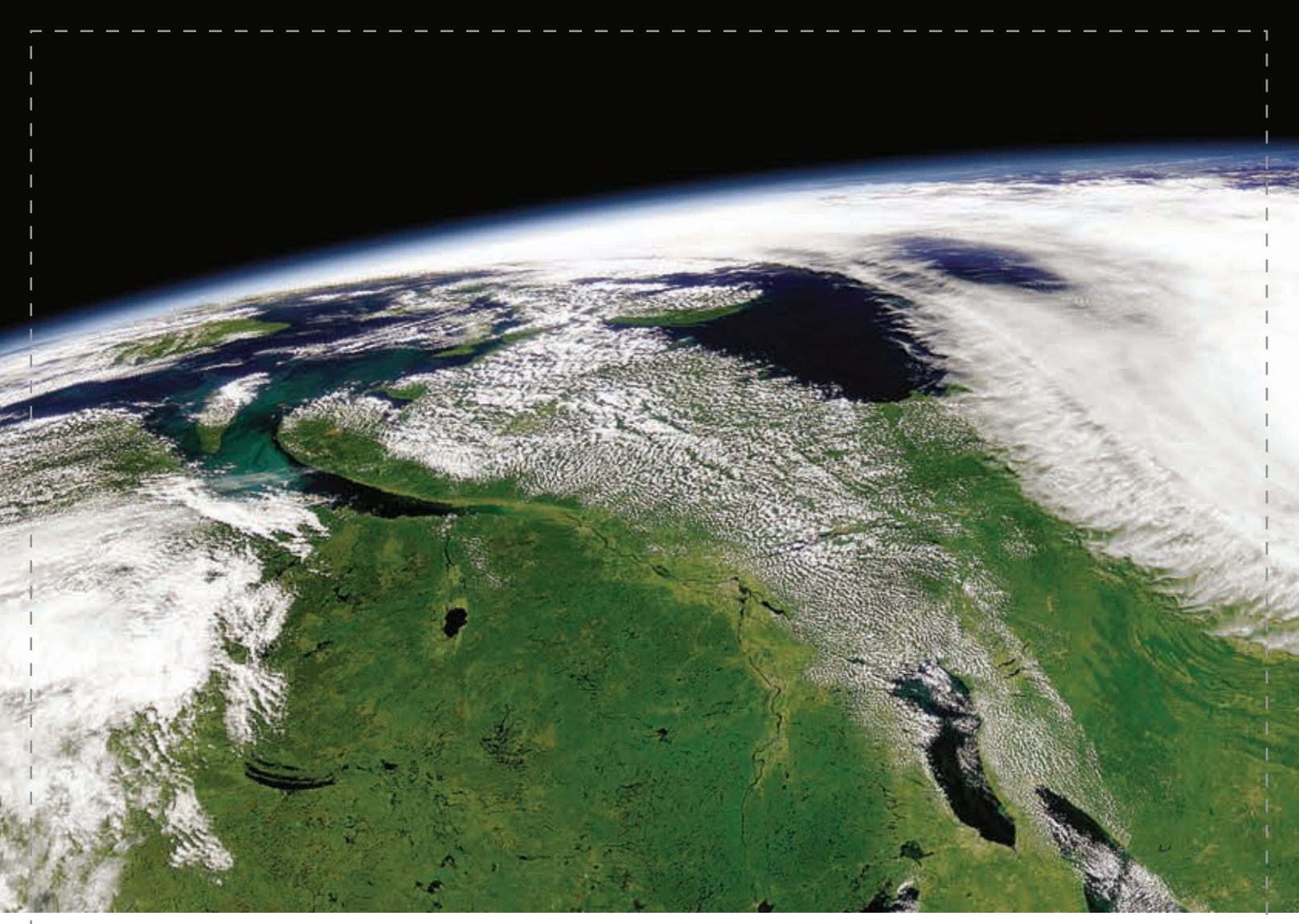


2 Geologic Systems

Earth is a dynamic planet because the materials of its various layers are in motion. The effects of both the hydrologic and the tectonic systems are dramatically expressed in this space photograph of eastern North America. The most obvious motion is that of the surface fluids: air and water. The complex cycle by which water moves from the oceans into the atmosphere, to the land, and back to the oceans again is the fundamental movement within the hydrologic system. The energy source that drives this system is the Sun. Its energy evaporates water from the oceans and causes the atmosphere to circulate, as shown above by the swirling clouds of hurricane Dennis. Water vapor is carried by the circulating atmosphere and eventually condenses to fall as rain or snow, which gravity pulls back to Earth's surface. Still acted on by the force of gravity, the water then flows back to the oceans in several subsystems (rivers, groundwater, and glaciers). In every case, gravity causes the water to flow from higher to lower levels.

Earth's lithosphere may appear to be permanent and stationary, but like the hydrosphere, it is in constant motion, albeit much, much slower. There is now overwhelming evidence that the entire lithosphere moves, and as it does, continents split and the fragments drift thousands of kilometers across Earth's surface perchance to collide with one another. The great Appalachian Mountain chain, visible here as a series of parallel ridges and valleys, formed when two continents collided hundreds of millions of years ago. The folded and crumpled rock layers formed a

Courtesy of SeaWiFS Project, NASA/Goddard Space Flight Center and ORBIMAGE

high mountain belt that was slowly eroded away by streams. Subsequently, the margin of North America formed as it rifted away from Africa. In fact, all of the structural features of our planet are the result of a simple system of moving lithospheric plates. Movement in this plate tectonic system is driven by the loss of internal heat energy.

The concept of a natural system, as developed for the study of geology, provides a framework for understanding how each part of Earth works and why it is constantly changing. Geologic systems are governed by natural laws that provide the keys to understanding Earth and all of its varied landscapes and processes.

In this chapter, we consider the fundamentals of natural systems. We also explore the basics of the hydrologic system and the tectonic system as the ultimate causes of geologic change.

Major Concepts

1. A natural system is a group of interdependent components that interact to form a unified whole and are under the influence of related forces. The materials in a system change in an effort to reach and maintain equilibrium.
2. Earth's system of moving water, the hydrologic system, involves the movement of water—in rivers, as groundwater, in glaciers, in oceans, and as water vapor in the atmosphere. As water moves, it erodes, transports, and deposits sediment, creating distinctive landforms and rock bodies.
3. Radiation from the Sun is the source of energy for Earth's hydrologic system.
4. A system of moving lithospheric plates—the plate tectonic system—explains Earth's major structural features. It operates from Earth's internal heat.
5. Where plates move apart, hot material from the mantle wells up to fill the void and creates new lithosphere. The major features formed where plates spread apart are continental rifts, oceanic ridges, and new ocean basins.
6. Where plates converge, one slides beneath the other and plunges down into the mantle. The major features formed at convergent plate margins are folded mountain belts, volcanic arcs, and deep-sea trenches.
7. Where plates slip horizontally past one another, transform plate boundaries develop on long, straight faults. Shallow earthquakes are common.
8. Far from plate margins, plumes of less-dense mantle material rise to shallow levels, feeding within-plate volcanoes and producing minor flexures of the lithosphere.
9. Earth's crust floats on the denser mantle beneath. The crust rises and sinks in attempts to maintain isostatic equilibrium.

Geologic Systems

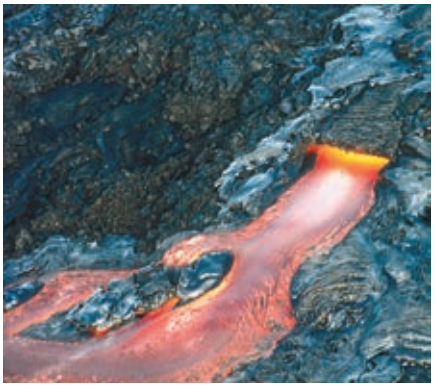
A system is a group of interdependent materials that interact with energy to form a unified whole. Most geologic systems are open; that is, they can exchange matter and energy across their boundaries.

