinent broke up, and the various continents slowly drifted into their present positions. The hypothesis suggested that the rock within mountain belts becomes deformed as the leading edge of a continental crust moves against and over the stationary oceanic crust. Earthquakes were presumably caused by continuing movement of the continents.

Until the 1960s, continental drift was not widely accepted. It was scoffed at by many geologists who couldn't conceive of how a continent could be plowing over oceanic crust. During the 1960s, after new data on the nature of the sea floor became available, the idea of continental drift was incorporated into the concept of plate tectonics. What was added in the plate tectonic hypothesis was the idea that oceanic crust, as well as continental crust, was shifting.

Step 4: Prediction. An obvious prediction, if plate tectonics is correct, is that if Europe and North America are moving away from each other, the distance measured between the two continents is greater from one year to the next. But we cannot stretch a tape measure across oceans, and, until recently, we have not had the technology to accurately measure distances between continents. So, in the 1960s, other testable predictions had to be made. Some of these predictions and results of their testing are described in the chapter on plate tectonics. One of these predictions was that the rocks of the oceanic crust will be progressively older the farther they are from the crest of a mid-oceanic ridge.

Step 5: Predictions are tested. Experiments were conducted in which holes were drilled in the deep-sea floor from a specially designed ship. Rocks and sediment were collected from these holes, and the ages of these materials were determined. As the hypothesis predicted, the youngest sea floor (generally less than a million years old) is near the mid-oceanic ridges, whereas the oldest sea floor (up to about 200 million years old) is farthest from the ridges (box figure 2).

This test was only one of a series. Various other tests, described in some detail later in this book, tended to confirm the hypothesis of plate tectonics. Some tests did not work out exactly as predicted. Because of this, and more detailed study of data, the original concept was, and continues to be, modified. The basic premise, however, is generally regarded as valid.

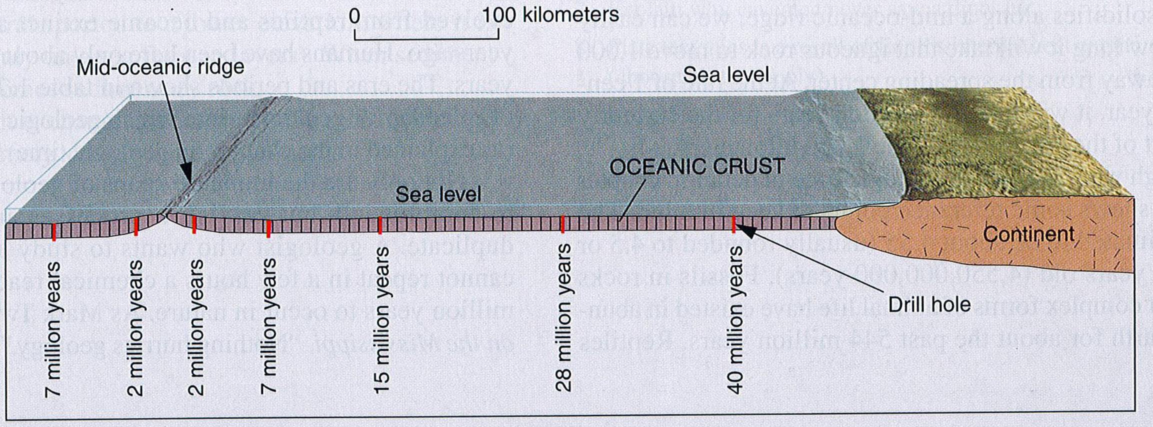
Step 6: The hypothesis becomes a theory. Most geologists in the world considered the results of this and other tests as positive, indicating that the concept is not reasonably disputable and very probably true. It then became the plate tectonic theory.

During the last few years, plate tectonic theory has been further confirmed by the results of very accurate satellite surveys that determine where points on separate continents are relative to one another. The results indicate that the continents are indeed moving relative to one another. Europe and North America *are* moving farther apart.

Although it is unlikely that plate tectonic theory will be replaced by something we haven't thought of yet, aspects that fall under plate tectonics' umbrella (for instance, exactly how does magma form at a convergent plate boundary?) continue to be analyzed and revised as new data become available.

Important Note

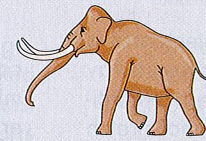
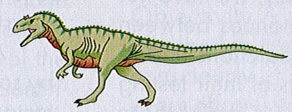
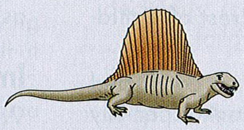
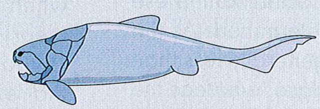
Words used by scientists do not always have the same meaning when used by the general public. A case in point is the word *theory.* To most people, a "theory" is what scientists regard as a "hypothesis." You may remember news reports about an airliner that exploded offshore from New York in 1996. A typical statement on television was: "One theory is that a bomb in the plane exploded; a second theory is that the plane was shot down by a missile fired from a ship at sea; a third theory is that a spark ignited in a fuel tank and the plane exploded." Clearly, each "theory" is a hypothesis in the scientific sense of the word. This has led to considerable confusion for nonscientists about science. You have probably heard the expression, "It's just a theory." Statements such as, "Evolution is just a theory," are used to imply that scientific support is weak. The reality is that theories such as evolution and plate tectonics have been so overwhelmingly verified that they come as close as possible to what scientists accept as being indisputable facts. They would, in laypersons' terms, be "proven."



BOX 1.4 ■ FIGURE 2

Ages of rocks from holes drilled into the oceanic crust. (Vertical scale of diagram is exaggerated.)

TABLE 1.2 Some Important Ages in the Development of Life on Earth

Millions of Years before Present	Noteworthy Life	Eras	Periods
4	Earliest hominids	 Cenozoic	Quaternary *Neogene *Paleogene
65	First important mammals		
	Extinction of dinosaurs		
	First dinosaurs	 Mesozoic	Cretaceous Jurassic Triassic
251			
300	First reptiles		Permian Pennsylvanian Mississippian
400	Fishes become abundant	 Paleozoic	Devonian Silurian Ordovician Cambrian
544	First abundant fossils		
600	Some complex, soft-bodied life	 Precambrian	(The Precambrian accounts for the vast majority of geologic time.)
3,500	Earliest single-celled fossils		
4,550	Origin of the Earth		

*Note, in 2009 the International Commission on Stratigraphy replaced the Tertiary Period with the Paleogene and Neogene Periods.

The rate of plate motion is relatively fast. If new magma erupts and solidifies along a mid-oceanic ridge, we can easily calculate how long it will take that igneous rock to move 1,000 kilometers away from the spreading center. At the rate of 1 centimeter per year, it will take 100 million years for the currently forming part of the crust to travel the 1,000 kilometers.

Although we will discuss geologic time in detail in chapter 8, table 1.2 shows some reference points to keep in mind. The Earth is estimated to be about 4.55 (usually rounded to 4.5 or 4.6) billion years old (4,550,000,000 years). Fossils in rocks indicate that complex forms of animal life have existed in abundance on Earth for about the past 544 million years. Reptiles became abundant about 230 million years ago. Dinosaurs evolved from reptiles and became extinct about 65 million years ago. Humans have been here only about the last 3 million years. The eras and periods shown in table 1.2 comprise a kind of calendar for geologists into which geologic events are placed (as explained in the chapter on geologic time).

Not only are the immense spans of geologic time difficult to comprehend, but very slow processes are impossible to duplicate. A geologist who wants to study a certain process cannot repeat in a few hours a chemical reaction that takes a million years to occur in nature. As Mark Twain wrote in *Life on the Mississippi*, "Nothing hurries geology."

Summary

Geology is the scientific study of Earth. We benefit from geology in several ways: (1) We need geology to find and maintain a supply of minable commodities and sources of energy; (2) Geology helps protect the environment; (3) Applying knowledge about geologic hazards (such as volcanoes, earthquakes, tsunamis, landslides) saves lives and property; and (4) We have a greater appreciation of rocks and landforms through understanding how they form.

Earth systems are the atmosphere, the hydrosphere, the biosphere, and the geosphere (or solid Earth system). The Earth system is part of the solar system.

Geologic investigations indicate that Earth is changing because of internal and surficial processes. Internal processes are driven mostly by temperature differences within Earth's mantle. Surficial processes are driven by solar energy. Internal forces cause the crust of Earth to move.

Plate tectonic theory visualizes the lithosphere (the crust and uppermost mantle) as broken into plates that move relative to each other over the asthenosphere. The plates are moving *away* from divergent boundaries usually located at the crests of mid-oceanic ridges where new crust is being created. Divergent boundaries can develop in a continent and split the continent. Plates move *toward* convergent boundaries. In ocean-continent convergence, lithosphere with oceanic crust is subducted under lithosphere with continental crust. Ocean-ocean convergence involves subduction in which both plates have oceanic crust and the creation of a volcanic island arc. Continent-continent convergence takes place when two continents collide. Plates slide past one another at transform boundaries. Plate tectonics and isostatic adjustment cause parts of the crust to move up or down.

Erosion takes place at Earth's surface where rocks are exposed to air and water. Rocks that formed under high pressure and temperature inside Earth are out of equilibrium at the surface and tend to alter to substances that are stable at the surface. Sediment is transported to a lower elevation, where it is deposited (commonly on a sea floor in layers). When sediment is cemented, it becomes sedimentary rock.

Although Earth is changing constantly, the rates of change are generally extremely slow by human standards.

Terms to Remember

asthenosphere 13
atmosphere 10
biosphere 10
continent-continent convergence 18
continental drift 22
convergent boundary 17
core 13
crust 13
data 22
divergent boundary 16
Earth system 10
equilibrium 21
erosion 21
geology 4
geosphere (solid Earth system) 10
hydrosphere 10
hypothesis 22
igneous rock 17
isostatic adjustment 20
lithosphere 13
magma 16
mantle 12
metamorphic rock 18
mid-oceanic ridges 16
ocean-continent convergence 18
ocean-ocean convergence 18
plate tectonics 13
scientific method 22
sediment 21
sedimentary rock 21
subduction zone 18
tectonic forces 13
theory 22
transform boundary 20

Testing Your Knowledge

Use the following questions to prepare for exams based on this chapter.

1. What is meant by *equilibrium?* What happens when rocks are forced out of equilibrium?
2. What tectonic plate are you currently on? Where is the nearest plate boundary, and what kind of boundary is it?
3. What is the most likely geologic hazard in your part of your country?
4. What are the three major types of rocks?
5. What are the relationships among the mantle, the crust, the asthenosphere, and the lithosphere?
6. What would the surface of Earth be like if there were no tectonic activity?
7. Explain why cavemen never saw a dinosaur.
8. Plate tectonics is a result of Earth's internal heat engine, powered by (choose all that apply)

   a. the Sun b. gravity

   c. heat flowing from Earth's interior outward

THE EARTH IN SPACE

The Earth is not alone in space. It is but one of eight **planets** and innumerable smaller bodies that orbit the Sun. We cannot yet explore these other planets directly, but with robotic spacecraft and Earth-based telescopes, astronomers can study and compare these other worlds to our home planet. These other planets differ greatly and are fascinating in their own right. Moreover, they give us a better understanding and appreciation of Earth.

