CHAPTER 1

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

Mount Robson, 3,954 meters (12,972 feet) above sea level, is the highest peak in the Canadian Rocky Mountains. *Photo © J. A. Kraulis/Masterfile*

LEARNING OBJECTIVES

- Know what physical geology is, and describe some of the things it is used for.
- Define a system, and describe the four Earth systems (spheres).
- Distinguish between the Earth's internal and external heat engines and list the processes driven by them.
- List the three major internal zones of the Earth.
- Describe the lithosphere and the asthenosphere.
- Sketch and label the different types of plate boundaries.
- Summarize the scientific method, and define the meaning of the word *theory*.
- Know the age of the Earth.

Have you ever looked out of the window of an airplane and wondered about the landforms that you see below you, or examined a pebble on a beach and wondered how it got there? Have you ever listened to a news report about a major natural disaster such as an earthquake, flood, or volcanic eruption, and asked yourself why it happened and what you would do if you found yourself in such a situation? What about the materials used to manufacture the electronics you use every day or the gasoline used to fuel your car-—have you ever thought about where they come from, how they formed, and how we exploit them? These topics are all parts of **geology**—the scientific study of the Earth. Geologists use the scientific method to explain natural aspects of the Earth, such as what it is made of and the processes that affect it, and to interpret Earth's history. This chapter is an introduction to geology. We will first explore the uses of geology before introducing some of the important concepts such as the modern theory of plate tectonics and geologic time. These concepts form a framework for the rest of the book. Understanding the "big picture" presented here will aid you in comprehending the chapters that follow.

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.)
- Explore the web links provided in this book. You will find they provide additional useful information.
- Be curious. Geologists are motivated by a sense of discovery. We hope you will be, too.

WHO NEEDS GEOLOGY?

Geology 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 the Earth. The 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.

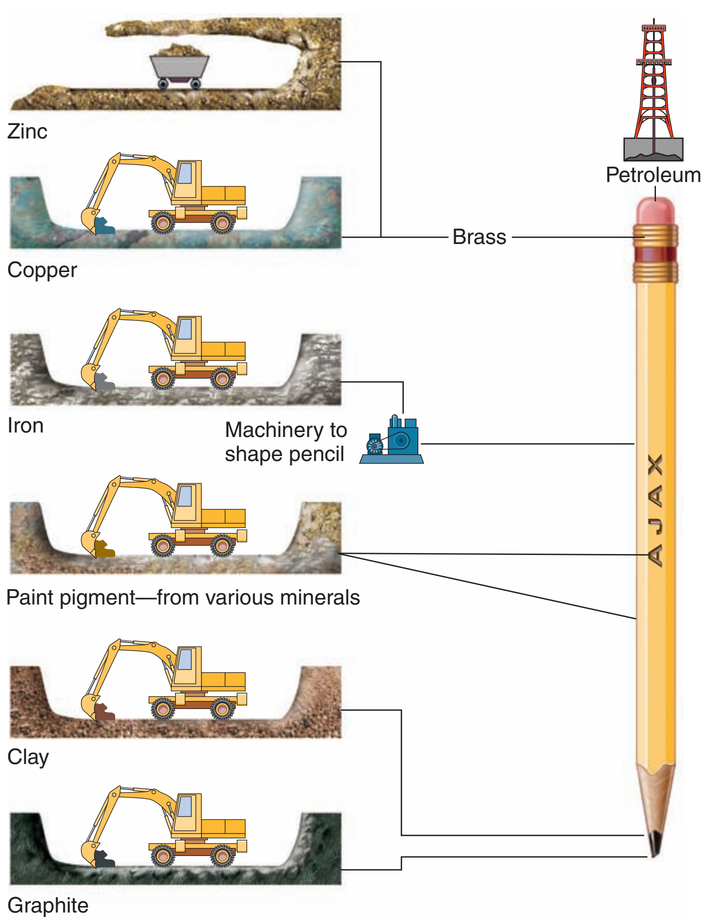


FIGURE 1.1
Earth's resources needed to make a wooden pencil.

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 much 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 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 or developing new extraction technologies 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 Minerals Education Coalition for every person living in the United States, approximately 17,333 kilograms (38,212 pounds; for metric conversions, go to appendix E) of resources, including energy resources, are mined annually. The amount of each commodity mined per person per year is 4,083 kilograms stone, 2,835 kilograms sand and gravel, 252 kilograms limestone for cement, 69 kilograms clays, 158 kilograms salt, 221 kilograms other nonmetals, 257 kilograms iron ore, 35 kilograms aluminum ore, 5 kilograms copper, 8 kilograms lead and zinc, 3 kilograms manganese, and 11 kilograms other metals. Americans' yearly per capita consumption of energy resources includes 3,430 liters (906 gallons) of petroleum, 2,570 kilograms of coal, 2,389 cubic meters (84,348 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 Deepwater Horizon 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).

ENVIRONMENTAL GEOLOGY 1.1

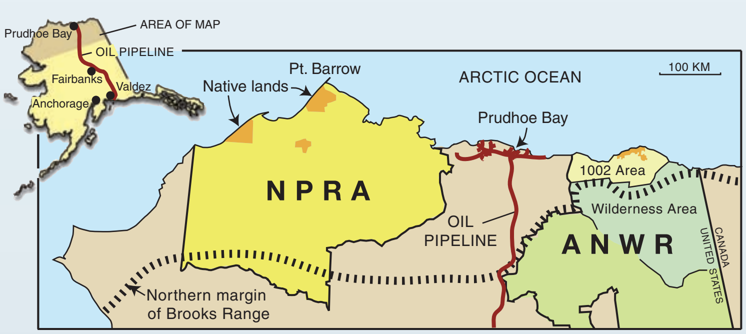
Delivering Alaskan Oil—The Environment versus the Economy

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 was 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.



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*

The 1,287-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 more than 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).