The world is a unified whole. Nothing in or on it exists as an isolated entity. Everything is interconnected. We may know myriad details about the many separate items found on or inside Earth, but most of us do not understand how the pieces are interrelated and fit together. Without some concept of how the world functions as a whole, we easily miss important relationships between seemingly isolated phenomena, such as the critical connections among rainfall, temperature, and landslides. To understand Earth and how it functions, we need a model or framework, a plan or map that shows how things are interrelated and how things operate. Such a framework is provided by the concept of the **system**.

What is a geologic system?

There are many different kinds of systems. You are undoubtedly familiar with many natural and artificial systems. An engineer may think of a system as a group of interacting devices that work together to accomplish a specific task. In your home, there is an electrical system, a plumbing system, and a heating system. Each functions as an independent unit in some way. Each transfers material or energy from one place to another, and each has a driving force that makes the system operate. In another example, a biologist conceives of a similar kind of system, but it is one composed of separate organs made of living tissues that work together. The circulatory system is composed of the heart, blood vessels, and other organs that together move blood through the body.

In the physical sciences, we speak of systems in very general terms; a system is that part of space in which we are interested. The space may contain various materials acted on by energy in different ways. By defining a system, we identify the extent of



(A) A closed system, such as a cooling lava flow, exchanges only radiant heat. Here, heat from the lava is lost to the atmosphere.

(B) Open systems, such as a river, exchange energy and matter. In a river, water and sediment are collected from the drainage area and flow through the system to the sea. Most geologic systems are open systems.

Figure 2.1 **Natural systems** may be closed or open.

the material being considered and the energy involved so that we can more clearly understand any changes.

What is a dynamic system? Can you give an example?

In each of these cases, a system is composed of individual items or components that work together to make a unified whole. In accomplishing specific tasks, material and energy move about and change from one form to another. Such a system is **dynamic**, in motion, rather than static or unchanging.

A *natural system* is a bit more complicated than a typical engineering system. For example, a geologic system may have real boundaries, such as the top and bottom of a flowing stream of water or the walls of a body of molten rock (**Figure 2.1**). Or it may have arbitrary boundaries defined for the specific purpose of study. Everything outside of the system's boundaries is the surroundings or environment and is not considered part of the system.

Earth's systems obviously are so broad in scope, and cover so many phenomena in the natural world, that we should be careful about how we use the term. Two types of systems are important in geology: (1) a **closed system** exchanges only heat (no matter); and (2) an **open system** exchanges both heat and matter with its surroundings. In a closed system, such as a cooling lava flow, heat is lost, but new material is neither added nor lost (Figure 2.1A). However, most geologic systems are open systems, in which matter and energy freely flow across the system's boundaries. A river system, for example (Figure 2.1B), gains water from springs, snowmelt, and rainfall as it flows toward the ocean.

Why is Planet Earth considered to be a natural system?

Earth itself is a system. It is a sphere of matter with distinct boundaries. Earth has been an essentially closed system since the end of the heavy meteorite bombardment some 4 billion years ago. Since then, no significant new material has entered the system (except meteorites and space dust), and, just as important, significant quantities have not left the system. Since the planet formed, however, its materials have experienced tremendous change. Solar energy enters this nearly closed system and causes matter (air and water) to move and flow in distinctive patterns. Heat energy from within Earth also causes motion resulting in earthquakes, volcanism, and shifting continents. Thus, a space photograph of our planetary home seen as a whole is a powerful image of a natural system—an image that imparts a sense of the oneness in a natural system.

On a much smaller scale, a river and all its branching tributaries is a natural system. The floor of the stream and the upper surface of the flowing water form some of its boundaries. Matter enters this system from the atmosphere as rain, snow, or groundwater and then flows through the river channel and leaves the system

as it enters the sea. As long as rain falls, the system will be supplied with matter, gravitational potential energy, and kinetic energy. The ultimate energy source for a river system is energy from the Sun. Its energy heats water in the ocean, evaporating it and lifting it into the atmosphere, and transporting it to the continents. The force of gravity causes the water to flow downslope to the sea.

Most other geologic systems are complex open systems like river systems. One type of complexity results from subsystems. For example, a river system is only part of the much larger hydrologic system that includes all possible paths of worldwide water movement. Atmospheric circulation of water vapor is another important subsystem of the hydrologic system. Oceanic currents are another; glaciers and groundwater are others. Each is a subset of the overall circulation of water and energy at Earth's surface.

Direction of Change in Geologic Systems

In all natural systems change occurs in the direction necessary to establish and maintain equilibrium—a condition of the lowest possible energy.

The very essence of Earth's geologic systems is the flow of energy and the movement of matter. As a result, materials on and in Earth are changed or rearranged. Yet, this change does not occur at random. It occurs in a definite, predictable way. By carefully examining a system, we can see how one component is connected to another in an invisible web. The individual threads of this network are so tightly interdependent that a change in any component, even a small change, causes change in the rest of the system. Predicting and understanding these changes is an important reason for using the system approach.

What determines the direction of change in a dynamic geologic system? For example, does water flow downhill or uphill? Does hot air rise or sink? Although the answers to these questions seem self-evident, they seem simple only because of your experience with natural systems driven by gravity. You have thousands of experiences each day that reveal many of the principles of gravity. These experiences allow you to predict what will happen in many different situations.

However, because you lack experience with other natural systems, there are many questions regarding direction of change that are more difficult for you to answer. For example, under what conditions of temperature or pressure does one mineral convert to a different mineral? At what temperature does rock melt? Or water freeze? Why does heat flow from one rock to another or from one region to another? When will solid rock break to cause an earthquake? In short, how can we predict the direction of change in any natural system?

What is equilibrium in a natural system?

Most of these questions can be answered, or at least better understood, because of one very simple principle. Changes in natural systems have a universal tendency to move toward a state of **equilibrium**—a condition of the lowest possible energy. This pattern holds for the landscape, earthquakes, volcanoes, flowing water, and many other geologic phenomena. This governing principle has been clearly established through painstaking experimentation by thousands of scientists working over several centuries. Thus, if we can deduce which of several possible conditions is lowest in energy, we can predict the direction of change in a natural system.

Another way to think about equilibrium is to consider it a condition in which the net result of the forces acting on a system is zero. It is a state of no permanent change in any characteristic of the system. Systems not in equilibrium tend to change in a direction to reach equilibrium. To better understand this idea, think of two boulders on a hillside. One sits high on the side of the hill and has much gravitational potential energy. Another sits on the valley floor and has very little gravitational potential energy. Which boulder is more likely to change its position? Obviously, only a small perturbation could send the first boulder rolling down the hillside. But any force exerted on the second boulder would cause only a modest and temporary change in position, and it would then roll back to its original position. The second boulder has low gravitational potential energy and is at an equilibrium position.