Starting from the Sun and working out, the eight planets are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune.[1] Figure 23.1 shows pictures of these eight distinctive objects and illustrates their relative size and appearance. Some are far smaller and others vastly larger than Earth, but all are dwarfed by the Sun.

The Sun

The Sun is a **star,** a huge ball of gas over 100 times the diameter of the Earth (figure 23.2) and over 300,000 times more massive. If the Sun were a volleyball, the Earth would be about the size of a pinhead, and Jupiter roughly the size of a nickel. The Sun's great mass is not just of academic interest: it generates the gravity that holds the planets in their orbits, preventing them from flying off into the cold of interstellar space. It also provides the energy that drives Earth's external heat engine.

The Sun differs from Earth not just in size but also in its composition. Like most stars, the Sun is made mainly of hydrogen (about 75% by mass). Hydrogen plays a critical role in the Sun because it is the fuel that keeps it shining. Within the Sun's core, the temperature and pressure are so high that hydrogen

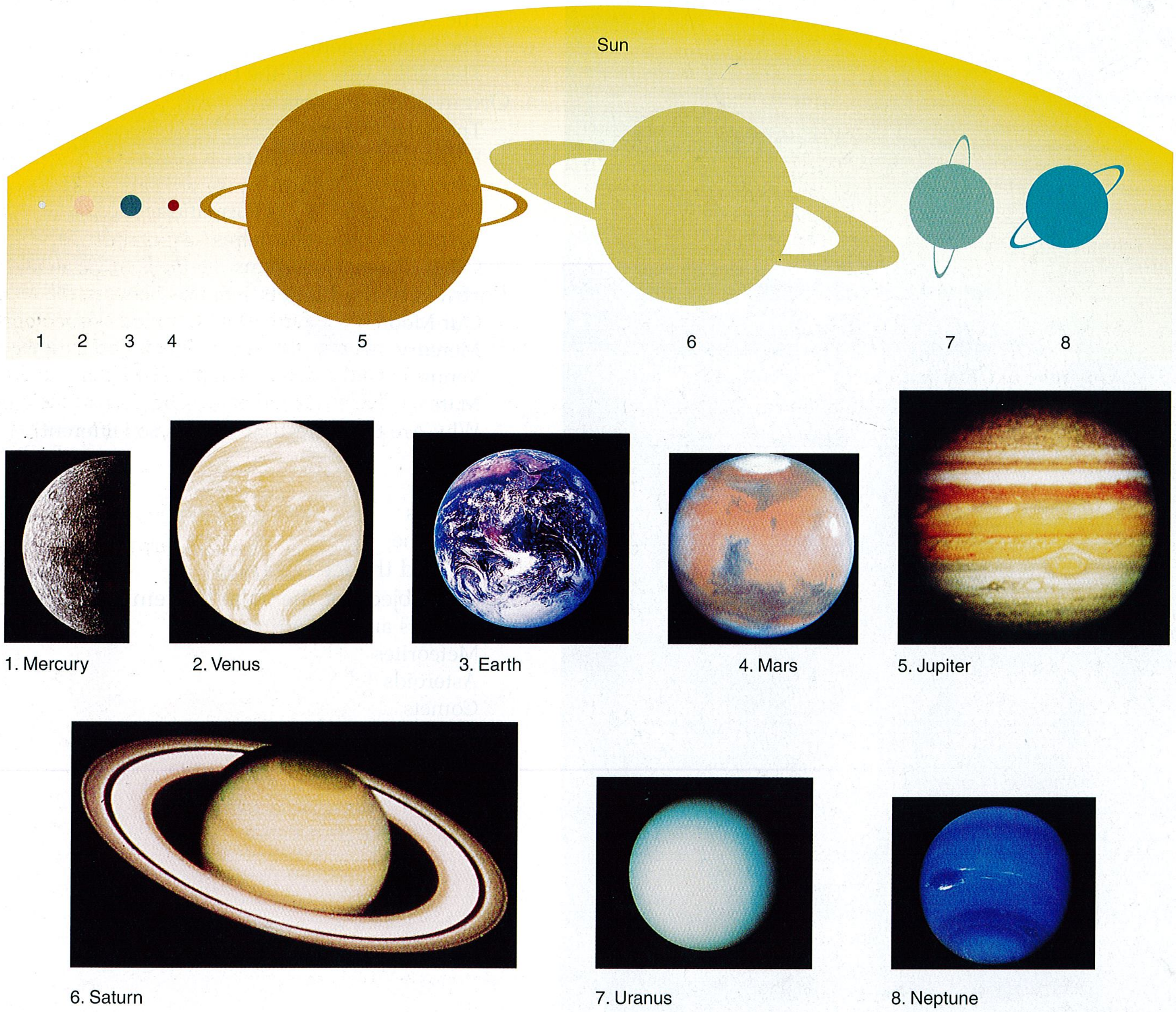


FIGURE 23.1

Images of the eight planets and a sketch at top showing them and Sun to approximately correct relative size. *Photos courtesy of NASA/JPL*

[1]Pluto was recently reclassified as an "ice dwarf," along with the other large icy bodies in the outer solar system.

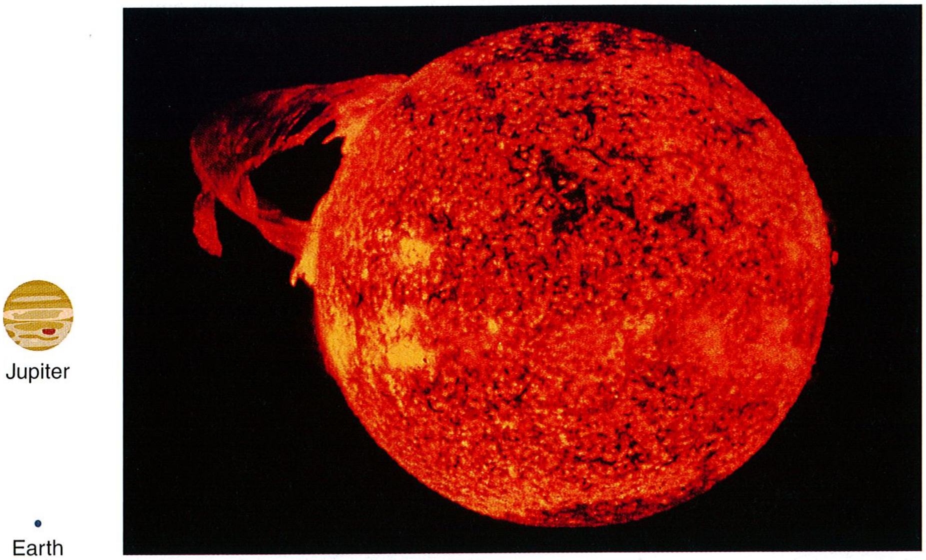


FIGURE 23.2
The Sun as viewed through a special filter that allows its outer gases to be seen. The Earth and Jupiter are shown to scale beside it. *Photo courtesy of Naval Research Laboratory*

atoms can fuse together to form helium atoms. That process releases energy, which flows to the Sun's surface and from there pours into space to illuminate and warm the planets.

The Solar System

The Sun, its eight planets and their moons, together with smaller objects such as asteroids and comets, form the **solar system.** Despite the diversity of its members, the solar system shows many regularities. For example, all the planets move around the Sun in the same direction. They all follow approximately circular orbits centered on the Sun (figure 23.3), and these orbits all lie approximately in the same plane. Only Mercury's orbit is tilted strongly, and even that is inclined by only 7° to Earth's orbit. Thus, the planets lie in a disk (figure 23.4) that is flatter than that of a U.S. twenty-five-cent piece.

Apart from their orbital regularities, the planets also show a regularity of composition and size. The four planets nearest the Sun (Mercury, Venus, Earth, and Mars) are basically balls of rock. That is, they are composed mainly of silicates surrounding an iron core.

The next four planets out from the Sun (Jupiter, Saturn, Uranus, and Neptune) are composed mainly of hydrogen gas and its compounds, such as ordinary water (H_2O), methane (CH_4), and ammonia (NH_3). These gases form thick atmospheres that cloak their liquid interior. In fact, they have no solid surface at all. Moreover, they dwarf the inner planets. For example, Jupiter, the largest of the four, has 300 times the mass of Earth and ten times its diameter. The many differences between the planets nearest the Sun and those farther out have led astronomers to put them in two categories: the **inner planets** (because they lie close to the Sun) and the **outer planets.** The inner planets are also sometimes called terrestrial planets because of their similarity to Earth. Similarly, the four big, outer planets are

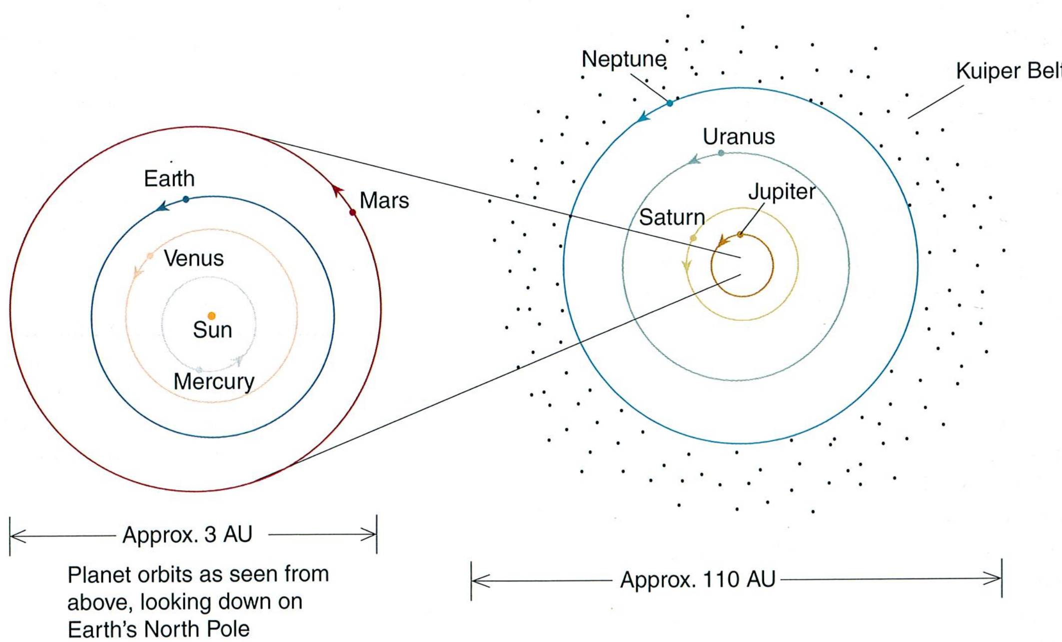


FIGURE 23.3
An artist's view of the solar system from above. The orbits are shown at the correct relative scale in the two drawings. Note: 1 AU is the average Earth-Sun distance.