BOX 1.1 ■ FIGURE 2

The Alaska pipeline. *Photo by David Applegate*

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

The original estimated cost of the pipeline was $900 million, but the final cost was $7.7 billion, making it, at that time, the costliest privately financed 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 its feeder pipes revealed much more corrosion than expected. As a result, it made a very costly scaling back of its oil production to replace pipes and make major repairs.

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*

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, more than 240,000 barrels of crude oil were spilled into the waters of Alaska's Prince William Sound. 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.

Recently, another large oil pipeline project has been causing much debate. The Keystone Pipeline is expected to deliver oil from Canada and the northern United States to refineries in the Midwest and the Gulf Coast of Texas. Although parts of the pipeline system are already operational, the proposed extension from Nebraska to Texas has faced strong criticism from environmentalists. The potential threat to the environment is certainly of concern. However, the alternative to the pipeline is transporting the oil by rail, which can be hazardous. On December 30, 2013, a train carrying crude oil collided with another train in North Dakota. The collision caused a large explosion and fire, leading to a partial evacuation of the nearby town of Casselton. Earlier in 2013, a train carrying crude oil derailed in Quebec, Canada, killing more than 40 people in the town of Lac-Megantic. A strong political motivation for approving the pipeline is the drive to reduce the United States' dependence on potentially unstable foreign oil sources.

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/fs045-02/

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

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 because 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 not only made it difficult 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 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.

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.*

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 was 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 tsunami 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 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 was almost 16,000 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.

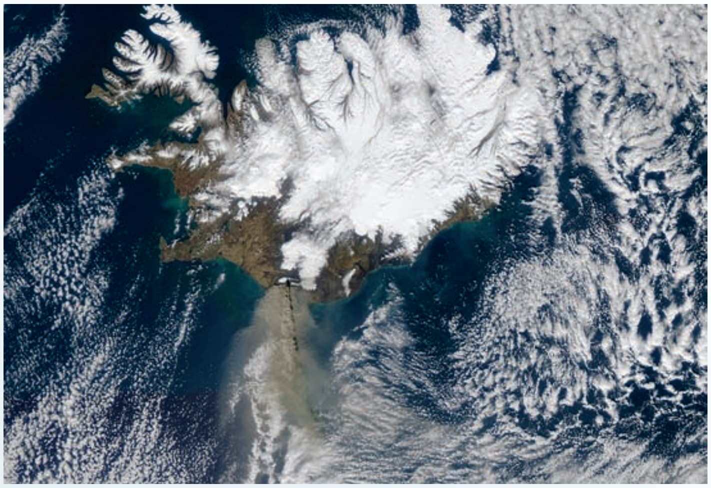
ENVIRONMENTAL GEOLOGY 1.2

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.



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*

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://earthice.hi.is/eruption_eyjafjallajokull_2010

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 twentieth century 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. 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

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*

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 then very slowly worn back down to plains. Studying how the 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 the 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 the 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 the 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.

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 but may have to spend months at a time on an offshore drilling platform. 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 underground water 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 are 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

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.

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. Volcanic eruptions and earthquakes are products of this heat engine.

Earth's *external* heat engine is driven by solar energy. 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.

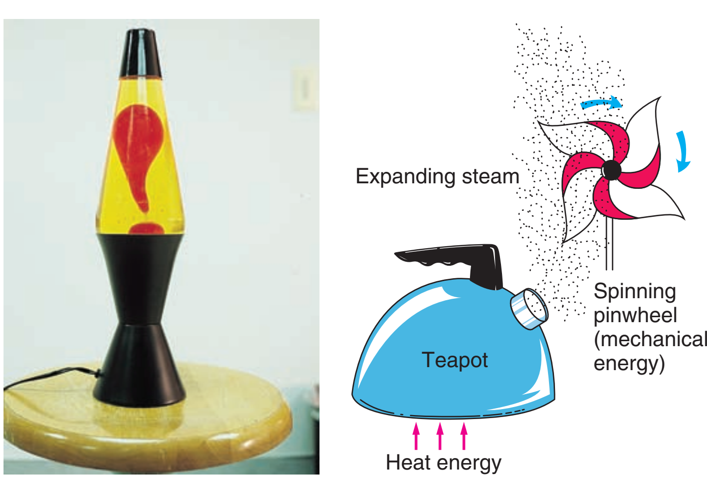


FIGURE 1.5

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*

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

Figure 1.7 shows the Earth's three major concentric zones. As described in more detail in chapter 17, the **mantle** is the most voluminous of these zones. 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.

The other two zones are the **crust** and the **core.** The core is believed to be mostly composed of the metals iron and nickel. It is divided into two zones, the solid inner core and the liquid outer core.

The crust of the Earth is analogous to the skin on an apple. The thickness of the crust is insignificant compared to the