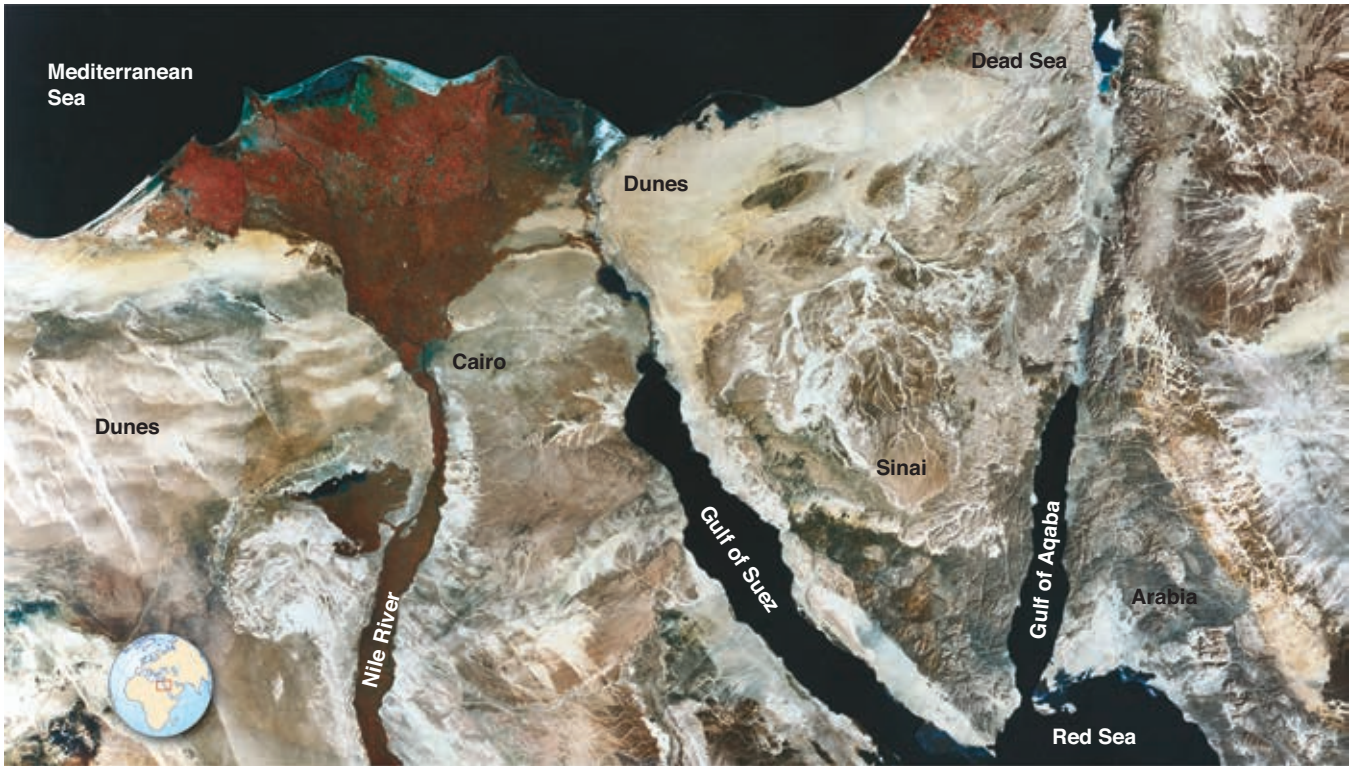
Now, imagine a third boulder that sits in a slight depression on the hillside. It is in a **metastable** position. A very small force would be insufficient to change its position permanently, but a larger force would push it over the brink and allow it to crash down the hill to a stable position.

A hot lava flow cools for similar reasons. It loses heat energy to its surroundings in order to reach equilibrium with its environment. If a change upsets this equilibrium, the system will naturally change in such a direction as to reestablish equilibrium under the new conditions.

In all such transformations, some energy is lost to the environment, generally as heat. Often, the lost heat energy is no longer available to cause change. A fundamental natural law holds that any system tends to "run down," meaning that it gradually loses energy of the sort that can cause change.

If you look carefully at a geologic system, you should be able to identify its equilibrium state. For example, what would be the equilibrium landscape formed by a river system? The state that would provide the very least gravitational potential agency would be one of flatness. Thus, a perfectly flat landscape with no hills, ridges, or valleys would be the equilibrium landscape. Of course, that state may never be perfectly achieved, because of the inability of erosion to keep up with other changes imposed on the river system.

In summary, the total energy of a system must decrease for a spontaneous change to occur. The change will proceed until equilibrium is attained and the energy is at



© NASA Information Systems/Science Photo Library

Figure 2.2 **Earth's geologic systems** are evident in this space photograph. The effects of the hydrologic system are revealed by river systems, even in this desert region of the Middle East. The Sinai Peninsula is etched by delicate networks of stream valleys, which disappear into the sandy desert along the shores of the Mediterranean Sea. Elsewhere, stream erosion has etched out the fractures in the rocks, but the drainage patterns are masked by wind-blown sand. The Nile River is flanked by farmlands (red). The Nile carries a tremendous volume of sediment to the sea, where it is deposited in a huge delta (dark red because of vegetation). The Nile River and its delta are a dramatic expression of the hydrologic system as running water erodes the highlands of central Africa and transports the sediment to the sea. An additional expression of the hydrologic system is the wave action along the delta front that reworks the sediment brought to the sea by the Nile and redeposits it as beaches and barrier bars. In this arid region, linear windblown sand dunes have developed on either side of the Nile Delta. The tectonic system is expressed by the rift of the Red Sea and the fracture system extending northward up the Gulf of Aqaba and into the Dead Sea–Jordan River valley. The Arabian Peninsula is moving to the northeast and, as it splits and moves away from Africa, a new ocean basin (the Red Sea) is born. The movement of tectonic plates is a clear expression of the fundamental dynamics of Earth's interior.

a minimum. The most stable state is always the one with the lowest energy. In other words, all materials attempt to achieve a balance with the chemical and physical forces exerted upon them, and they will change to arrive eventually at equilibrium. This effort results in progressive changes in any planetary material that is exposed to an environment different from that in which it formed. Although this equilibrium state is the preferred state of all systems, there are many intermediate or metastable states, adding to the complex problem of understanding Earth's dynamic systems.

Systems, Equilibrium, and Geology

The dual concepts of systems and equilibrium, as developed for the study of geology, provide a framework for understanding how each part of Earth works and why it is constantly changing. Order can be seen in all scales of time and space. Nothing is random. Everything, from a grain of sand on a beach to a lake, mountain range, or canyon, is there because it was formed in a systematic way by an organized interaction of matter and energy. Dynamic geologic systems are governed by natural laws, which provide the keys to understanding Earth and all its landscapes and processes.

The major geologic systems are the hydrologic system and the tectonic system. Perhaps no other place on Earth illustrates the operation of these two grand systems as well as the Middle East (**Figure 2.2**). This satellite photograph may at first appear to be a chaotic jumble of colors and textures, but careful examination shows that every feature is a product of these two dynamic systems. Carefully read the figure caption to understand this important point.

The Hydrologic System

The hydrologic system is the complex cycle through which water moves from the oceans, to the atmosphere, over the land, and back to the oceans again. Water in the hydrologic system—moving as surface runoff, groundwater, glaciers, waves, and currents—erodes, transports, and deposits surface rock material.

The complex motion of Earth's surface water—the **hydrologic system**—operates on a global scale. It unites all possible paths of water into a single, grand system of motion. The term hydrologic is rooted in the Greek term *hydor* for "water." The basic elements of the system can be seen from space (**Figure 2.3**) and are diagrammed in **Figure 2.4**. The system operates as energy from the Sun heats water in the oceans, the principal reservoir for Earth's water. As it is heated, the water evaporates. Most of the water vapor condenses and returns directly to the oceans as rain. Atmospheric circulation carries the rest over the continents, where it is precipitated as rain, sleet, hail, or snow.

Water that falls on the land can take a variety of paths. The greatest quantity returns to the atmosphere by evaporation, but the most visible return is to the oceans by surface runoff in river systems, which funnel water back to the oceans. Some water also seeps into the ground and moves slowly through pore spaces in the soil and rocks, where it is available to plants. Part of the water is used by the plants, which "exhale" it into the atmosphere, but much of it slowly seeps into streams and lakes. In polar regions or in high mountains, water can be temporarily trapped on a continent as glacial ice, but the glacial ice gradually moves from cold centers of accumulation into warmer areas, where melting occurs and the water returns to the oceans as surface runoff.

In short, water in the hydrologic system is constantly moving as vapor, rain, snow, surface runoff, groundwater, and glaciers, or even in ocean waves and currents. As it moves across the surface, it erodes and transports rock material and then deposits it as deltas, beaches, and other accumulations of sediment. Consequently, the surface materials, as well as the water, are in motion—motion that results in a continuously changing landscape.