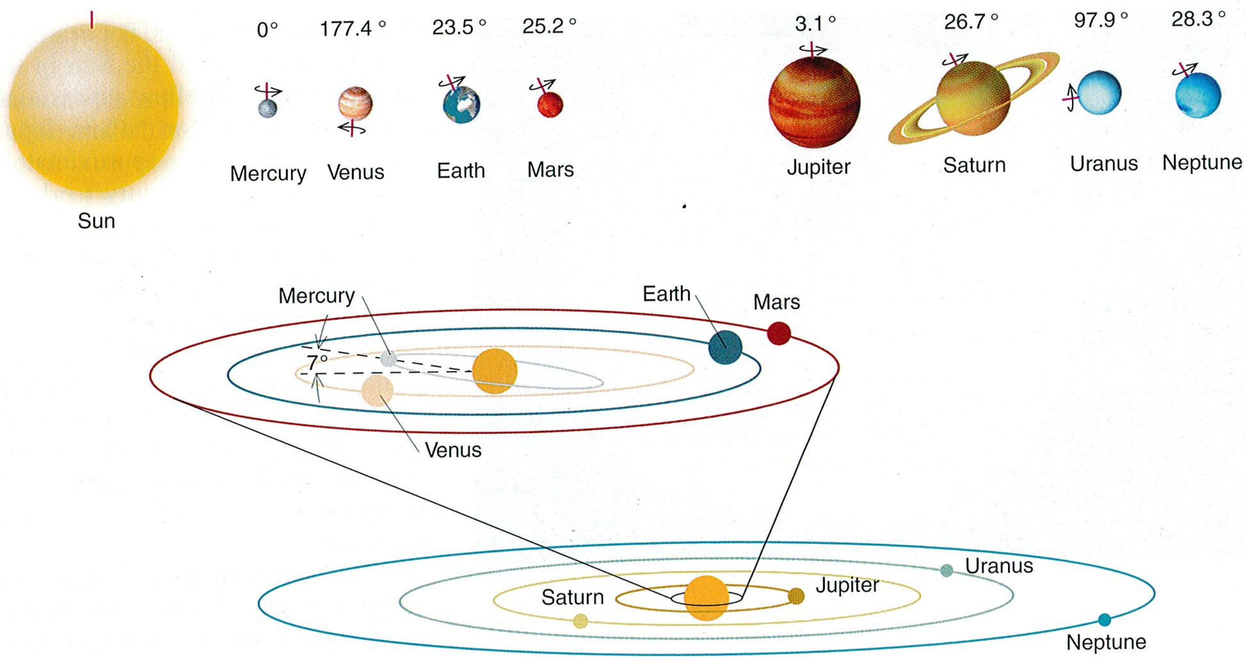


FIGURE 23.4
Planets and their orbits from the side. Sketches also show the orientation of the rotation axes of the planets and Sun. Orbits and bodies are not to the same scale. (Technically, Venus's tilt angle is about 177°, but it can also be described as 3° [180°−177°], with a "backwards," or retrograde spin.)

sometimes called the Jovian planets because of their similarity to Jupiter. They are also often referred to as gas giants. Their gaseous nature means they lack surface features such as we see on the inner planets. Their moons, on the other hand, have many extremely curious surface features, some of which are as yet not well understood. Figure 23.5 shows cutaway views of the eight planets and illustrates their structural differences.

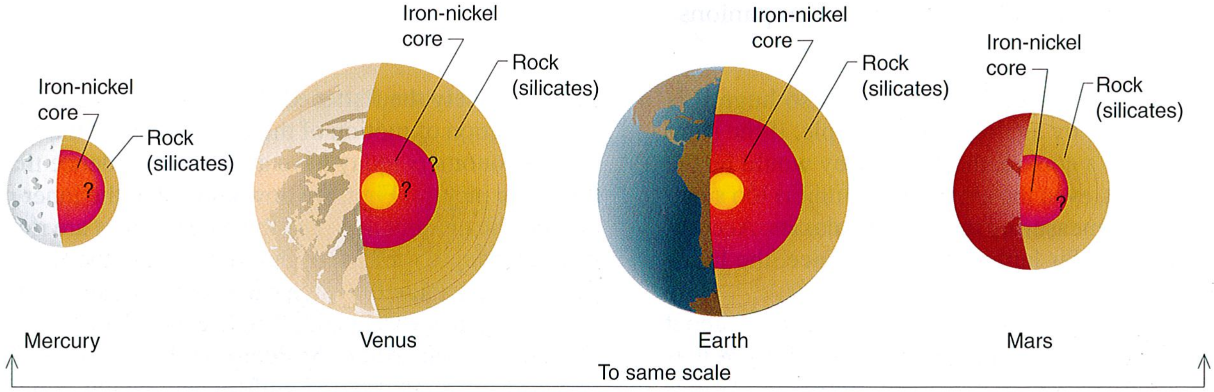
The inner planets and outer planets are separated by the asteroid belt, a region occupied by thousands of rocky bodies. Beyond the outer planets lies a region referred to as the trans-Neptunian region. It contains the Kuiper Belt, a ring of debris similar to the asteroid belt but composed mainly of ice, and the Oort cloud, a remote frigid zone named in honor of the Dutch astronomer Jan Oort, who hypothesized its existence.

The smaller objects in the solar system—the asteroids, the Kuiper Belt objects (KBOs), and the comets—form three very different families. **Asteroids** are rocky or metallic objects, while the KBOs and **comets** are icy objects. Most asteroids orbit between Mars and Jupiter, in the asteroid belt. Comets come from two sources. Some are from the Kuiper Belt, a region that extends from a little past Neptune's orbit to well beyond Pluto's. Most comets, however, come from the Oort cloud over a thousand times farther from the Sun than Pluto (figure 23.6). Comets are far too dim for us to see them while they are in the Oort cloud, and they become visible only if they move into the inner solar system. You might wonder how astronomers know the composition of these distant objects. One of the most powerful ways to learn that information is from analysis of the sunlight reflected from their surface or atmosphere. When light passes through a gas or reflects from a surface, atoms there absorb some of the colors. The missing colors may then be matched against laboratory samples to give information about what kinds of atoms are present. Yet another way to infer a planet's composition is to measure its density. You may recall from chapter 2 that an object's density is its mass divided by its volume. We saw there that density is an important clue to the identity of minerals. Similarly, astronomers can use density to deduce a planet's composition and structure. In the case of Venus, Mars, and Jupiter, we have additional confirmation from space probes that have penetrated their atmospheres or landed on their surface.

Our knowledge of the solar system would be more complete if the planets were not so remote. For example, Neptune's orbit lies about 4.5 billion kilometers (2.8 billion miles) from the Sun. To measure such a vast distance in miles or kilometers is as meaningless as to measure the distance between New York and Tokyo in inches. Thus, astronomers use a much larger unit based on the Earth's average distance from the Sun. That distance, about 150 million kilometers, we call the **astronomical unit** (AU). The solar system out to Neptune has a diameter of about 60 AU. If we include the Oort cloud at the fringes of the solar system, where the comets generally orbit, the system is approximately 100,000 AU across (figure 23.6).

The Milky Way and the Universe

Just as the Earth is but one of many planets orbiting the Sun, so too is the Sun but one of a vast swarm of stars orbiting within our galaxy, the **Milky Way.** Astronomers estimate that the Milky Way contains some 100 billion stars spread throughout



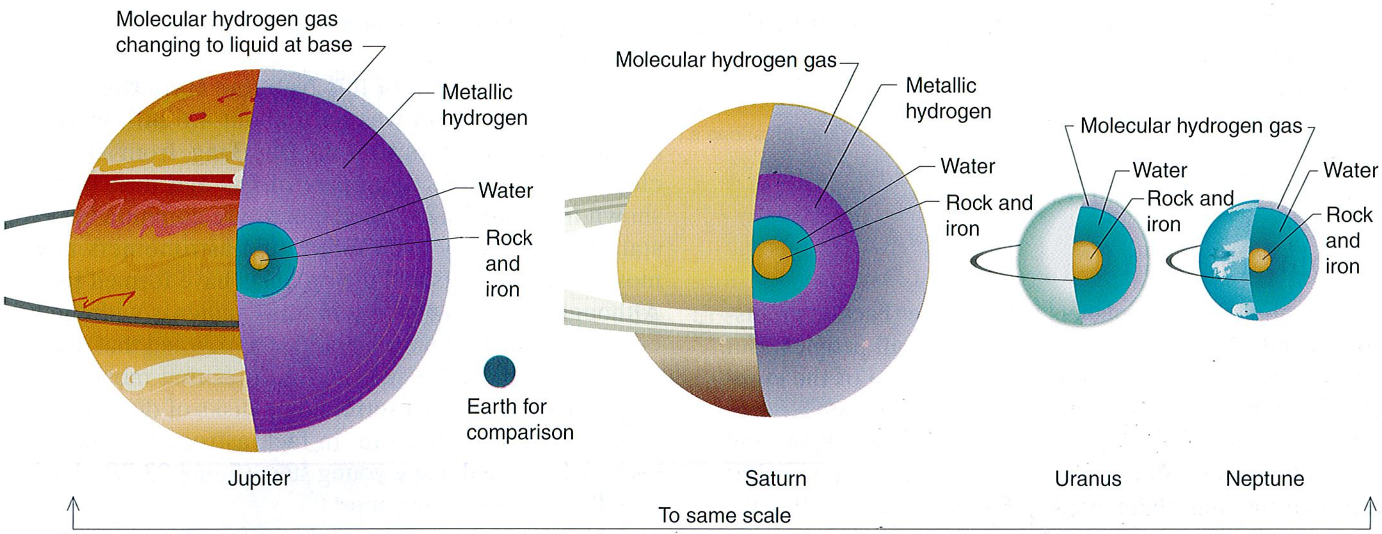


FIGURE 23.5

Sketches of the interiors of the planets. Details of sizes and composition of inner regions are uncertain for many of the planets.