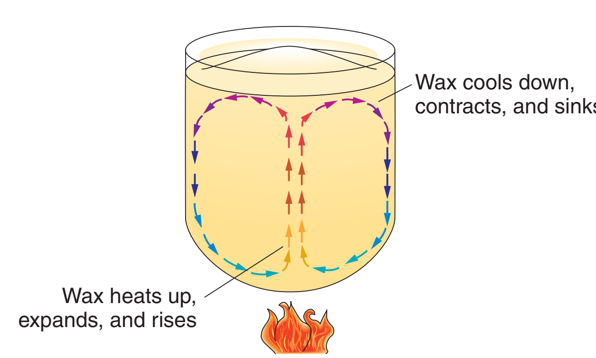


FIGURE 1.6

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

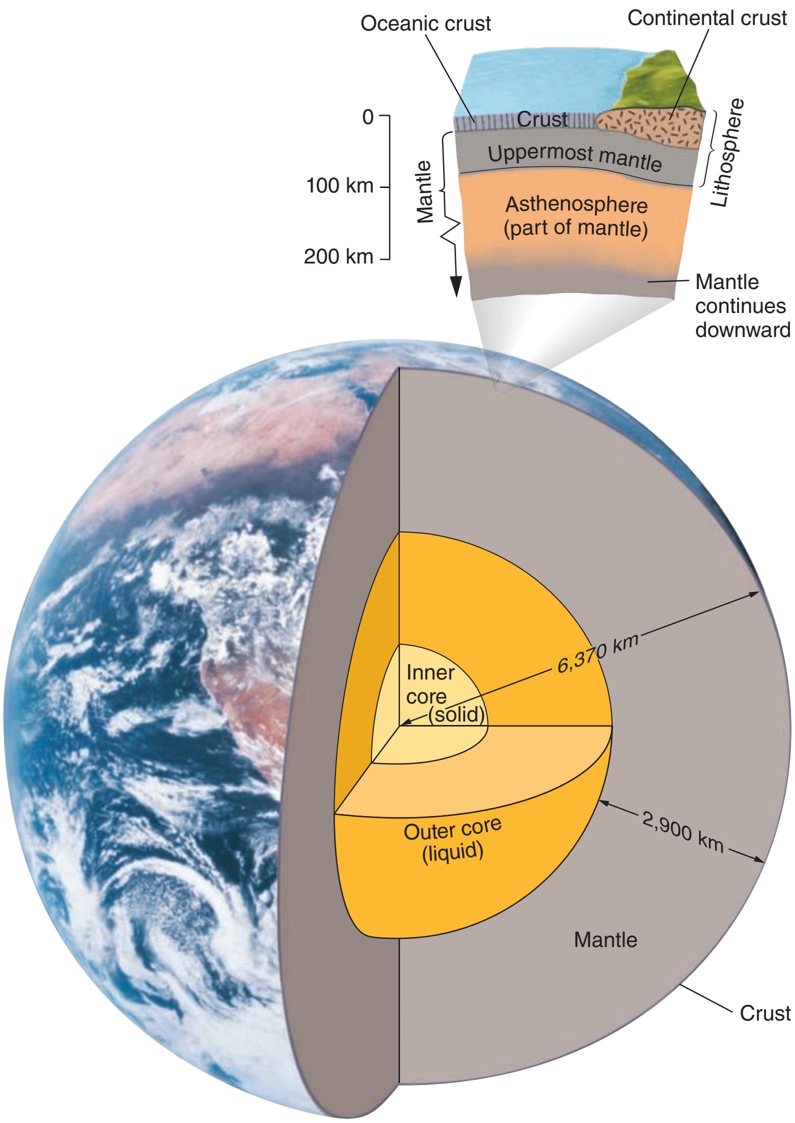


FIGURE 1.7

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*

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.

The 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 Earth's core and mantle and the lower parts of the crust 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. Chapter 17 explores the evidence used to understand the interior of the Earth.