One of the best ways to gain an accurate conception of the magnitude of the hydrologic system is to study space photography. These photographs provide a view of the system in operation on a global scale. A traveler arriving from space would see

Courtesy of SeaWiFS Project, NASA/Goddard Space Flight Center and ORBIMAGE

Figure 2.3 **The hydrosphere**, the thin film of water that makes Planet Earth unique, is essential for life. Earth is just the right distance from the Sun for water to exist as a liquid, solid, and gas. If it were closer to the Sun, our oceans would evaporate; if it were farther from the Sun, the oceans would freeze solid. Drawing energy from the Sun, it moves in great cycles from the oceans to the atmosphere and over the landscape in river systems, ultimately returning to the oceans.

that the surface of Earth is predominantly water (Figure 2.3). The movement of water from the oceans to the atmosphere is expressed in the flow patterns of the clouds. The atmosphere and moving cloud cover are among the most distinctive features of Earth as it is viewed from space. The great river systems stand out markedly when compared with the surfaces of the Moon and Mercury, where impact craters dominate stark landscapes. Without hydrologic systems, the surfaces of these planets have remained largely unmodified for billions of years.

In addition, the swirling, moisture-laden clouds carry an enormous amount of energy. For instance, the kinetic energy produced by a hurricane amounts to roughly 100 billion kilowatt-hours per day. That is much more than the energy used by all of the people of the world in one day.

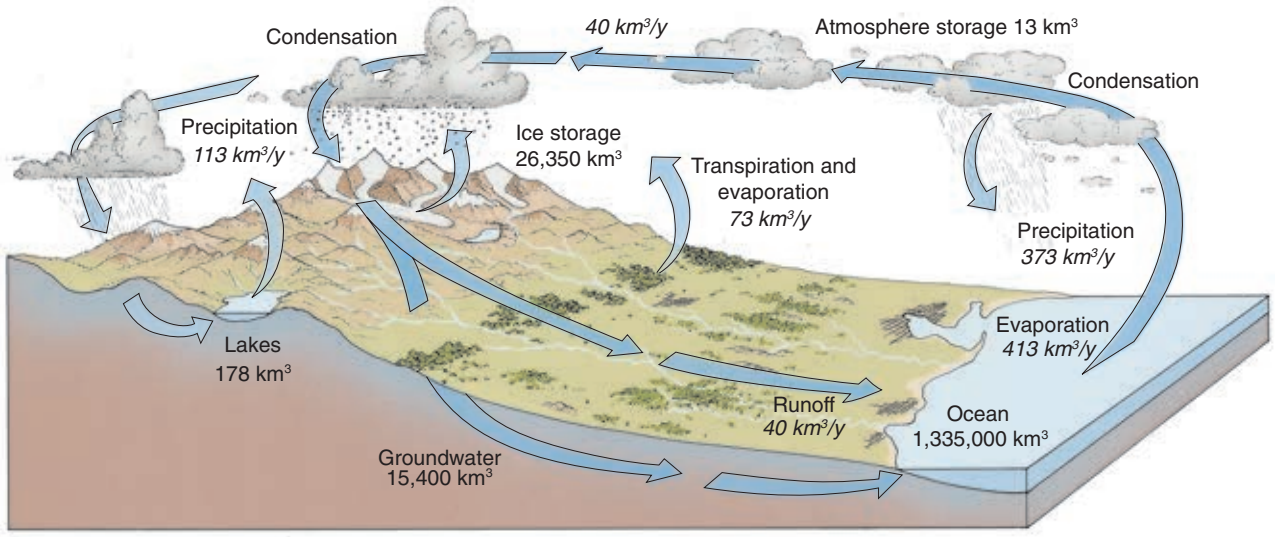


Figure 2.4 **The circulation of water** in the hydrologic system is powered by solar energy, as shown in this block diagram. Water evaporates from the oceans, circulates with the atmosphere, and eventually condenses as rain or snow where it cools. Much of the water that falls on the continents returns to the oceans by surface runoff and groundwater seepage. Variations in the major flow patterns of this system include the temporary storage of water in lakes and glaciers. Within this major system are many smaller cycles, or shortcuts, such as evaporation from lakes and transpiration from plants.

How much water is in motion in the hydrologic system?

Another way to grasp the magnitude of the hydrologic system is to consider the volume of water involved. From measurements of rainfall and stream discharge, together with measurements of heat and energy transfer in bodies of water, scientists have calculated that if the hydrologic system were interrupted and water did not return to the oceans by precipitation and surface runoff, sea level would drop 1 m per year. All of the ocean basins would be completely dry within 4000 years. The "recent" ice ages demonstrate this point clearly: The hydrologic system was partly interrupted, as much of the water that fell on the Northern Hemisphere froze and accumulated to form huge continental glaciers, preventing the water from flowing immediately back to the oceans as surface runoff. Consequently, sea level dropped more than 100 m during the most recent ice age.

As a final observation, consider what the hydrologic system has produced. It eroded millions of tons of rock from the Grand Canyon, carved the fantastic peaks of the Himalaya mountains, and deposited the vast Mississippi delta. The hydrologic system also created the small streams and valleys around your hometown. There is little, if any, surface on Earth that is not affected in some way by the work of the hydrologic system. When you go for a walk in the country, it is very likely you will be walking over a surface formed by running water, a young surface (geologically speaking) that is still developing.

Major Subsystems of the Hydrologic System

The enormous energy of the hydrologic system is apparent in each subsystem by which water moves—rivers, glaciers, groundwater, oceans, and wind. All erode, transport, and deposit material and create new landforms in the process. We will explore the details of each major geologic system in subsequent chapters, but for now let us examine some results of the water movement over Earth.

Atmosphere–Ocean System Earth's oceans are vast reservoirs of liquid water that together with the gases in the atmosphere create the **climate system**. Circulation in these envelopes of fluid is driven by heat from the Sun. The uneven heating of Earth's surface causes the atmosphere to convect, winds to blow, causes evaporation of huge quantities of water vapor into the atmosphere, and drives ocean currents. In addition,

variations in this convection system set up a regular pattern for the distribution of precipitation and temperature around the entire globe. Thus, the climate is controlled by the materials and energy in this system. In turn, the climate controls how the hydrologic system operates in a local area.

River Systems Most water precipitated onto the land returns directly to the oceans through surface drainage systems—**river systems**. The amount of water in Earth's rivers appears vast, but in fact it is startlingly small; it is only about 0.0001% of the total water on Earth, or 0.005% of the water not in the oceans. Water flows through rivers very rapidly, at an average rate of 3 m per second. At this rate, water can travel through the entire length of a long river in a few weeks. This means that, although the volume of the water in rivers at any given time is small, the total volume passing through river systems in a given period can be enormous. As a result, most of the landscape is dominated by features formed by running water.

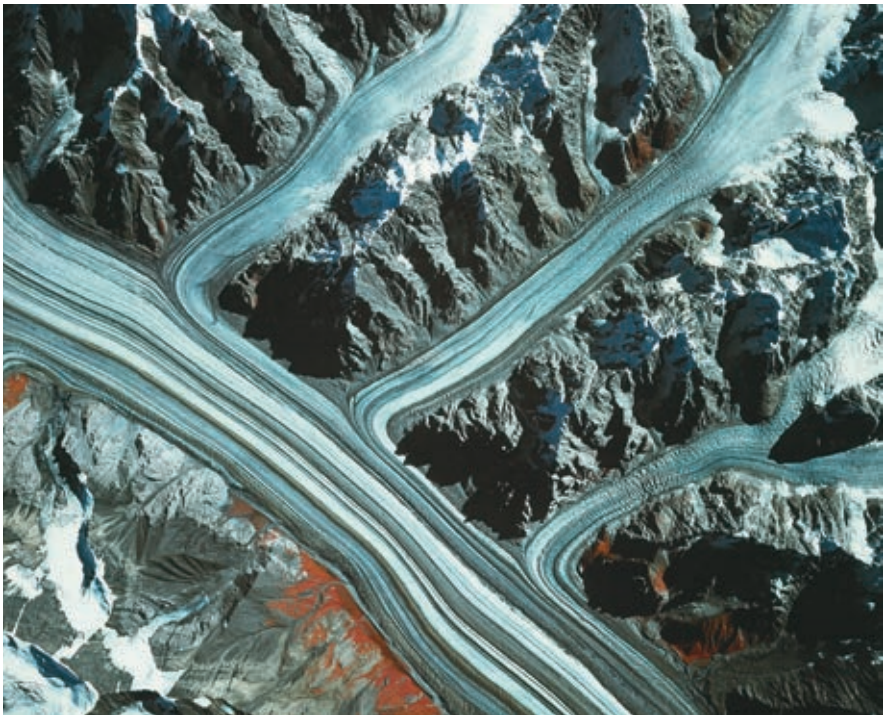
What are the major components of the hydrologic system and how do they operate?