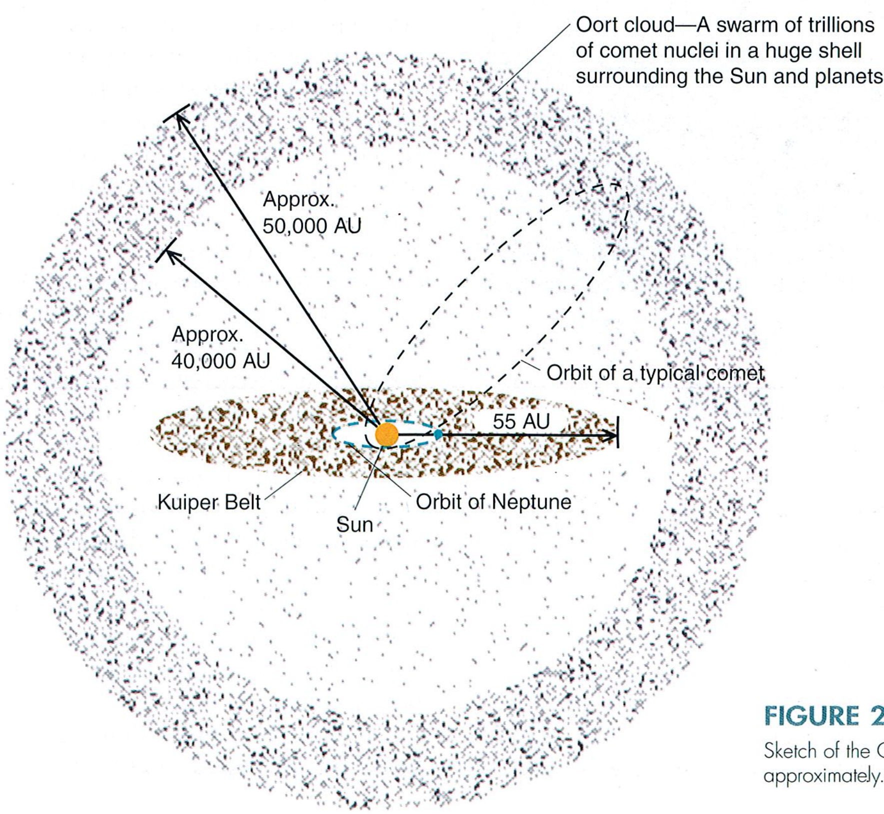


FIGURE 23.6

Sketch of the Oort cloud and the Kuiper Belt. The dimensions shown are known only approximately. Orbits and bodies are not to scale.

a roughly disk-shaped volume. That volume is so huge it is difficult to imagine, even by analogy. For example, if the solar system were the size of a cookie, the Milky Way would be the size of the Earth. In fact, even the astronomical unit is too small to be a sensible unit for measuring the size of galaxies. Accordingly, astronomers use a far larger unit of distance, the light-year, to measure such sizes.

One light-year is the distance light travels in a year—about 10 trillion kilometers. In these immense units, the Milky Way is roughly 100,000 light-years in diameter. But the Milky Way is just one among myriads of other galaxies. Together, these galaxies with all their stars and planets form the visible **universe.** The universe is believed to have formed 13.75 billion years ago during the Big Bang.

ORIGIN OF THE PLANETS

The Solar Nebula

Speculation about how the planets formed dates back to prehistoric times and the creation myths of virtually all peoples. But among the first scientific hypotheses were those of the eighteenth century by Immanuel Kant, a German philosopher, and Pierre Simon Laplace, a French mathematician. Kant and Laplace independently proposed that the solar system originated from a rotating, flattened disk of gas and dust called the **solar nebula.** In this model, the outer part of the disk became the planets, and the center became the Sun. This simple picture explains nicely the flattened shape of the system and the common direction of motion of the planets around the Sun.

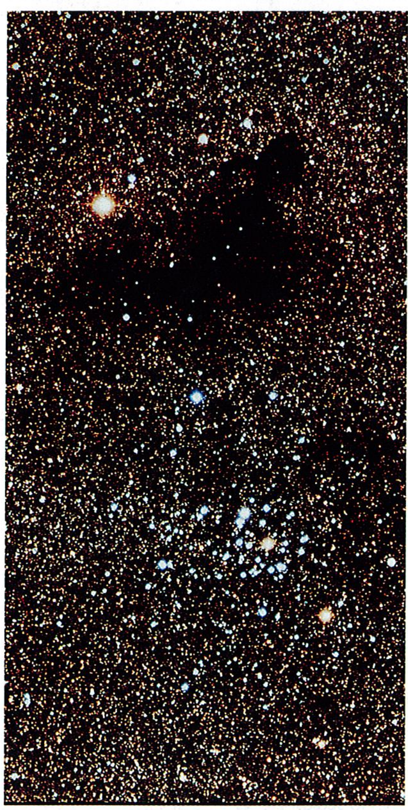
Astronomers today have additional evidence that supports this basic picture. First, we now know that the inner planets are rich in silicates and iron, and the outer planets are rich in hydrogen. Second, to the best of our knowledge, the Earth, Sun, and Moon are all about the same age—about 4.6 billion years old—suggesting they formed in a single event. Third, the surfaces of objects like our Moon, Mercury, and the moons of the outer planets are heavily scarred with ancient craters, suggesting that they were bombarded with infalling objects in the distant past. With this evidence, we can now discuss how astronomers think the planets were born.

The modern form of this **Nebular Hypothesis** proposes that our solar system was born about 4.6 billion years ago, roughly 9 billion years after the Big Bang, from an interstellar cloud, an enormous aggregate of gas and dust like the one shown in figure 23.7*A*. Such clouds are common between the stars in our galaxy even today, and astronomers now think most, if not all, stars and their planets have formed from them. Although our main concern in this chapter is with the birth of our own solar system, we should bear in mind that our hypothesis applies more broadly and implies that most stars could have planets or at least surrounding disks of dust and gas from which planets might form. In fact, astronomers observe just such disks around many young stars (figure 23.7*B*), lending the hypothesis additional support.

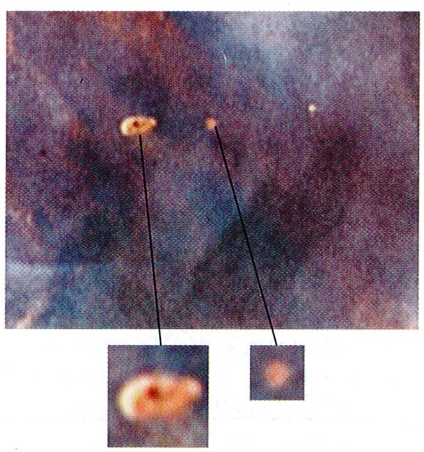
Although interstellar clouds are found in many shapes and sizes, the one that became the Sun and its planets was probably a few light-years in diameter and was made mostly of hydrogen (71%) and helium (27%) gas, with tiny traces of other chemical elements. In addition to gas, the cloud also contained microscopic dust particles. From analysis of the radiation absorbed and emitted by such dust particles, astronomers know they are made of a mixture of silicates, iron compounds, carbon compounds, and water frozen into ice.

The cloud that became our solar system began its transformation into the Sun and planets when the gravitational attraction between the particles in the cloud caused it to collapse inward, as shown in figure 23.8*A*. The collapse may have been triggered by a star exploding nearby or by a collision with another cloud. But because the cloud was rotating, it flattened, as shown in figure 23.8*B*. Flattening occurred because rotation retarded the collapse perpendicular to the cloud's rotation axis.

It probably took a few million years for the cloud to collapse and



A



B

FIGURE 23.7

(*A*) Photograph of an interstellar cloud (the dark region at top) that may be similar to the one from which the solar system formed. This dark cloud is known as Barnard 86. The star cluster is NGC 6520. (*B*) The small blobs in this picture are protostars and their surrounding disk of dust and gas. They are in the Orion Nebula, a huge cloud of gas and dust about 1,500 light-years from Earth. *Photo A by David Malin, courtesy of Anglo-Australian Telescope Board; photo B courtesy of Space Telescope Science Institute*

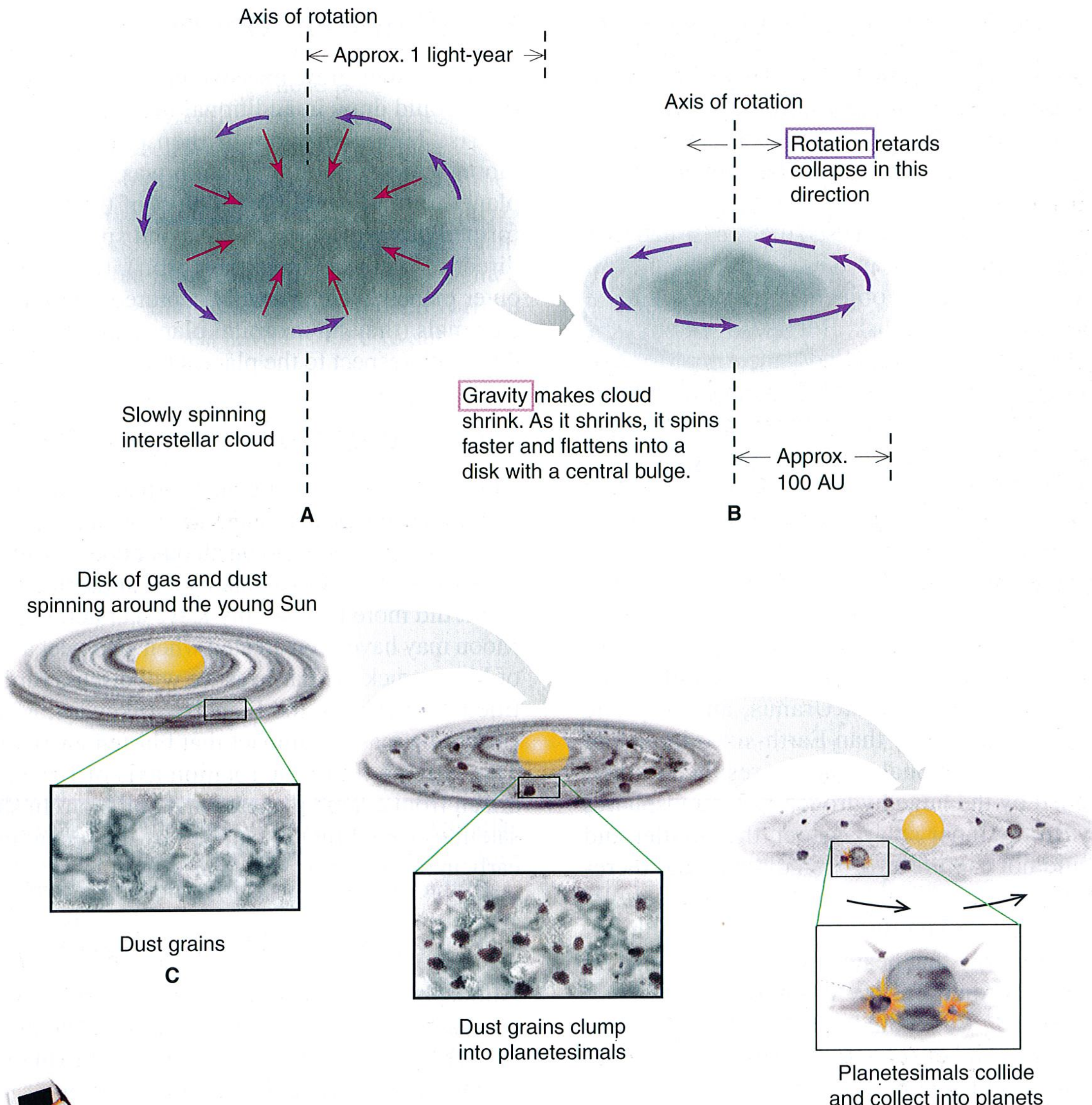


FIGURE 23.8
Sketch illustrating the (*A*) collapse of an interstellar cloud and (*B*) its flattening. (*C*) Artist's depiction of the condensation of dust grains in the solar nebula and the formation of planetesimals.

form a rotating disk with a bulge in the center that became the Sun. Over a few more million years, dust particles in the disk began to stick together, perhaps helped by static electric forces such as those that make lint cling to clothes in a dryer. As the particles slowly grew in size, they were more likely to collide with other particles, hastening their growth. But the composition of these particles depended strongly on where in the disk they formed. In the inner part of the disk (where the particles were near the Sun), it was too warm for water-ice to condense. Solid particles there were thus composed almost entirely of silicate and iron-rich material. Only at about Jupiter's distance from the Sun was the disk cold enough for water-ice to condense on the particles. Thus, particles in those outer regions consisted of silicate and iron-rich material *plus* frozen water. Although water molecules were relatively abundant throughout the cloud, they could only freeze onto particles in the outer disk. As a result, those particles grew much larger than the particles in the inner disk. Thus, the nebula became divided into two regions: an inner zone of silicate and iron particles, and an outer zone of similar particles onto which ice also condensed.