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

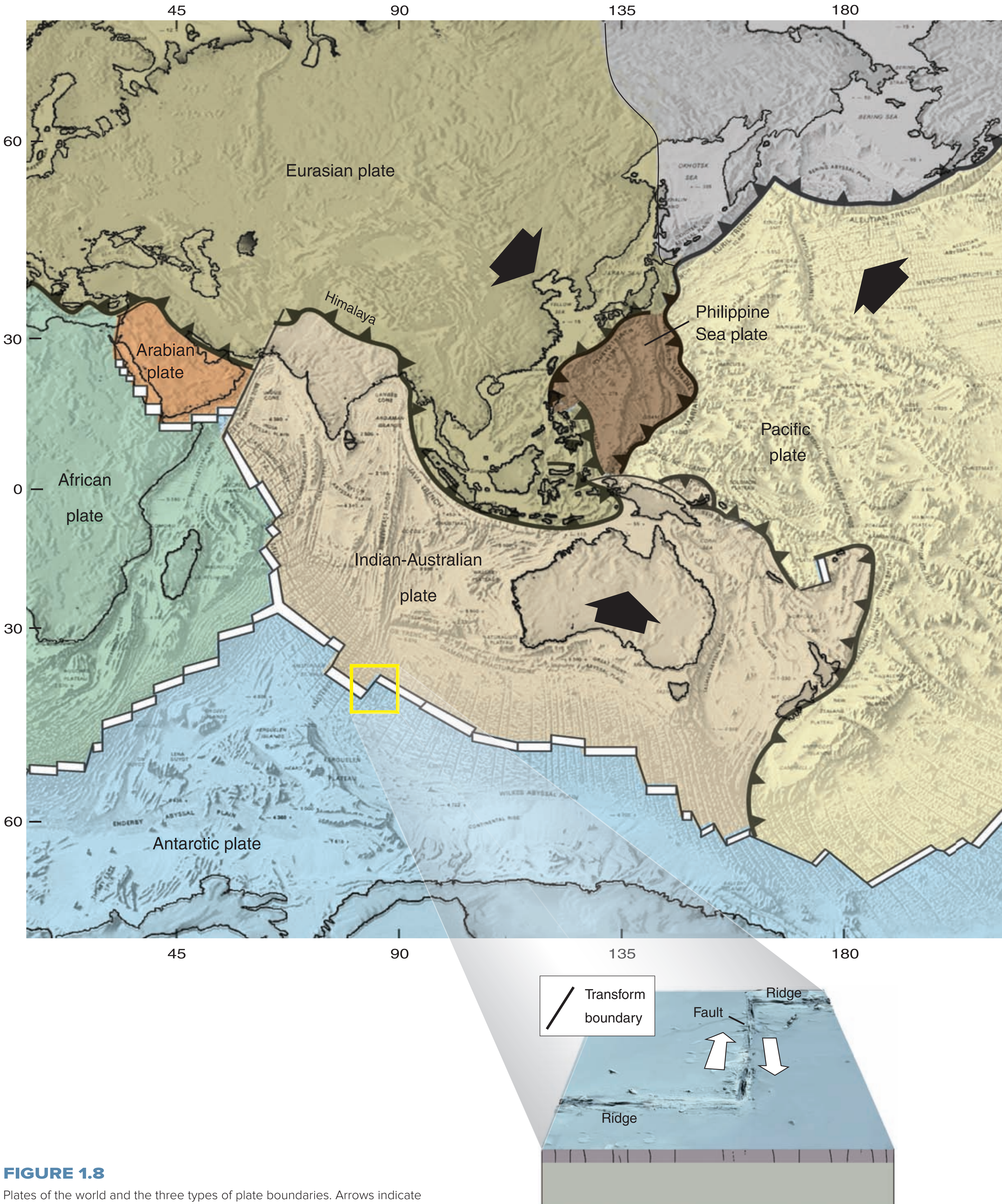


FIGURE 1.8

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

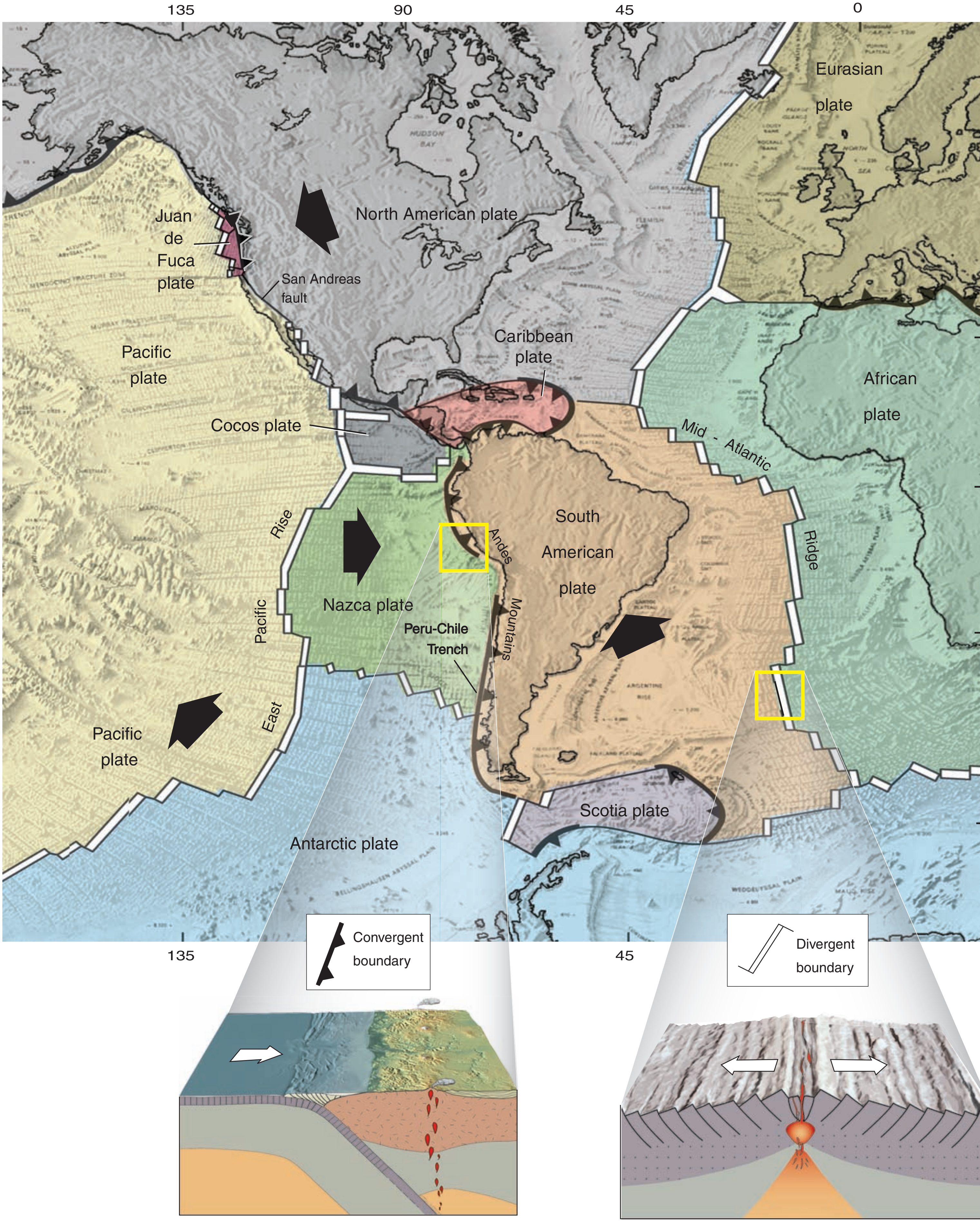

135
90
45
0
60
30
0
30
60
135
45
Eurasian plate
North American plate
Juan de Fuca plate
San Andreas fault
Caribbean plate
Pacific plate
African plate
Cocos plate
Mid - Atlantic Ridge
South American plate
Andes Mountains
Rise
Pacific
East
Nazca plate
Peru-Chile Trench
Pacific plate
Scotia plate
Antarctic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

TABLE 1.1 Three Types of Plate Boundaries

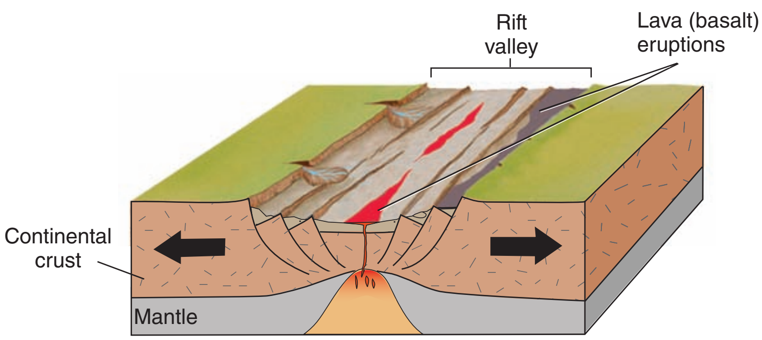
Boundary	What Takes Place	Result
Divergent	Plates move apart	Creation of new ocean floor with submarine volcanoes; mid-oceanic ridge; small to moderate earthquakes
Convergent	Plates move toward each other	Destruction of ocean floor; creation and growth of mountain range with volcanoes; subduction zone; 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.