From viewpoints on the ground, we cannot appreciate the prevalence of stream channels on the surface of Earth. From space, however, we readily see that stream valleys are the most abundant landforms on the continents. In arid regions, where vegetation and soil cover do not obscure our view, the intricate network of stream valleys is most impressive (**Figure 2.5**). Most of the surface of every continent is somehow related to the slope of a stream valley, which collects and funnels surface runoff toward the ocean.

Another important aspect of a river system is that it provides the fluid medium that transports huge amounts of sand, silt, and mud to the oceans. These sediments form the great deltas of the world, which are records of the amount of material washed off the continents by rivers. The Nile Delta is a classic example (Figure 2.2). The Nile

Courtesy of NASA

Figure 2.5 **River systems** are clear records of how the hydrologic system sculpts the land. They testify to the magnitude of this vast interconnected system of moving water, for few areas on land are untouched by stream erosion. In this photograph of a desert region, details of the delicate network of tributaries are clearly shown. On the Moon, Mercury, and Mars, craters dominate the landscape, but on the continents of Earth, stream valleys are the most abundant landforms.



Courtesy of U.S. Department of Agriculture

Figure 2.6 **Valley glaciers**, such as these in Alaska, occur where more snow accumulates each year than is melted in the summer. Over many years, this cycle allows accumulating snow to build the glaciers. Valley glaciers originate in the snowfields of high mountain ranges and slowly flow as large tongues of ice down preexisting stream valleys. The moving ice is a powerful agent of erosion and modifies the valleys in which it flows. The dark lines on the glaciers are rock debris derived from the valley walls.

River is confined to a single channel far upstream from Cairo. It then splits into a series of branching channels, from which the sediment carried by the river is eventually deposited as new land in the Mediterranean Sea. The main channels slowly shift their courses back and forth across the delta, and the older extensions of the delta are eroded back by ocean waves and currents.

Why are glaciers considered to be part of the hydrologic system?

Glacial Systems In cold climates, precipitation falls as snow, most of which remains frozen and does not return immediately to the ocean as surface runoff. If more snow falls each year than melts during the summer months, huge bodies of ice build up to form glaciers (**Figure 2.6**). Large valley glaciers originate from snowfall in high mountains and slowly flow down valleys as rivers of ice. **Glacier systems** greatly modify the normal hydrologic system because the water that falls upon the land does not return immediately to the ocean as surface runoff. It is not until the glaciers melt at their lower end that water flows back to the sea, seeps into the ground, or evaporates.

At present, the continent of Antarctica is almost entirely covered with a continental glacier, a sheet of ice from 2.0 to 2.5 km thick. It covers an area of 13 million km^2—an area larger than the United States and Mexico combined. An ice sheet similar to that now on Antarctica covered a large part of North America and Europe during the last ice age, and it retreated only within the last 18,000 years. As the ice moved, it modified the landscape by creating many lakes and other landforms in Canada and the northern United States, including the Great Lakes.

Water in the form of ice constitutes about 80% of the water not in the oceans, or about 2% of Earth's total water—far more than is in our streams and rivers. Water in glaciers moves very slowly and may remain in a glacier for thousands or even millions of years. Present estimates suggest that water resides in a glacier for about 10,000 years on average.

Groundwater Systems Another segment of the hydrologic system is the **groundwater system**—the water that seeps into the ground and moves slowly through the pore spaces in soil and rocks. Surprisingly, about 20% of the water not in the oceans occurs as groundwater. As it slowly moves, groundwater dissolves soluble rocks (such as limestone) and creates caverns and caves that can enlarge and collapse to form surface depressions called sinkholes. This type of dissolution-generated landform is common

Courtesy of U.S. Department of Agriculture

Figure 2.7 **Groundwater** is a largely invisible part of the hydrologic system because it occupies small pore spaces in the soil and rocks beneath the surface. It can, however, dissolve soluble rocks, such as limestone, to form complex networks of caves and subterranean passageways. As the caverns enlarge, their roofs may collapse, forming circular depressions called sinkholes. The hundreds of lakes shown in this false-color photograph of the area west of Cape Canaveral, Florida, occupy sinkholes and testify to the effectiveness of groundwater as a geologic agent.

in Kentucky, Florida, Indiana, and western Texas and is easily recognized from the air (**Figure 2.7**). Sinkholes commonly create a pockmarked surface somewhat resembling the cratered surface of the Moon. They may also become filled with water and form a series of circular lakes.

Shoreline Systems The hydrologic system also operates in **shoreline systems** along the shores of all continents, islands, and inland lakes through the unceasing work of waves. The oceans and lakes are bodies of mobile water subject to a variety of movements—waves, tides, and currents. All of these movements erode the coast and transport vast quantities of sediment (for example, the Nile Delta in Figure 2.2). The effects of shoreline processes are seen in wave-cut cliffs, shoreline terraces, deltas, beaches, bars, and lagoons.

Eolian (Wind) Systems The hydrologic system also operates in the arid regions of the world. In many deserts, river valleys are still the dominant landform. There is no completely dry spot on Earth. Even in the most arid regions some rain falls, and climate patterns change over the years. River valleys can be obliterated, however, by dunes of wind-blown sand that cover parts of the desert landscape (Figure 2.2).

The circulation of the atmosphere forms the **eolian system**. Wind can transport enormous quantities of loose sand and dust, leaving a distinctive record of the wind's activity. In the broadest sense, the wind itself is part of the hydrologic system, a moving fluid on the planet's surface.

The Tectonic System

The tectonic system involves the movement of the lithosphere, which is broken into a mosaic of separate plates. These plates move independently, separating, colliding, and sliding past one another. The margins of the plates are sites of considerable geologic activity, such as seafloor spreading, continental rifting, mountain building, volcanism, and earthquakes.

Geologists have long recognized that Earth has its own source of internal energy. It is repeatedly manifested by earthquakes, volcanic activity, and folded mountain belts. But it was not until the middle 1960s that a unifying theory developed to explain Earth's dynamics. This theory, known as **plate tectonics**, provides a master plan of Earth's internal dynamics. The term tectonics, like the related word architecture, comes from the Greek *tektonikos* and refers to building or construction. In geology, tectonics is the study of the formation and deformation of Earth's crust that results in large-scale features.

Evidence for this revolutionary theory of lithospheric movement comes from many sources. It includes data on the structure, topography, and magnetic patterns of the ocean floor; the locations of earthquakes; the patterns of heat flow in the crust; the locations of volcanic activity; the structure and geographic fit of the continents; and the nature and history of mountain belts.