Within each zone, the growing particles began to collide as they orbited in the disk. If the collisions were not too violent, the particles would stick (much as gently squeezing two snowballs together fuses them). By such processes, smaller particles grew steadily in size until they were kilometers across, as illustrated schematically in figure 23.8*C*. These larger objects are called **planetesimals** (that is, small, planetlike bodies). Because the planetesimals near the Sun formed from silicate and iron particles, while those farther out were cold enough that they could incorporate ice and frozen gases, two main types of planetesimals developed: rocky-iron ones near the Sun and icy-rocky-iron ones farther out.

Formation of the Planets

As time passed, the planetesimals themselves began to collide. Computer simulations show that some collisions led to the shattering of both bodies, but less-violent collisions led to merging, with the planetary orbits gradually becoming approximately circular.

Merging of the planetesimals increased their mass and thus their gravitational attraction. That, in turn, helped them grow even more massive. At this stage, objects large enough to be called planets were orbiting in the disk. But because there were two types of planetesimals (rocky and icy) according to their location in the inner or outer disk, two types of planets formed.

Planet growth was especially rapid in the outer parts of the solar nebula. Planetesimals there had more material from which to grow because ice was about ten times more abundant than silicate and iron compounds. Additionally, once a planet grew somewhat larger than the diameter and mass of the Earth, it was able to attract and retain gas by its own gravity. Because hydrogen was overwhelmingly the most abundant material in the solar nebula, planets large enough to tap that reservoir could grow vastly larger than those that formed only from solid material. Thus, Jupiter, Saturn, Uranus, and Neptune may have begun as slightly larger than Earth-sized bodies of ice and rock, but their gravitational attraction resulted in their becoming surrounded by the huge hydrogen-rich atmospheres that we see today. In the inner solar system, the smaller and warmer bodies could not capture hydrogen directly and therefore remained small.

As planetesimals struck the growing planets, their impact released gravitational energy that heated both the planetesimal and the planet. Gravitational energy is liberated whenever something falls. For example, if you drop a bowling ball into a box of tennis balls, the impact scatters the tennis balls in all directions, giving them kinetic energy—energy of motion. In much the same manner, planetesimals falling onto a planet's surface give energy to the atoms in the crustal layers, energy that appears as heating. You can easily demonstrate that motion can generate heat by hitting an iron nail a dozen or so times with a hammer and then carefully touching the nail: the metal will feel distinctly hot. Imagine now the vastly greater heating resulting from mountain-sized masses of rock plummeting onto a planet at velocities of tens of kilometers per second. The heat so liberated, in combination with radioactive heating (as occurs even today within the Earth), partially or completely melted the planets and allowed matter with high density (such as iron) to sink to their cores, while matter with lower density (such as silicate rock) "floated" to their surfaces, a process known as planetary **differentiation.** The Earth's iron core probably formed by this process, and astronomers believe that the other terrestrial planets formed iron cores and rocky crusts and mantles in much the same way. A similar process probably occurred for the outer planets when rock and iron material sank to their cores. Heat left over from this planetary formation process, along with radioactive decay, drives the Earth's internal heat engine.

Formation of Moons

Once a planet grew massive enough so that its gravitational force could draw in additional material, it became ringed with debris. This debris could then collect into lumps to form moons. Thus, moon formation was a scaled-down version of planet formation. Although most of the large moons probably formed this way (they revolve and spin in the same plane and direction as the planets they orbit), the smaller moons of the outer planets were probably captured asteroids and small planetesimals (they have orbital planes and directions that are random with respect to the planets they orbit).

Final Stages of Planet Formation

During the last stage of planet formation, leftover planetesimals bombarded the planets and blasted out huge craters such as those we see on the Moon and on all other bodies with solid surfaces in the solar system. Occasionally, an impacting body was so large that it did more than simply leave a crater. For example, Earth's Moon may have been created when an object a few times the size of Mars struck the Earth, as we will discuss further in the section titled "Portraits of the Planets." Likewise, Mercury may have suffered a massive impact that blasted away much of its crust. The extreme tilt of the rotation axis of Uranus may also have arisen from a large planetesimal collision. In short, planets and satellites were brutally battered by the remaining planetesimals early in the history of our solar system.

Formation of Atmospheres

Atmosphere formation was the last part of the planet-forming process. The inner and outer planets are thought to have formed atmospheres differently, a concept that explains their very different atmospheric compositions. The outer planets probably captured most of their atmospheres directly from the solar nebula, as mentioned in the "Formation of the Planets" section. Because the nebula was rich in hydrogen and helium, so are the atmospheres of the outer planets.

The inner planets were not massive enough and were too hot to capture gas directly from the solar nebula and are therefore deficient in hydrogen and helium. The atmospheres of Venus, Earth, and Mars probably formed by a combination of processes: volcanic eruptions releasing gases from their interiors; vaporization of comets and icy planetesimals that have struck them; and gases freed from within the planetesimals out of which the planets themselves formed. Objects such as Mercury and the Moon, which have only traces of atmosphere, show few signs of volcanic activity within the last few billion years. Moreover, these smaller bodies have such weak gravity that any atmospheric gases they originally possessed escaped easily from them.

Other Planetary Systems

This theory for the origin of the solar system explains many of its features, but astronomers still have many questions about the

Sun and its family of planets and moons. Answers to some of these questions are beginning to emerge from the discovery of planets around dozens of other stars. These planets are typically far too dim to be seen directly with present telescopes, although one has recently been imaged directly (figure 23.9). Rather, they are detected by the slight gravitational tug they exert on their parent stars. That tug can be detected by analyzing the light from such stars. Over 200 of these *extrasolar* planets have been detected so far. Such observations have delighted astronomers by confirming that planets have indeed formed around other stars. However, they have also led to surprises. For example, many of these systems have huge, Jupiter-like planets very close to their parent stars. One hypothesis for this puzzling observation is that the planets formed farther out and "migrated" inward toward the star. Such shifts in orbits may also have happened in our solar system. For example, many astronomers think that Neptune has migrated outward from an original orbit that was nearer the Sun. Thus, although we know that our solar system is not unique, we have yet to fully understand its properties and origin.

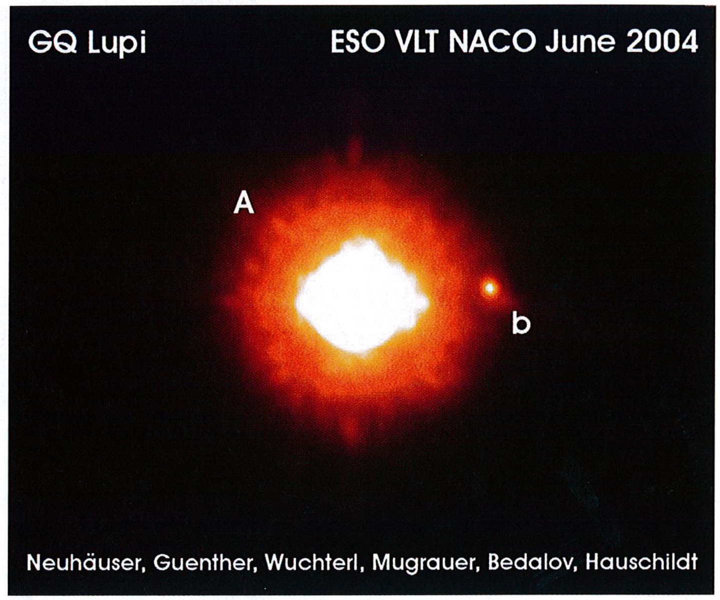


FIGURE 23.9
First confirmed image of a planet (labeled *b* in the image) orbiting a star (GQ Lupi) other than the Sun. *Image courtesy ESO/VLT*

PORTRAITS OF THE PLANETS

What is the nature of these planets whose birth we have discussed? In this section, we will work our way through our solar system, describing each of the terrestrial planets in turn. Table 23.1 summarizes the physical properties, such as size and mass, of the eight planets and our Moon. Table 23.2 summarizes their orbital properties. The four large gas giant planets (Jupiter, Saturn, Uranus, and Neptune) have no solid surfaces to describe geologically. However, the surfaces of their rocky and icy moons will be discussed in turn. Before we consider planets far from Earth, however, it will help us to look at the only object beyond Earth that has been visited by humans, and from which rock samples have been returned and studied—our Moon.

Our Moon

The Moon is our nearest neighbor in space, a natural satellite orbiting the Earth. It is the frontier of direct human exploration and of great interest to astronomers. Unlike Earth, it is essentially a dead world, with neither plate tectonic nor current volcanic activity. Although extensive volcanism occurred early in the Moon's geologic history, it was largely confined to lower elevations of the lunar *nearside* (the side that permanently faces toward the Earth). This localized volcanism, coupled with the Moon's lack of atmosphere, means that many of its surface features are virtually unaltered since its youth. Its surface thus

TABLE 23.1 Physical Properties of the Planets and Our Moon

Name	Radius (compared to Earth)	Radius (Equator) (km)	Mass (compared to Earth)	Mass (kg)	Average Density (g/cm^3)
Mercury	0.382	2,439	0.055	3.30×10^{23}	5.43
Venus	0.949	6,051	0.815	4.87×10^{24}	5.25
Earth	1.00	6,378	1.00	5.97×10^{24}	5.52
Our Moon	0.27	1,738	0.012	7.35×10^{22}	3.3
Mars	0.533	3,397	0.107	6.42×10^{23}	3.93
Jupiter	11.19	71,492	317.9	1.90×10^{27}	1.33
Saturn	9.46	60,268	95.18	5.68×10^{26}	0.69
Uranus	3.98	25,559	14.54	8.68×10^{25}	1.32
Neptune	3.81	24,764	17.13	1.02×10^{26}	1.64

TABLE 23.2 Orbital Properties of the Planets

Name	Distance from Sun*		Period		Orbital Inclination†	Orbital Eccentricity
	(AU)	(10^6 km)	Years	(Earth Days)	Degrees	
Mercury	0.387	57.9	0.2409	(87.97)	7.00	0.206
Venus	0.723	108.2	0.6152	(224.7)	3.39	0.007
Earth	1.00	149.6	1.0	(365.26)	0.00	0.017
Mars	1.524	227.9	1.8809	(686.98)	1.85	0.093
Jupiter	5.203	778.3	11.8622	(4,332.59)	1.31	0.048
Saturn	9.539	1,427.0	29.4577	(10,759.22)	2.49	0.056
Uranus	19.19	2,869.6	84.014	(30,685.4)	0.77	0.046
Neptune	30.06	4,496.6	164.793	(60,189)	1.77	0.010

*These values are half the long diameter of the orbit.
†With respect to the Earth's orbit.

bears a record of events in the early solar system that gives clues not only to the Moon's birth but to that of the solar system as well.