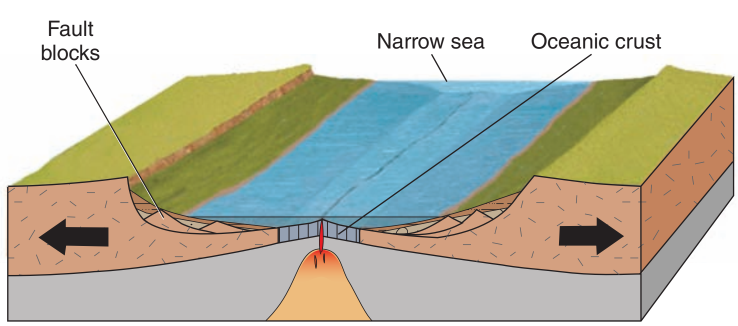
Divergent Boundaries

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, which runs for approximately 16,000 kilometers (10,000 miles) from northeast of Greenland to the South Atlantic, is a classic, well-developed example. Motion along a mid-oceanic ridge causes small to moderate earthquakes.

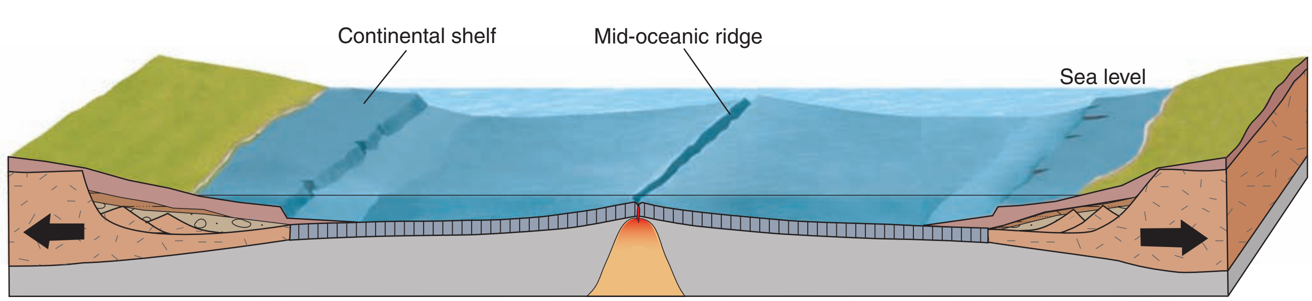
Although most divergent boundaries present today are located within oceanic plates, a divergent boundary typically initiates within a continent. It begins when a split, or *rift,* in the continent is caused either by extensional (stretching) forces within the continent or by the upwelling of hot asthenosphere 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.



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.

With continued separation, the valley deepens, the crust beneath 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 descending or *subducting* beneath the South American plate,

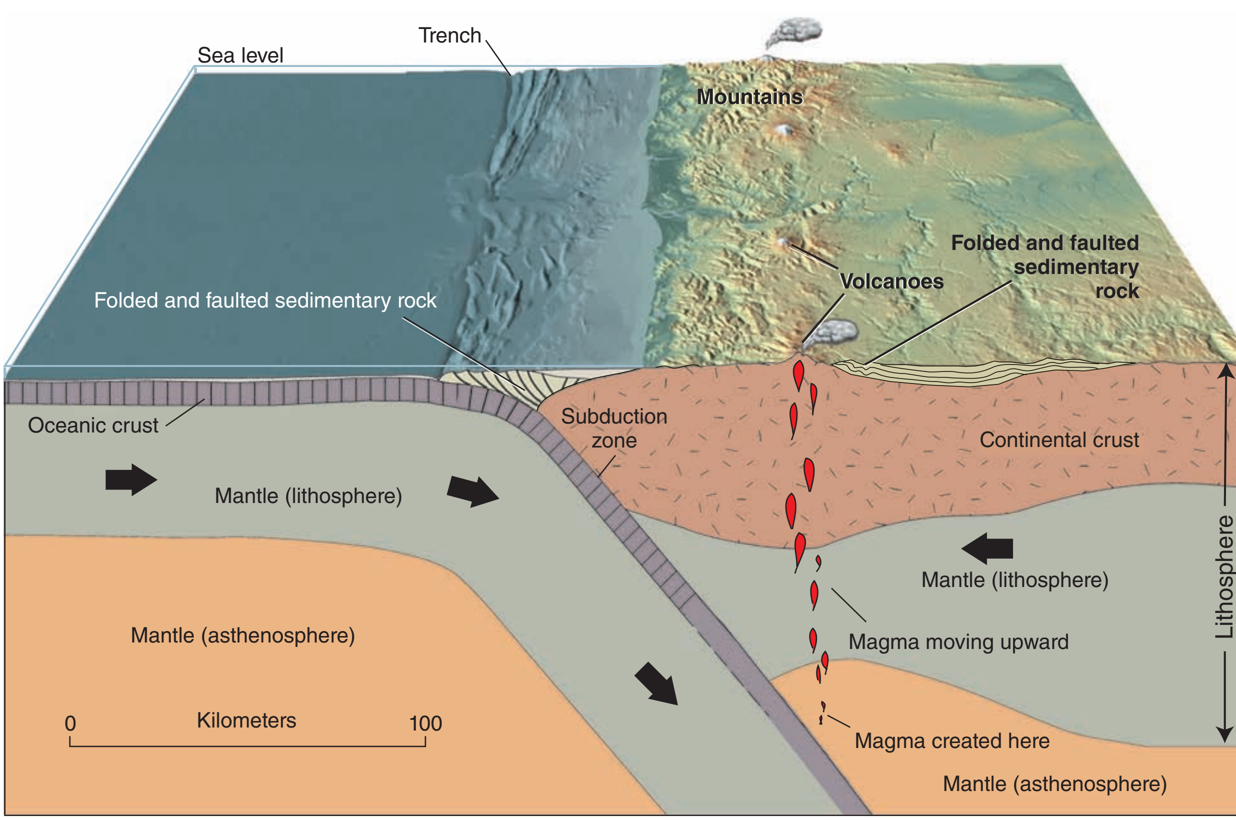


FIGURE 1.10

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.