The basic elements of the tectonic system are simple and can be easily understood by carefully studying **Figure 2.8**. The lithosphere, which includes Earth's crust and part of the upper mantle, is rigid, but the underlying asthenosphere slowly flows. A fundamental tenet of plate tectonics is that the segments, or **plates**, of the rigid

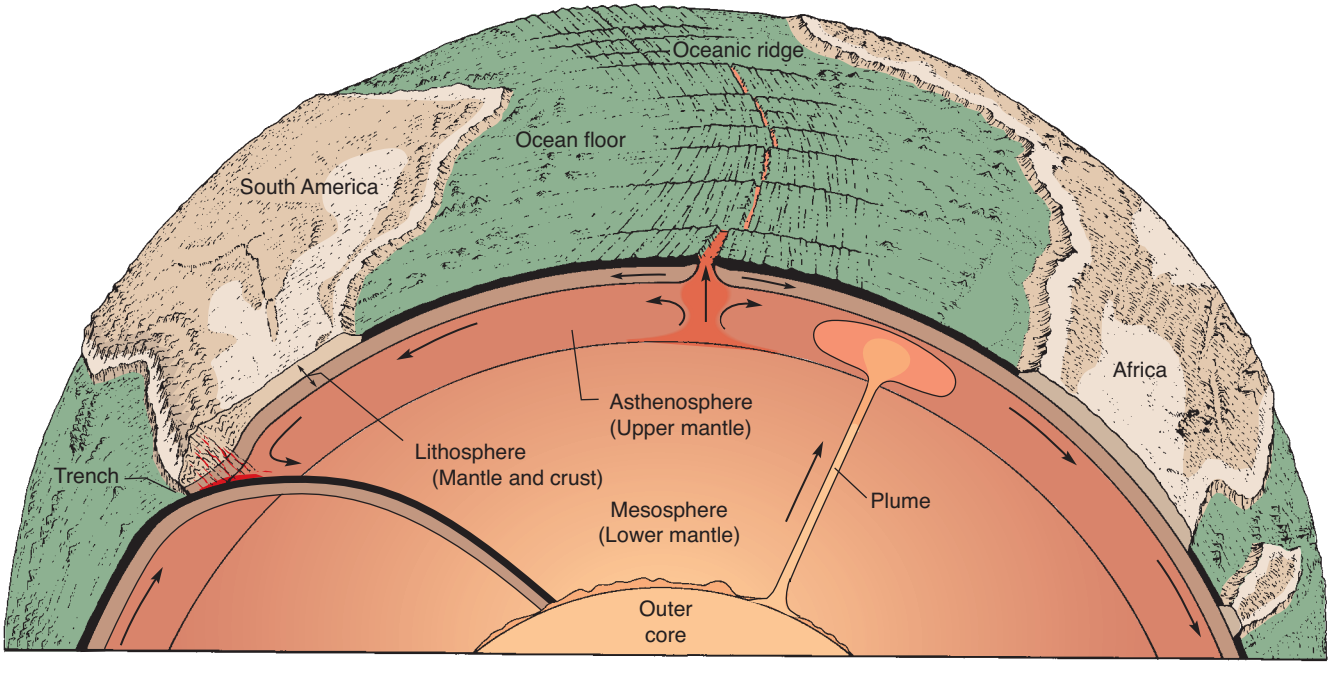


Figure 2.8 **The tectonic system** is powered by Earth's internal heat. The asthenosphere is more plastic than either the overlying lithosphere or the underlying lower mantle. Above the plastic asthenosphere, relatively cool and rigid lithospheric plates split and move apart as single mechanical units (along the ocean ridges). As this happens, molten rock from the asthenosphere wells up to fill the void between the lithospheric plates and thus creates new lithosphere. Very slow convection occurs in the mantle. Some plates contain blocks of thick, lower-density continental crust, which cannot sink into the denser mantle. As a result, where a plate carrying continental crust collides with another plate, the continental margins are deformed into mountain ranges. Plate margins are the most active areas on Earth—the sites of the most intense volcanism, seismic activity, and crustal deformation. Locally, convection in the deep mantle creates rising mantle plumes.

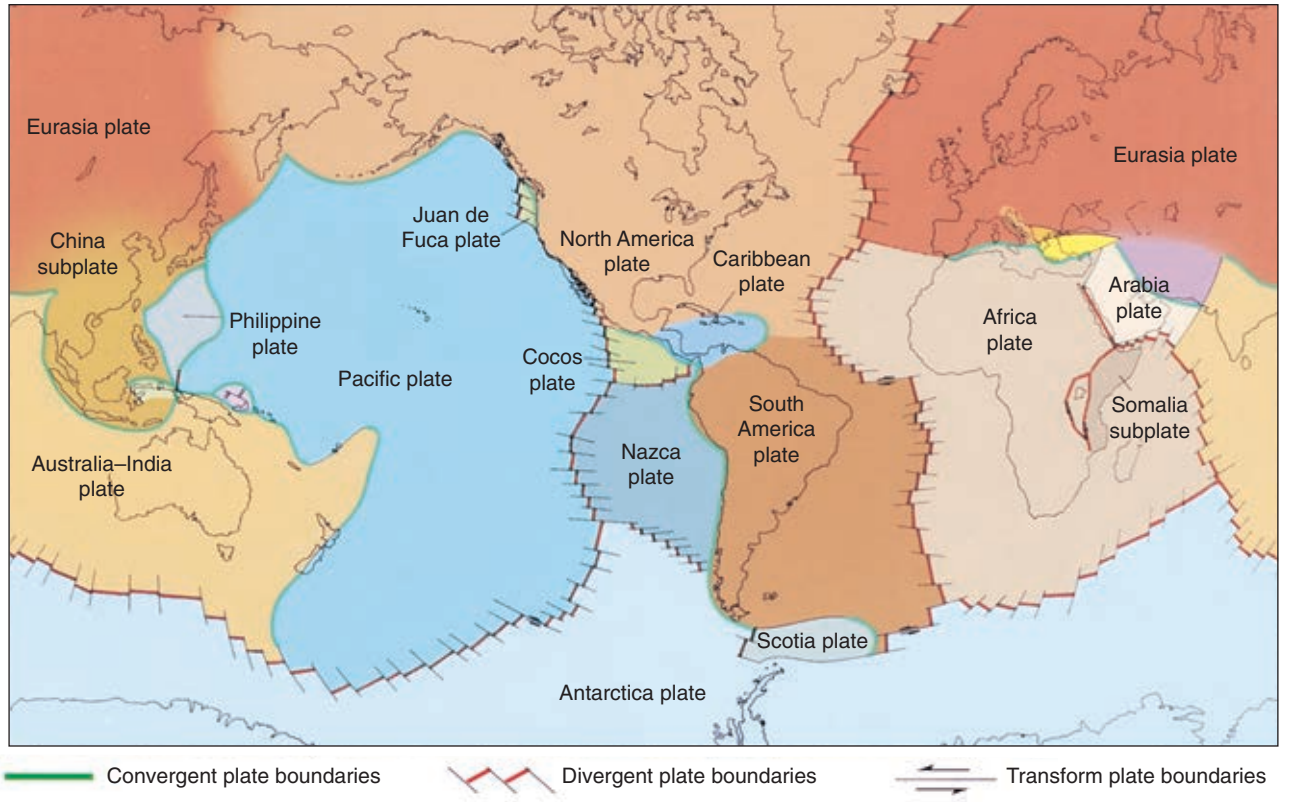


Figure 2.9 **A mosaic of plates** forms Earth's lithosphere, or outer shell. The plates are rigid, and each moves as a single unit. There are three types of plate boundaries: (1) the axis of the oceanic ridge, where the plates are diverging and new oceanic crust is generated (red lines); (2) transform faults, where the plates slide past each other (the short lines slicing across the divergent boundaries); and (3) subduction zones, where the plates are converging and one descends into the asthenosphere (blue lines).

lithosphere are in constant motion relative to one another and carry the lighter continents with them.

Plates of oceanic lithosphere form as hot mantle material rises along mid-oceanic ridges; they are consumed in **subduction** zones, where one converging plate plunges downward into the hotter mantle below (Figure 2.8). The descent of these plates is marked by deep-sea trenches that border island arcs and some continents. Where plates slide by one another, large fractures form. The movement and collision of plates accounts for most of Earth's earthquakes, volcanoes, and folded mountain belts, as well as for the drift of its continents.

From the standpoint of Earth's dynamics, the boundaries of plates are where the action is. As seen in **Figure 2.9**, plate boundaries do not necessarily coincide with continental boundaries, although some do. There are seven very large plates and a dozen or more small plates (not all of which are shown in Figure 2.9). Each plate is as much as a few hundred kilometers thick. Plates slide over the more mobile asthenosphere below, generally at rates between 1 and 10 cm per year. Because the plates are internally quite rigid, they become most deformed along their edges.