Origin and History

Lunar rocks brought back to Earth by the *Apollo* astronauts have led astronomers to radically revise their ideas of how the Moon formed. Before the *Apollo* program, lunar scientists had three hypotheses of the Moon's origin. In one, the Moon was originally a small planet orbiting the Sun that approached the Earth and was captured by its gravity (capture hypothesis). In another, the Moon and Earth were "twins," forming side by side from a common cloud of dust and gas (twin formation hypothesis). In the third, the Earth initially spun enormously faster than now and formed a bulge that ripped away from it to become the Moon (fission hypothesis).

The failure of evidence based on lunar surface samples to confirm any of the three hypotheses led astronomers to consider alternatives, and a completely different picture of the Moon's origin has emerged. According to the new hypothesis, the Moon formed from debris blasted out of the Earth by the impact of an object about the size of Mars, as shown in figure 23.10*A*. The great age of lunar rocks (returned samples have ages of up to 4.45 billion years) and the absence of any enormous impact feature on the Earth indicate that this event must have occurred during the Earth's own formation, at least 4.5 billion years ago. The colliding body melted and vaporized millions of cubic kilometers of the Earth's crust and mantle and hurled it into space in an incandescent plume. Although most of this debris would have rained back down on Earth, some of it remained in orbit and its gravity gradually drew it together into what we now see as the Moon.

After the Moon's birth, stray fragments of the ejected rock pelted its surface, creating the craters that blanket the highlands. A few huge fragments plummeting onto the Moon later in its formation process blasted enormous holes that later flooded with molten interior rock to become the maria. Since about 3.5 billion years ago, the Moon has experienced no major changes. It has been a virtually dead world for all but the earliest times in its history, experiencing only a much decreased rate of ongoing meteor impact events.

Description

General Features

The Moon is about one-fourth the diameter of the Earth and is a barren ball of rock possessing no air, water,[2] or life. In the words of lunar astronaut Buzz Aldrin, the Moon is a place of "magnificent desolation." But you don't have to walk on the Moon to see its desolation. Even to the naked eye, the Moon is a world of grays; yet even gray has its variety, as you can see where the dark, roughly circular areas stand out from the lighter background, as shown in figure 23.11.

Surface Features

Through a small telescope or even a pair of binoculars, you can see that the dark areas of the Moon are smooth while the bright areas are covered with numerous large, circular pits called *craters,* as illustrated in figure 23.12*A* and *B.* Craters usually have a raised rim and range in size from microscopic holes to gaping scars in the Moon's crust as much as 240 kilometers across. The larger craters have mountain peaks or peak rings at their center (figure 23.12*C*). Still larger lunar *impact basins* range up to

[2]Astronomers have found some evidence for extremely small amounts of water frozen in perpetually shadowed craters near the Moon's poles.

Orbital Eccentricity
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0.017
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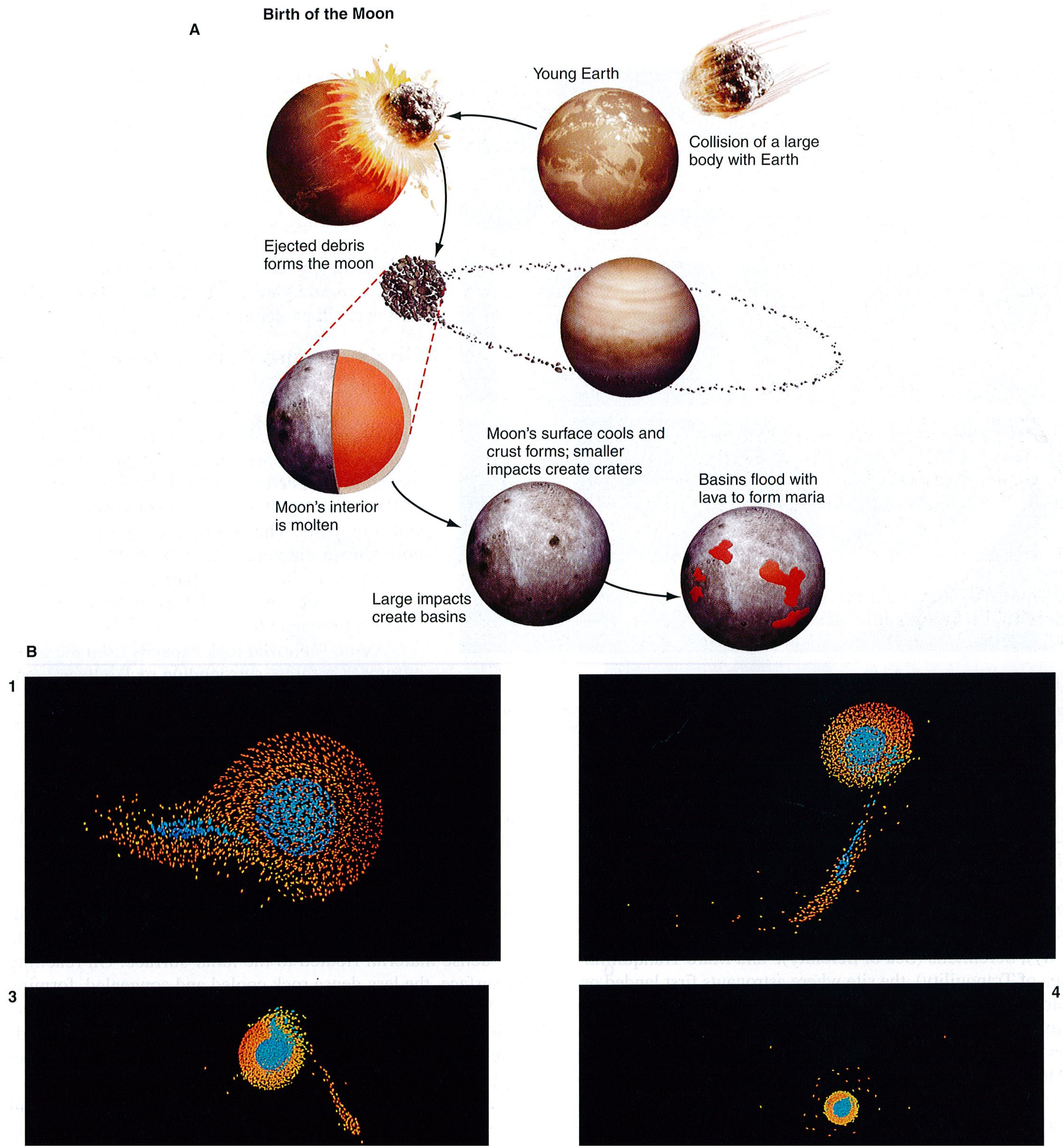


Pluto's orbit is peculiar. It crosses Neptune's, but because it is also more highly tilted than the orbits of the other planets, Pluto passes well above or below Neptune when the crossings occur. Its odd orbit in combination with its small mass once led some astronomers to hypothesize that Pluto was originally a satellite of Neptune that escaped and now orbits the Sun independently. Today, however, astronomers think almost the reverse—that Neptune has "captured" Pluto. The reason for this hypothesis is that Pluto's orbital period of 247.7 years is nearly exactly one-and-one-half times Neptune's. Thus, Pluto makes two orbits around the Sun for every three made by Neptune. This match of orbital periods gives Neptune's gravitational attraction on Pluto a cumulative effect that has probably "tugged" it into its current orbit. In fact, several dozen other icy KBOs, objects a few hundred kilometers to slightly larger than Pluto in diameter, have been found orbiting at nearly the same distance from the Sun as Pluto.

MINOR OBJECTS OF THE SOLAR SYSTEM

Orbiting the Sun and scattered throughout the solar system are numerous bodies much smaller than the planets—asteroids and comets. Asteroids are generally rocky objects in the inner solar system. Comets are icy bodies and spend most of their time in the outer solar system. These small members of the Sun's family, remnants from the formation of the solar system, are of great interest to planetary scientists and astronomers because they are our best source of information about how long ago and under what conditions the planets formed. In fact, many (if not most) asteroids and comets may be planetesimals—the solid bodies from which the planets were assembled—that have survived nearly unchanged from the birth of the solar system. Apart from their scientific value, asteroids and comets are fascinating objects both for their beauty and potential for danger to life on Earth.

Meteors and Meteorites

If you have spent even an hour looking at the night sky in a dark location away from city lights, you have probably seen a "shooting star," a streak of light that appears in a fraction of a second and as quickly fades. Astronomers call this brief but lovely phenomenon a **meteor.**

A meteor is the glowing trail of hot gas and vaporized debris left by a solid object heated by friction as it moves through the Earth's atmosphere. The solid body itself, while in space and before it reaches the atmosphere, is called a *meteoroid.*

Heating of Meteors

Meteors heat up on entering the atmosphere for the same reason a reentering spacecraft does. When an object plunges from space into the upper layers of our atmosphere, it collides with atmospheric molecules and atoms at an initial velocity of 10 to 70 kilometers per second. These collisions convert some of the body's energy of motion (kinetic energy) into heat and vaporize matter from its surface. Most of the heating occurs between about 100 and 50 kilometers altitude, in the outer fringes of the atmosphere. The trail of hot evaporated matter and atmospheric gas emits light, making the glow that we see.

Most meteors that we see last only a few seconds and are made by meteoroids the size of a pea or smaller. These tiny objects are heated so strongly that they completely vaporize. Larger pieces, though heated and partially vaporized, are so drastically slowed by air resistance that they may survive the ordeal and reach the ground. We call these fragments found on the Earth **meteorites.**

Meteorites

Meteorites are divided into three broad categories: stony (composed mainly of silicate minerals), iron (composed mainly of metallic iron-nickel), and stony iron (a mixture of both metaltic and silicate material). Ninety-four percent of all meteorites that fall on Earth are stony and of these, 86% are classed as chondrites, named for the small rounded particles known as chondrules that they contain (figure 23.34). Chondrules appear to have originated as molten droplets formed by rapid melting and cooling. Where this may have occurred is not known.

Chondrules contain traces of radioactive material, which can be used to measure their age. They are extremely old, 4.56 billion years, and are believed to be among the first solids to have formed in the solar nebula.