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.

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

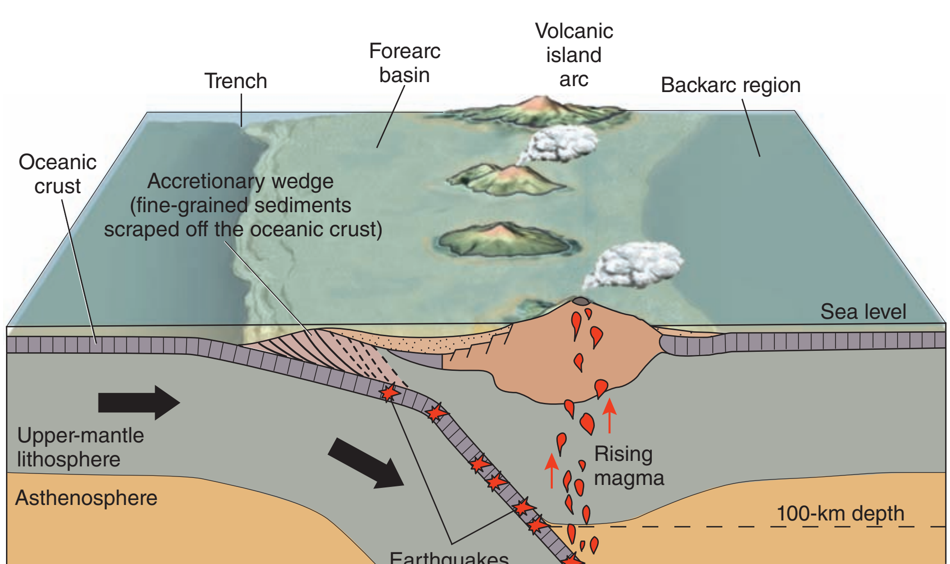


FIGURE 1.11
A volcanic island arc forms as a result of oceanic-oceanic plate convergence.

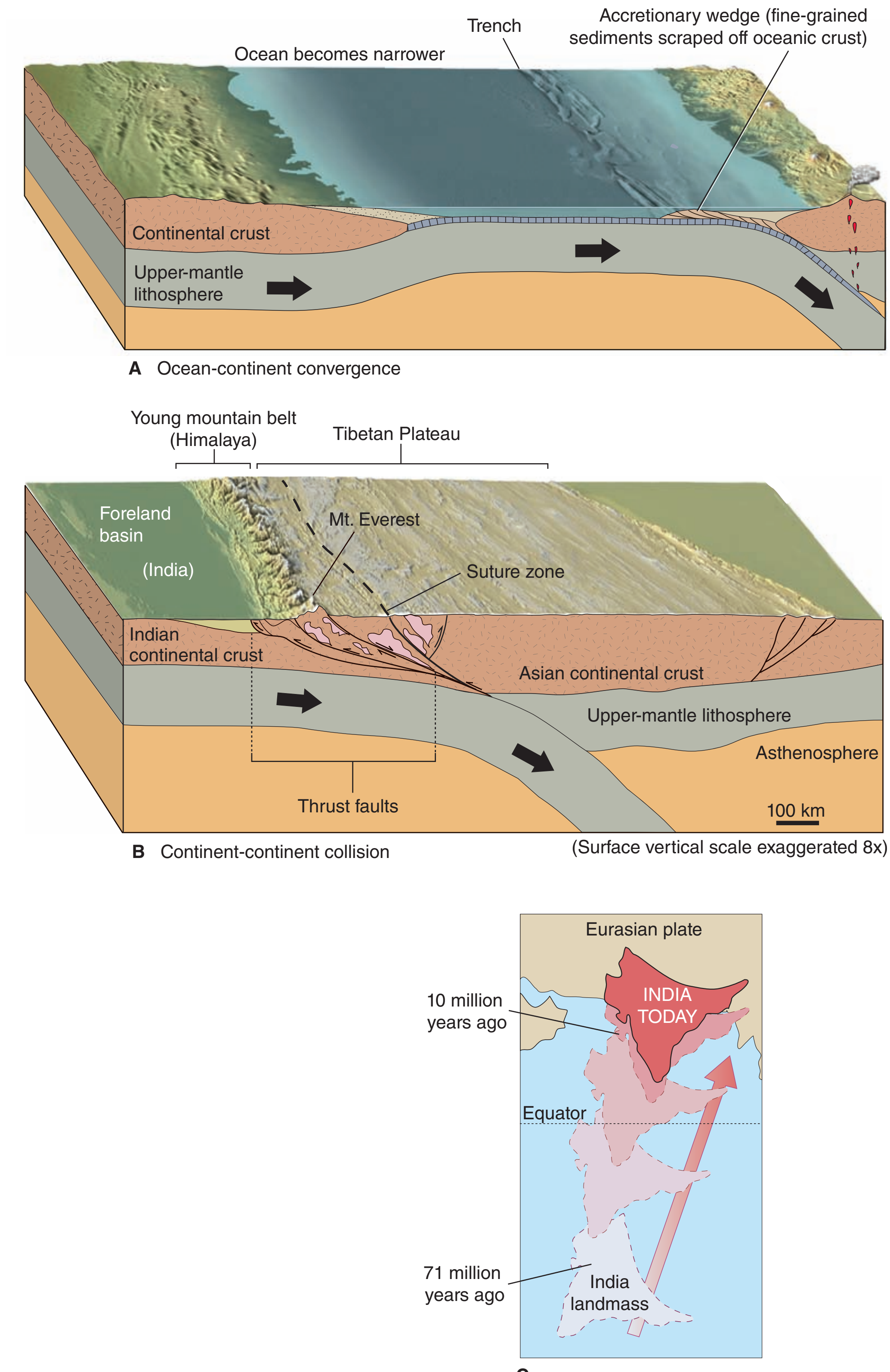


FIGURE 1.12

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.