What is the source of energy for the tectonic system?

The basic source of energy for tectonic movement is believed to be Earth's internal heat, which is transferred by **convection**. In a simple model of Earth's convecting interior, hot mantle material rises to the lithosphere's base, where it then moves laterally, cools, and eventually descends to become reheated, continuing the cycle. A familiar example of convection can be seen while heating a pot of soup (**Figure 2.10**). Heat applied to the base of the pot warms the soup at the bottom, which therefore expands and becomes less dense. This warm fluid rises to the top and is forced to move laterally while it cools. Consequently, it becomes denser and sinks, setting up a continuing cycle of convection.

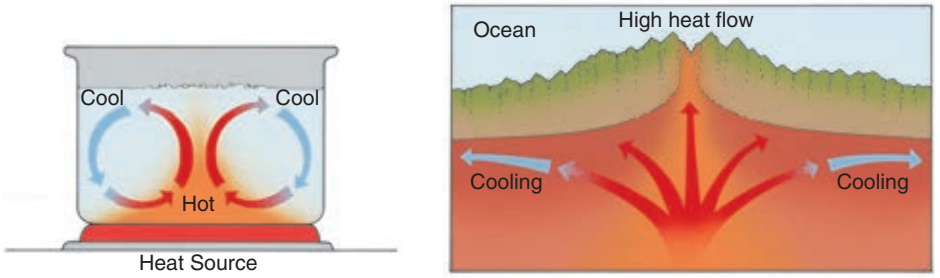


Figure 2.10 **Convection in the mantle** can be compared to convection in a pot of soup. Heat from below causes the material to expand and thus become less dense. The warm material rises by convection and spreads laterally. It then cools, and thus becomes denser, and sinks. It is reheated as it descends, and the cycle is repeated.

Major Subsystems of the Tectonic System

Many features of the ocean basins and continents can be nicely explained by the plate tectonic system. We will consider many of them in detail elsewhere in the text, but let us look briefly at the major features of the planet and how they fit into the tectonic system. The different types of plate boundaries are, in effect, subsystems of the tectonic system. Each creates specific geologic phenomena. We have illustrated each boundary type with an example from the continents.

What are the major subsystems of the tectonic system and how do they operate?

Divergent Plate Boundaries The plates move apart at **divergent plate boundaries**, which coincide with mid-oceanic ridges (Figure 2.9). Hot molten material from the deeper mantle wells up to fill the void. Some of this material erupts on the seafloor as lava. The molten rock solidifies and forms new lithosphere. The mid-oceanic ridges stand high because their material is hot and, therefore, less dense than the colder adjacent oceanic crust.

The most intense volcanism on Earth occurs at divergent plate boundaries, but it is largely concealed below sea level. When oceanic earthquake locations are plotted on a map, they outline with dramatic clarity the divergent plate boundaries (**Figure 2.11**). Most of these are shallow earthquakes, quite unlike those found where plates converge.

Most divergent boundaries occur on the seafloor (**Figure 2.12**), but continental rifts also develop where divergent boundaries form on the continents. Such a continental rift eventually creates a new ocean basin. The great rift of the Red Sea (Figure 2.2) displays many features of a continental rift. The Red Sea is an extension of the mid-oceanic ridge of the Indian Ocean, which splits the Sinai and Arabian peninsulas from Africa. Take the time to locate the area shown in this remarkable photograph (Figure 2.2) on the topographic map on the inside covers of this book. The structure of the area is dominated by the long, linear fault valley that forms the north end of the Red Sea and Gulf of Suez. Note the sharp contrast where faults have juxtaposed young, light-colored sediments against the ancient shields as this region is slowly ripping asunder. New seafloor is forming on the floor of the Red Sea. This rift expresses dramatically the tensional stresses in the lithosphere and the way these stresses affect Earth's surface.

Transform Plate Boundaries The oceanic ridges are commonly broken and offset along lines perpendicular to the ridges. These offsets are large faults expressed by their own high ridges and deep valleys. **Transform plate boundaries** occur where plates horizontally slide past one another (**Figure 2.13**). Shallow earthquakes are common along all transform boundaries (Figure 2.11), but volcanic eruptions are uncommon.

Most transform plate boundaries are on the seafloor, but the best-known example of this type of fault on a continent is the great San Andreas Fault system in California (Figure 2.13). The fault zone is marked by sharp linear landforms, such as straight and narrow valleys, straight and narrow ridges, and offset stream valleys. The San Andreas Fault system is an active boundary between the Pacific plate to the west and the North America plate to the east. The Pacific plate is moving at about 6 cm per