Some chondritic meteorites contain small amounts of organic compounds such as amino acids and kerogen and are called carbonaceous chondrites. Amino acids are the same complex molecules used by living things for the construction of their proteins and genetic material. Thus, the presence of

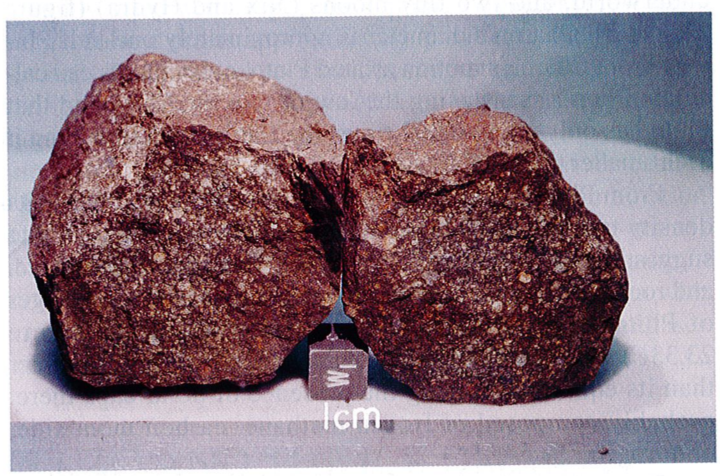


FIGURE 23.34

A chondrite meteorite. Note the many circular chondrules of which it is composed. Such meteorites are made primarily of dust to sand-sized grains of silicate minerals. *Photo by NASA/JPL* amino acids in meteoritic matter indicates that the raw material of life can form in space and that it is likely to have been available right from the start within the solar system. It is believed that most meteors are fragments of asteroids.

Asteroids

Asteroids are small, generally rocky bodies that orbit the Sun. Most lie in the asteroid belt, a region between the orbits of Mars and Jupiter. Asteroids range tremendously in diameter, from Ceres—about 930 kilometers (about the size of Texas) across—down to bodies only a few meters in diameter. Most are irregularly shaped (figure 23.35). Only Ceres and a few dozen other large asteroids are approximately spherical. Because of their large size, their gravitational force is strong enough to compact their material into a sphere. Small bodies with weak gravities remain irregular and are made more so by collisions blasting away pieces. Collisions leave the parent body pitted and irregularly shaped, and the fragments become smaller asteroids in their own right.

Origin of Asteroids

The properties of asteroids that we have discussed (composition, size, and their location between Mars and Jupiter) give us clues to their origin and support the solar nebula hypothesis for the origin of the solar system. In fact, the asteroids are probably fragments of planetesimals, the bodies from which the planets were built. Although science-fiction movies and TV shows like to show the asteroids as a dense swarm, they are actually very widely separated—typically, thousands of kilometers apart. The ones we see today failed to be incorporated into a planet, probably as the result of their nearness to Jupiter, whose immense gravity disturbed their paths sufficiently to keep them from aggregating into a planet.

Farther from the main belt are the Apollo asteroids, whose orbits carry them into the inner solar system across the Earth's orbit. Although there are about 1,000 such Earth-crossing asteroids, larger than one kilometer in diameter, the chance of collision in the near future is slim. Nevertheless, on the average, one such body hits the Earth about every 10,000 years.

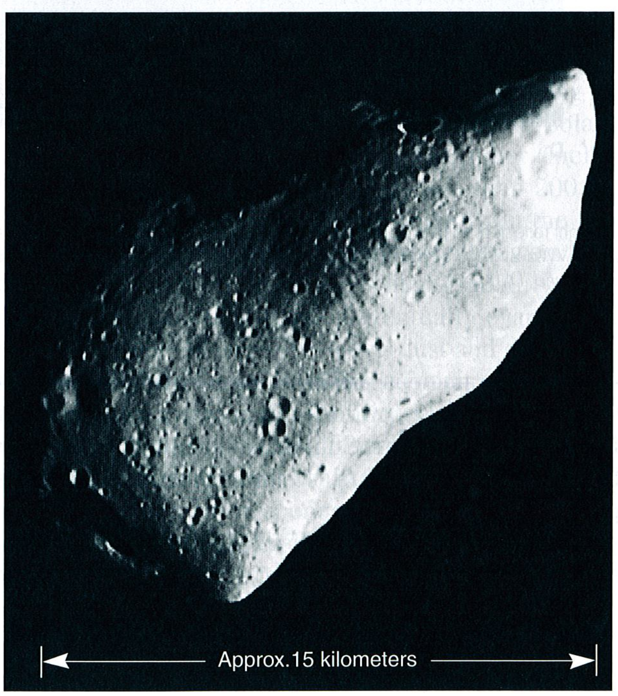


FIGURE 23.35
The asteroid Gaspra, as imaged by the *Galileo* spacecraft. *Photo by NASA/JPL*

Comets

A bright comet is a stunning sight, as you can see in figure 23.36*A*. But such sights are now sadly rare for most people because light pollution from our cities drowns the view. Comets have long been held in fear and reverence, and their sudden appearance and equally sudden disappearance after a few days or so have added to their mystery.

Structure of Comets

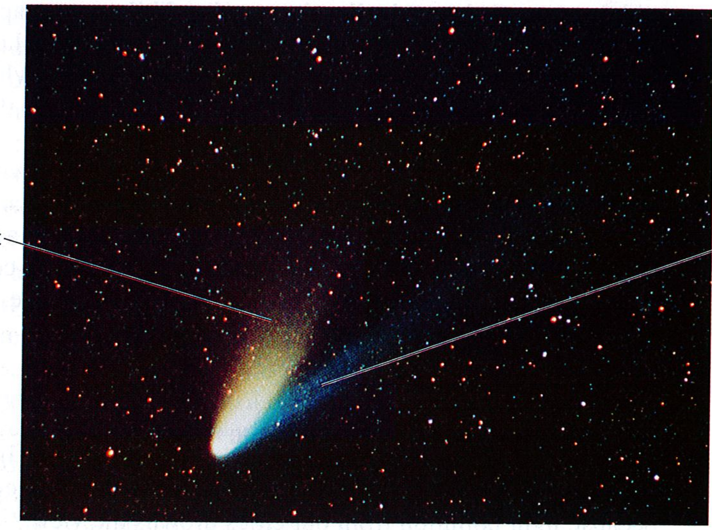
Comets consist of two main parts, as illustrated in figure 23.36*B*. The largest part is the long tail, a narrow column of dust and gas that may stretch across the inner solar system for as much as 100 million kilometers (nearly an AU!).

The tail emerges from a cloud of gas called the *coma,* which may be some 100,000 kilometers in diameter (more than ten times or so the size of the Earth). Despite the great volume of the coma and the tail, these parts of the comet contain very little mass. The gas and dust are extremely tenuous, and so a cubic centimeter of the gas contains only a few thousand atoms and molecules. By terrestrial standards, this would be considered a superb vacuum. This extremely rarified gas is matter that the Sun's heat has sublimated off the icy heart of the comet, its nucleus.

The comet nucleus is a block of ices and dust that have frozen in the extreme cold of the outer solar system into an irregular mass averaging perhaps a bit less than 10 kilometers in diameter. The nucleus of a comet (figure 23.36*C*) has been described as a giant "iceberg" or "dirty snowball," and it contains most of the comet's mass. Our best information about the nucleus comes from studies of Comets Halley, Borelly, Wild-2, and Tempel-1 (figure 23.36*D*) made by the *Giotto, Deep Space-1, Stardust,* and *Deep Impact* spacecraft, respectively. All four comets appear to have densities well under 1 gram per cubic centimeter, a value implying that the icy material of the nucleus is "fluffy," like snow, not hard and compacted like pure ice.

Origin of Comets

Astronomers think that most comets come from the Oort cloud, the swarm of trillions of icy bodies believed to lie far beyond the Kuiper Belt orbit of Pluto, as we discussed in the section titled "The Solar System." Astronomers think the Oort cloud formed from planetesimals that originally orbited near the giant



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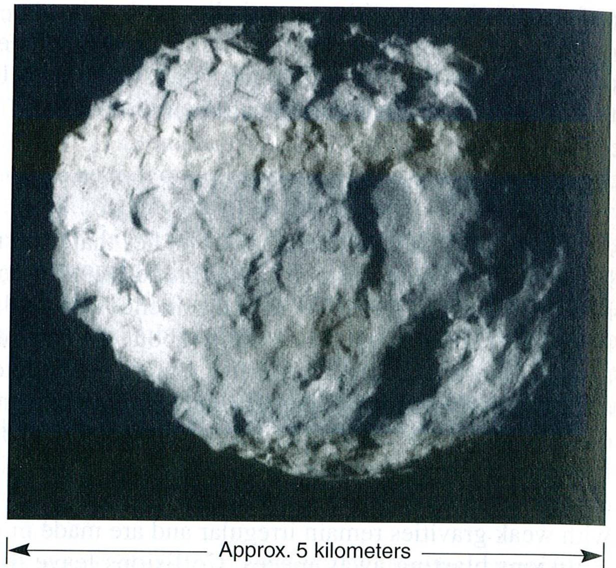

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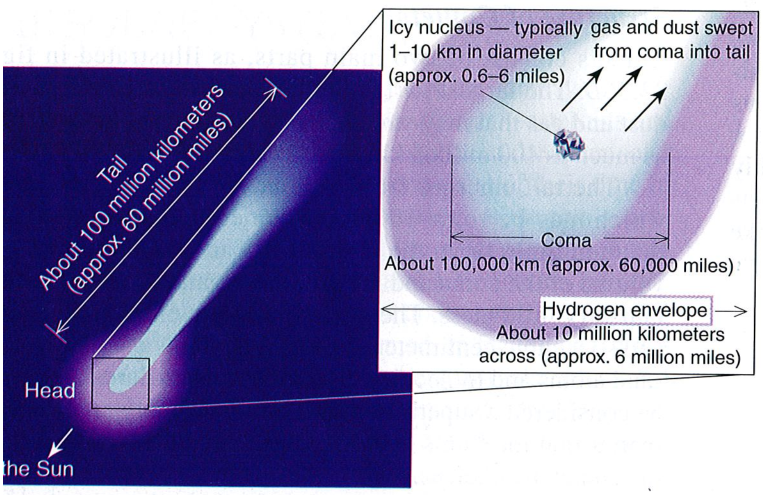

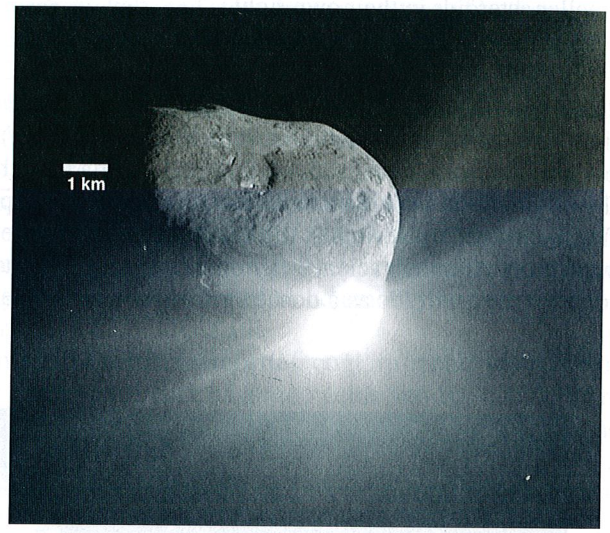

D

URE 23.36

notograph of Comet Hale-Bopp in the evening sky. Note the blue tail (gas) and the whitish tail (sunlight reflected from tiny dust particles). (B) Artist's depiction of the structure of a t showing the tiny nucleus, surrounding coma, and the long tail. (C) Image of the nucleus of comet Wild-2. (D) Nucleus of Comet Tempel-1, just after the artificially produced ct designed to eject gas and dust for scientific study. *Photo (A) courtesy of Mike Skrutskie; Photos (C) and (D) by NASA/JPL*

ets and were tossed into the outer parts of the solar system he gravitational force of those planets. Some comets also n to come from the Kuiper Belt, which begins near the orbit eptune and appears to extend to about 55 AU from the Sun. netary astronomers are greatly interested in this region use it appears to be the birthplace of Pluto, Charon, and tune's moon Triton.