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 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

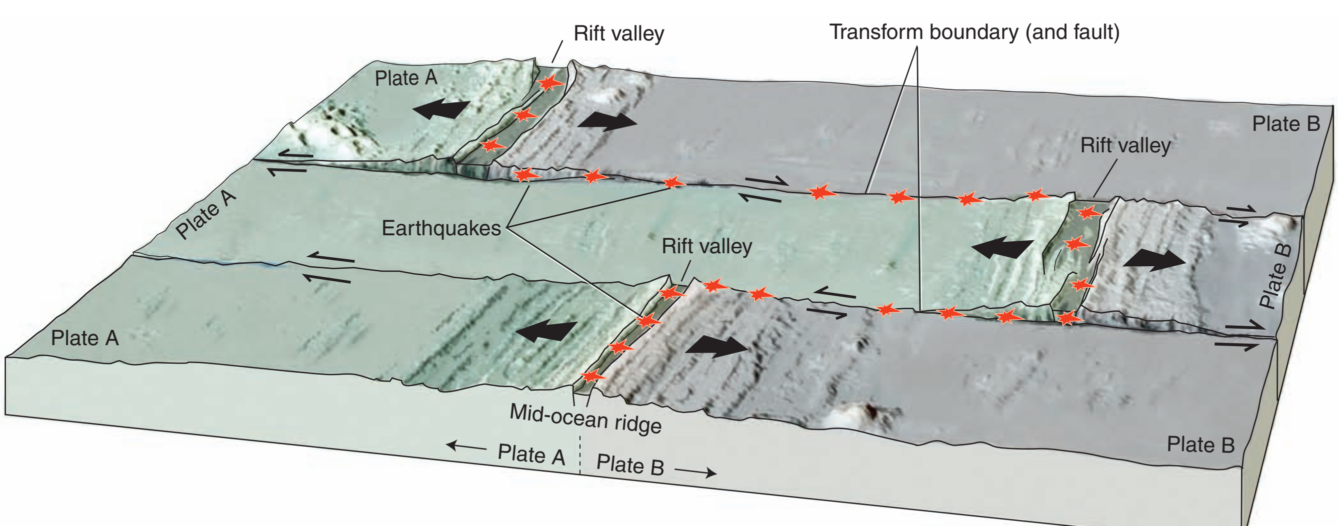


FIGURE 1.13

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.

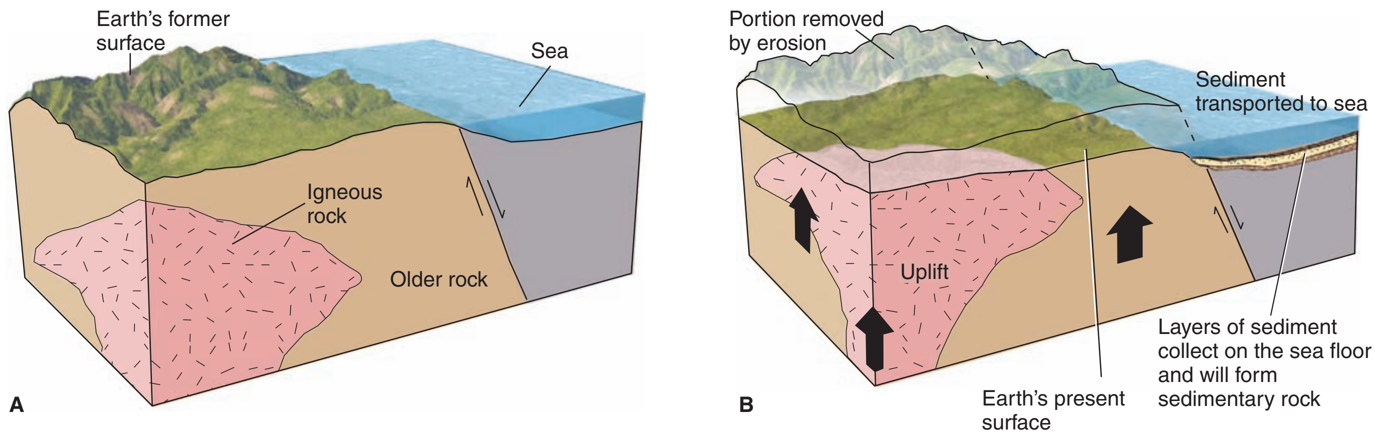


FIGURE 1.14

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.

by solar energy, comes into play. Circulation of the atmosphere and hydrosphere is mainly driven by solar energy. 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 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.*

Try to comprehend the vastness of deep time by going to the "Comprehending Geologic Time" section 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 rapidly, 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 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).

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.

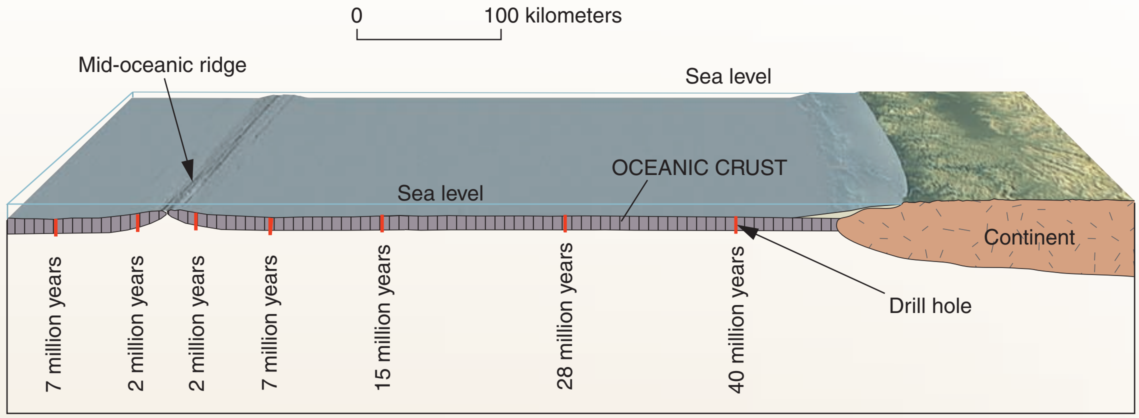
Step 3: Hypotheses proposed. Most of the questions being asked were treated as separate problems wanting separate hypotheses. Some appeared interrelated. One hypothesis, **continental drift**, did address several questions. It was advocated by Alfred Wegener, a German scientist, in a book published in 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 1).



BOX 1.4 ■ FIGURE 1

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

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

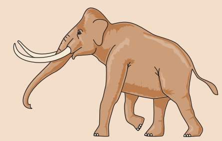
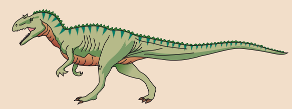
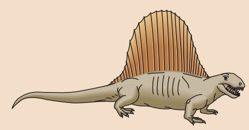
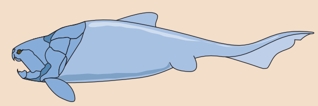
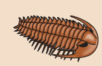
Words used by scientists do not always have the same meaning when used by the general public. A case in point is the word *theory.* To most people, a "theory" is what scientists regard as a "hypothesis." For example, news reports about an airliner that exploded offshore from New York in 1996 included statements like this: "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."

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 541 million years. Reptiles became abundant about 230 million years ago. Dinosaurs evolved from reptiles and became extinct about 66 million years ago. Humans have been here only about the last 5 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."

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

Millions of Years before Present	Noteworthy Life		Eras	Periods
5	Earliest hominids		**Cenozoic**	Quaternary *Neogene *Paleogene
66	First important mammals Extinction of dinosaurs			
	First dinosaurs		**Mesozoic**	Cretaceous Jurassic Triassic
252				
			**Paleozoic**	Permian Pennsylvanian Mississippian Devonian Silurian Ordovician Cambrian
300	First reptiles			
400	Fishes become abundant			
541	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 Precambrian is not an era; it is a long span of time that predates the Paleozoic era.

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 11
atmosphere 8
biosphere 8
continent-continent convergence 16
continental drift 20
convergent boundary 15
core 10
crust 10
data 20
divergent boundary 14
Earth system 8
equilibrium 19
erosion 19
geology 2
geosphere (solid Earth system) 8
hydrosphere 8
hypothesis 20
igneous rock 15
isostatic adjustment 18
lithosphere 11
magma 14
mantle 10
metamorphic rock 16
mid-oceanic ridges 14
ocean-continent convergence 16
ocean-ocean convergence 16
plate tectonics 11
scientific method 20
sediment 19
sedimentary rock 19
subduction zone 16
tectonic forces 11
theory 20
transform boundary 18

Testing Your Knowledge

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

1. Examine the photo of the Canadian Rockies on the first page of this chapter. Which of the four Earth systems can you see? How are they interacting with each other?
2. What is the most likely geologic hazard in your part of your country?
3. What are the three major types of rocks?
4. What are the relationships among the mantle, the crust, the asthenosphere, and the lithosphere?
5. What tectonic plate are you currently on? Where is the nearest plate boundary, and what kind of boundary is it?
6. Draw a sketch of each of the major types of plate boundaries. Show the direction of plate motion.
7. Subduction occurs at ocean-continent and ocean-ocean convergent boundaries but not at continent-continent convergent boundaries. Why is this?
8. What would the surface of Earth be like if there were no tectonic activity?
9. Explain why prehistoric cave dwellers never saw a dinosaur.
10. 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 is
    a. physical geology.
    b. historical geology.
    c. geochemistry.
    d. paleontology.
11. Which is a geologic hazard?
    a. earthquake
    b. volcano
    c. mudflows
    d. floods
    e. wave erosion at coastlines
    f. landslides
    g. all of the preceding
12. Plate tectonics is a result of Earth's internal heat engine, powered by (choose all that apply)
    a. the magnetic field.
    b. the Sun.
    c. gravity.
    d. heat flowing from Earth's interior outward.
13. A typical rate of plate motion is
    a. 3–4 meters per year.
    b. 1 kilometer per year.
    c. 1–10 centimeters per year.
    d. 1,000 kilometers per year.
14. Volcanic island arcs are associated with
    a. transform boundaries.
    b. divergent boundaries.
    c. ocean-continent convergence.
    d. ocean-ocean convergence.
15. Oceanic and continental crust differ in
    a. composition. b. density.
    c. thickness. d. all of the preceding.
16. The forces generated inside Earth that cause deformation of rock as well as vertical and horizontal movement of portions of Earth's crust are called
    a. erosional forces. b. gravitational forces.
    c. tectonic forces. d. all of the preceding.
17. Plate tectonics is a(n)
    a. conjecture. b. opinion.
    c. hypothesis. d. theory.
18. The lithosphere is
    a. the same as the crust.
    b. the layer beneath the crust.
    c. the crust and uppermost mantle.
    d. only part of the mantle.
19. Erosion is a result of Earth's external heat engine, powered by (choose all that apply)
    a. the Sun.
    b. gravity.
    c. heat flowing from Earth's interior outward.
    d. the Earth's magnetic field.