Each comet nucleus moves along its own path, and those in the Oort cloud take millions of years to complete an orbit. With orbits so far from the Sun, these icy bodies receive essentially no heat from the Sun, so their gases and ices remain deeply frozen.

These distant objects are invisible to us on Earth, but sometimes a comet's orbit changes, carrying it closer to us and the

Sun. Such orbital changes may arise from the chance passage of a star far beyond the outskirts of the solar system during its orbit around the center of the Milky Way galaxy.

As the comet falls inward toward the inner solar system, the Sun's radiation heats it and begins to sublimate the ices. At a distance of about 5 AU from the Sun (Jupiter's orbit), the heat is enough to vaporize the ices, forming gas that escapes to make a coma around the comet nucleus. The escaping gas carries tiny dust grains that were frozen into the nucleus with it. The comet then appears through a telescope as a dim, fuzzy ball. As the comet falls ever nearer the Sun, its gas escapes even faster, but now the Sun begins to exert additional forces on the cometary gas and dust.

Formation of the Comet's Tail

Sunlight striking dust grains imparts a tiny force to them, a process known as radiation pressure. We don't feel radiation pressure when sunlight falls on us because the force is tiny and the human body is far too massive to be shoved around by sunlight. However, the microscopic dust grains in the comet's coma do respond to radiation pressure and are pushed away from the Sun.

The tail pushed out by radiation pressure is made of dust particles, but figure 23.36*A* shows that comets often have a second tail. That tail is created by the outflow of the solar wind.

The solar wind blows away from the Sun at about 400 kilometers per second. It is very tenuous, containing only a few atoms per cubic centimeter. But the material in the comet's coma is tenuous, too, and the solar wind is dense enough by comparison to blow it into a long plume. Thus, two forces, radiation pressure and the solar wind, act on the comet to drive out a tail. Because those forces are directed away from the Sun, the comet's tail always points more or less away from the Sun.

Although most comets that we see from Earth swing by the Sun on orbits that will bring them back to the inner solar system only after millions of years, a small number (including Halley's) reappear at time intervals of less than 200 years. Astronomers think that these objects come from the Kuiper Belt. They may also be responsible for meteor showers because as they repeatedly orbit the Sun, its heat gradually whittles them away: all the ices and gases eventually evaporate, and only the small amount of solid matter, dust and grit, remains. This fate is like that of a snowball made from snow scooped up alongside the road, where small amounts of gravel have been packed into it. If such a snowball is brought indoors, it melts and evaporates, leaving behind only the grit accidentally incorporated in it. So, too, the evaporated comet leaves behind in its orbit grit that continues to circle the Sun. The material left by the comet produces a delightful benefit: it is a source of meteor showers. Meteor showers tend to recur at the same time each year, as the Earth passes through cometary dust trails crossing its orbit.

GIANT IMPACTS

Every few thousand years, the Earth is hit by a huge meteoroid, a body tens of meters or more in size. A large meteoroid will produce not only a spectacular glare as it passes through the atmosphere but also an enormous blast on impact. The violence of such events arises because a meteoroid has a very large kinetic energy, that is, energy of motion, which is released when it hits the ground or when it breaks up in the atmosphere.

The energy so released can be huge. A body 20 meters in diameter, about the size of a small house, would have on impact the explosive power of a thermonuclear bomb and make a crater about one-half kilometer in diameter. Were such a body to hit a heavily populated area, it would obviously have catastrophic results.

Giant Meteor Impacts

One of the most famous meteor impacts was the event that formed the giant crater in northern Arizona. About 50,000 years ago, a meteoroid estimated to have been some 50 meters in diameter hit the Earth about 40 miles east of what is now Flagstaff. Its impact vaporized tons of rock, which expanded and peeled back the ground, creating a crater about 1.2 kilometers across and 200 meters deep (see box 7.1 figure 1 in chapter 7).

More recently, in 1908, a small comet or asteroid broke up in our atmosphere over a largely uninhabited part of north-central Siberia. This so-called *Tunguska event,* named for the region where it hit, leveled trees radially outward from the blast point to a distance of some 30 kilometers. The blast was preceded by a brilliant fireball in the sky and was followed by clouds of dust that rose to the upper atmosphere. Casualties were few because the area was so remote.

Not all impacts have so few casualties, however. In the distant past, about 65 million years ago, at the end of the Cretaceous period, an asteroid hit the Earth. Its impact and the subsequent disruption of the atmosphere are blamed for exterminating the dinosaurs and many less conspicuous but widespread creatures and plants (see box 8.2).

Other mass extinctions have occurred earlier and later than the Cretaceous event. These may have resulted from similar impact events, but many scientists believe that massive volcanic eruptions or drastic changes in sea level may have played a role as well. Thus, like so many of the most interesting issues in science, this story has no definitive explanation at this time.

Summary

ıe Earth is just one of eight planets orbiting our Sun. The anets closest to the Sun (the inner planets—Mercury, ənus, Earth, and Mars) are rocky and are similar in size. They ffer greatly from the outer planets (Jupiter, Saturn, Uranus, ıd Neptune). Pluto is small and icy and is now considered a *varf planet,* along with Ceres and the largest Kuiper Belt ıjects. Smaller objects—asteroids and comets—also orbit the ın, and all these objects formed in our solar system.

The motion of the planets around the Sun within a flat, sk-shaped region and their compositional differences give ıes to their origin. Astronomers think that our solar system rmed from the collapse of a slowly spinning interstellar oud of dust and gas. Rotation flattened the cloud into a sk—the *solar nebula.* Dust particles within the disk stuck gether and gradually grew in size, eventually becoming lid objects a few kilometers across—*planetesimals.* The ınetesimals, aided by the gravity of their large mass, drew gether and formed planets. Near the Sun, it was too warm r the planetesimals to capture or incorporate much water. ıe objects near the Sun, therefore, are composed mainly of icates and iron particles. Farther from the Sun, it was cold ough for water-ice to be captured, which allowed larger ınetesimals to form. These eventually grew big enough to pture gas directly from the solar nebula, producing the four s giant planets.

In the late stages of their growth, the planets were bomrded with surviving planetesimals still orbiting the Sun. The pact of these objects created craters on their surfaces. Some ınetesimals (or their fragments) exist even today as *asteroids* d *comets.*

Size strongly affects a planet's history. All planets were ıbably born hot, but small ones (such as Mercury) cooled ickly and are inactive today, lacking volcanic and tectonic ivity. Larger planets (such as Earth and Venus, and a few of larger moons) remain hot enough to have geologically ive surfaces. Their surfaces are altered now mainly by proısses driven by their internal heat, but impacts of asteroidal or netary objects still occur and on rare occasions have devasng results.

Terms to Remember

asteroid 604
astronomical unit 604
comet 604
differentiation 608
dwarf planet 628
greenhouse effect 616
inner planet 603
meteor 630
meteorite 630
Milky Way 604
Nebular Hypothesis 606
outer planet 603
planet 602
planetesimal 607
solar nebula 606
solar system 603
solar wind 615
star 602
universe 606

Testing Your Knowledge

1. What is the approximate shape of the solar system?
2. What evidence supports the hypothesis that the solar system formed from a rotating disk of dust and gas?
3. What is meant by a planetesimal?
4. Why is the surface of Venus hotter than the surface of Mercury, despite Mercury being closer to the Sun?
5. What has created the craters on the Moon?
6. Why is the Earth much less cratered than the Moon?
7. What has led to the formation of two very different types of planets in the solar system?
8. Where do comets come from?
9. What created the rings of Saturn and the other large planets?
10. Which of the following is evidence that Jupiter's composition is rich in hydrogen?
    a. Its large mass
    b. Its large density
    c. Its low density
    d. Its distance from the Sun
11. Why do Mercury and the Moon lack an atmosphere?
    a. They formed after all the gas had been used up.
    b. They are so cold that all their gases have frozen into deposits below their surface.
    c. They formed before the solar nebula had captured any gas.
    d. They are so small that their gravity is too weak to retain an atmosphere.

12. Why would it be difficult to land a spacecraft on Jupiter?
    a. Jupiter has no solid surface.
    b. Jupiter's immense gravity would squash it.
    c. Jupiter's intense magnetic field would destroy it.
    d. The clouds are so thick it would be hard to navigate to a safe spot.
13. Scientists think that water may once have flowed on Mars. The evidence for this is
    a. fossil fish found in several craters
    b. channels that resemble dried-up riverbeds
    c. frozen lakes along the Martian equator
    d. photographs made in the late 1800s that show blue spots that were probably lakes
14. The core of a comet is composed of
    a. molten iron
    b. frozen gases and dust
    c. liquid hydrogen
    d. uranium
15. Why are most asteroids not spherical?
    a. Their gravity is too weak to pull them into a sphere and they have been fragmented by impacts.
    b. The Sun's gravity distorts them.
    c. Strong magnetic fields in their molten core makes them lumpy.
    d. The statement is false. Nearly all asteroids are spherical.
16. What causes meteor showers such as those that occur near August 12?
    a. The breakup of an asteroid in our upper atmosphere
    b. Bursts of particles ejected from the Sun
    c. A comet being captured into orbit around the Earth
    d. The Earth passing through the trail of debris left by a comet

Expanding Your Knowledge

1. What obvious evidence suggests that the lunar highlands are older than the maria?
2. What has led to the inner planets having iron cores?
3. What is the likely origin of the main asteroid belt and the Kuiper Belt?
4. Why is it not surprising that the Moon lacks folded mountain ranges like we have on Earth?

Exploring Web Resources

www.mhhe.com/plummer14e
McGraw-Hill's Connect® website for *Physical Geology,* Fourteenth Edition, features a wide variety of study aids, such as animations, quizzes, answers to the end-of-chapter multiple choice questions, additional readings and Google Earth exercises, Internet exercises, and much more. The URLs listed in this book are given as links in chapter web pages, making it easy to go to a website without typing in its URL. The Connect® website can also be used by instructors to create and share course materials and assignments with students.

photojournal.jpl.nasa.gov
NASA Planetary Photojournal

www.pdsa.jpl.nasa.gov/planets
Welcome to the Planets

www.seds.org
Students for the Exploration and Development of Space

www.hawastsoc.org/solar/homepage.html
Views of the Solar System, by Calvin Hamilton

www.esa.int/SPECIALS/Mars_Express/index.html
Mars Express Mission Homepage

Animations

You can find the following animations in the eBook on ConnectPlus® (**www.mcgrawhillconnect.com**) or at the book's website (**www.mhhe.com/plummer14e**).

23.8 Formation of the solar system
23.10 Impact formation of the Moon