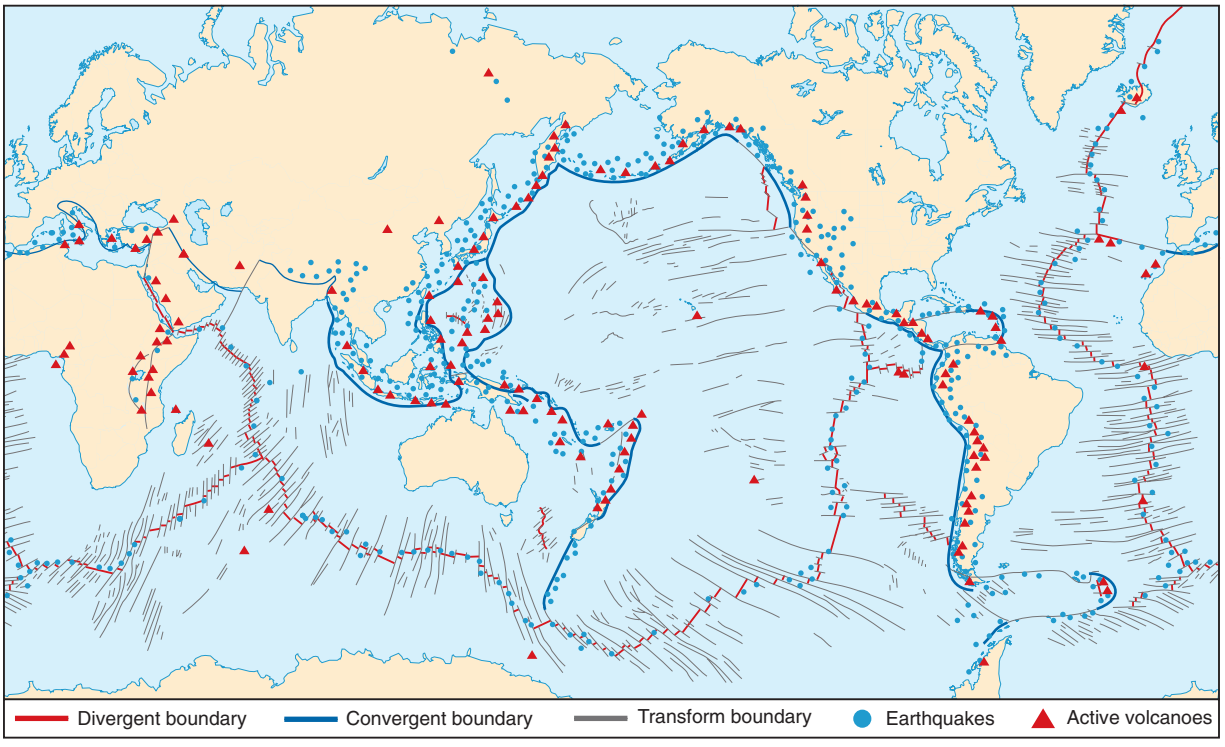
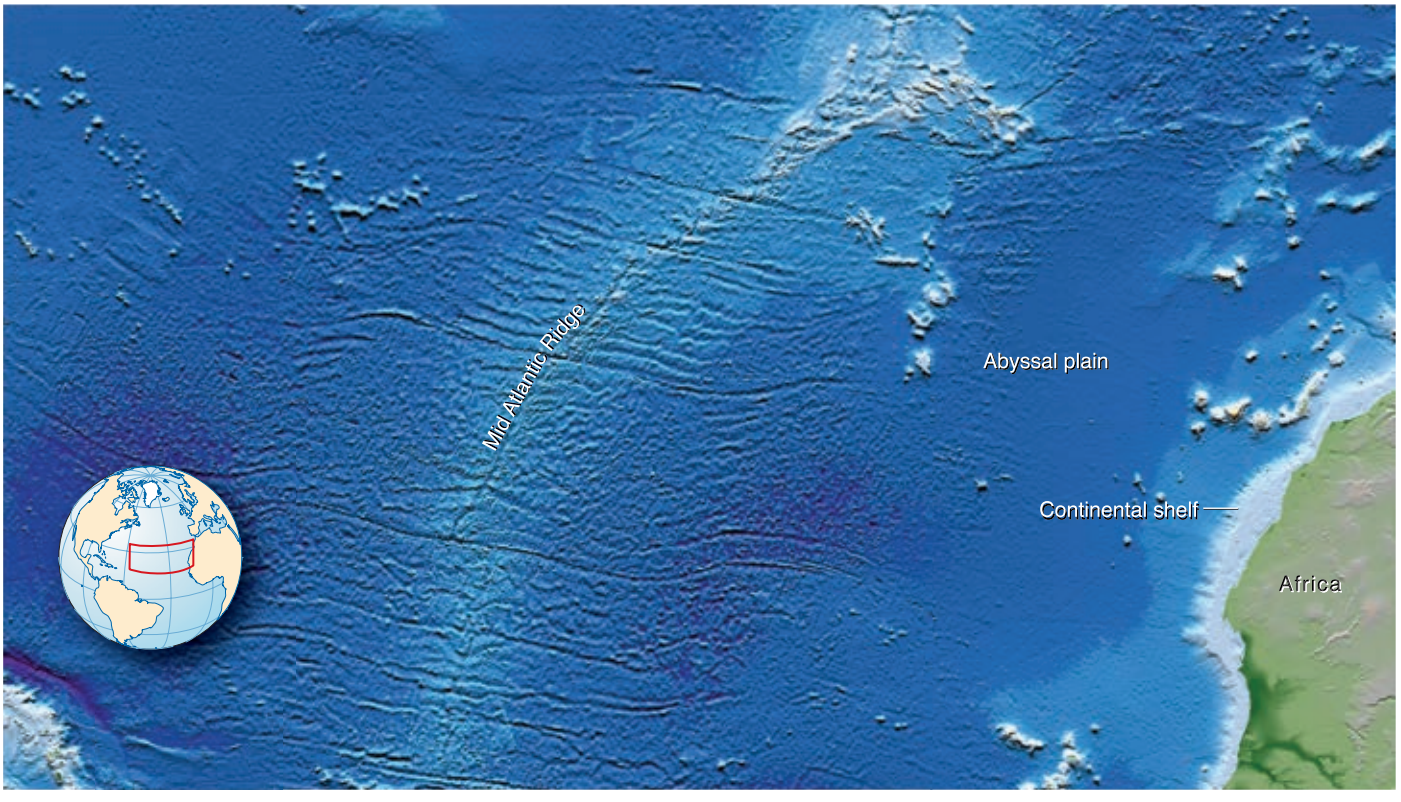
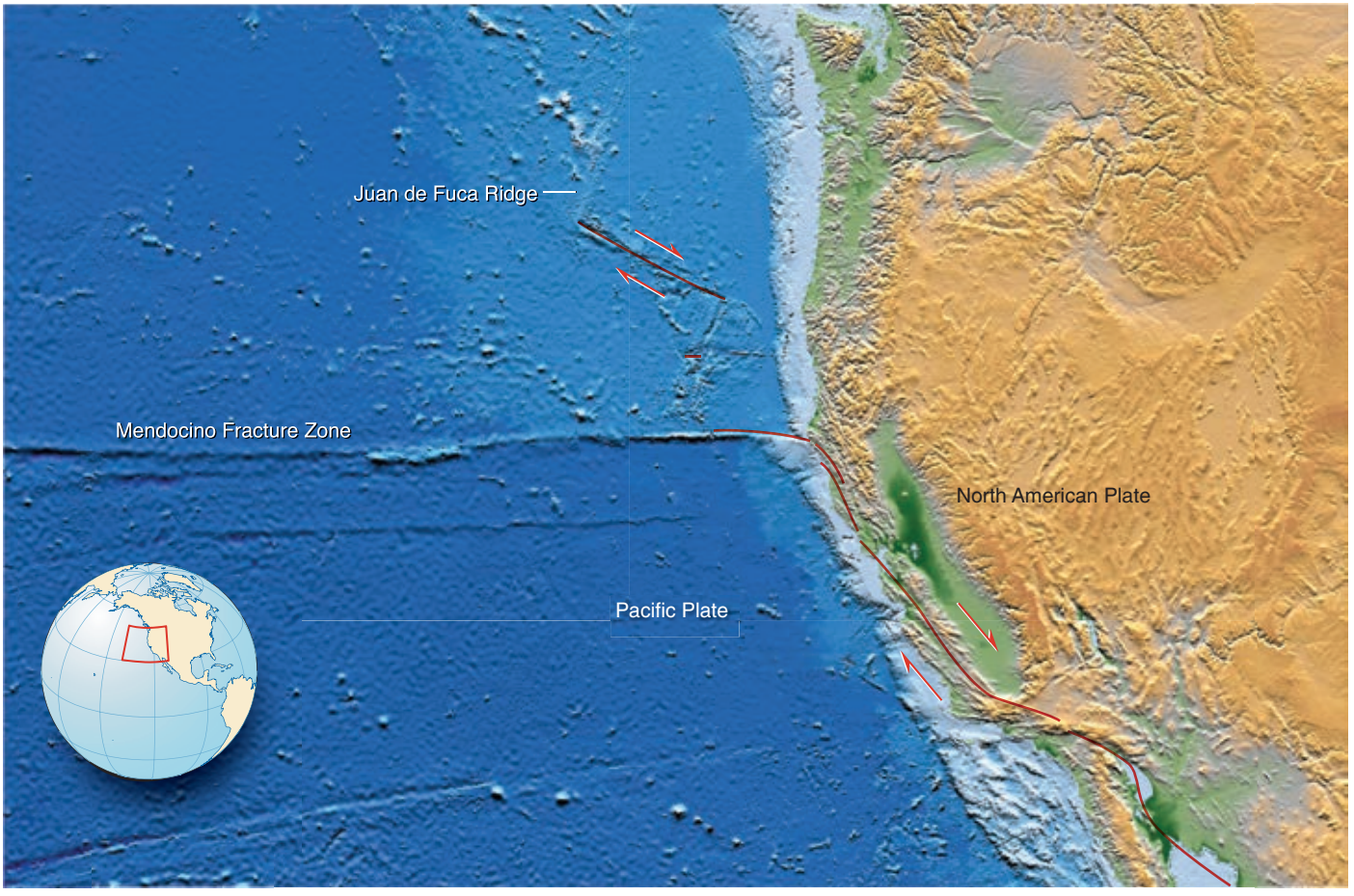


Figure 2.11 **Earthquakes and active volcanoes** outline plate margins with remarkable fidelity. At divergent plate boundaries, shallow earthquakes, submarine volcanic eruptions, and tensional fractures occur. Transform boundaries have shallow earthquakes but generally lack active volcanoes. Along convergent margins, there are deep earthquakes, volcanic eruptions, trenches on the seafloor, and folded mountain belts. Isolated areas of volcanism and earthquakes reveal the locations of active mantle plumes.



Base map by Ken Perry, Chalk Butte, Inc.

Figure 2.12 **The Mid-Atlantic Ridge** is a divergent plate boundary and marks the spot where new lithosphere is forming and where two plates are separating. The North America plate is slowly moving west and Africa on the Eurasia plate is moving east. Earthquakes and volcanoes are concentrated along the crest of the ridge. Transform faults cut the ridge and offset it.



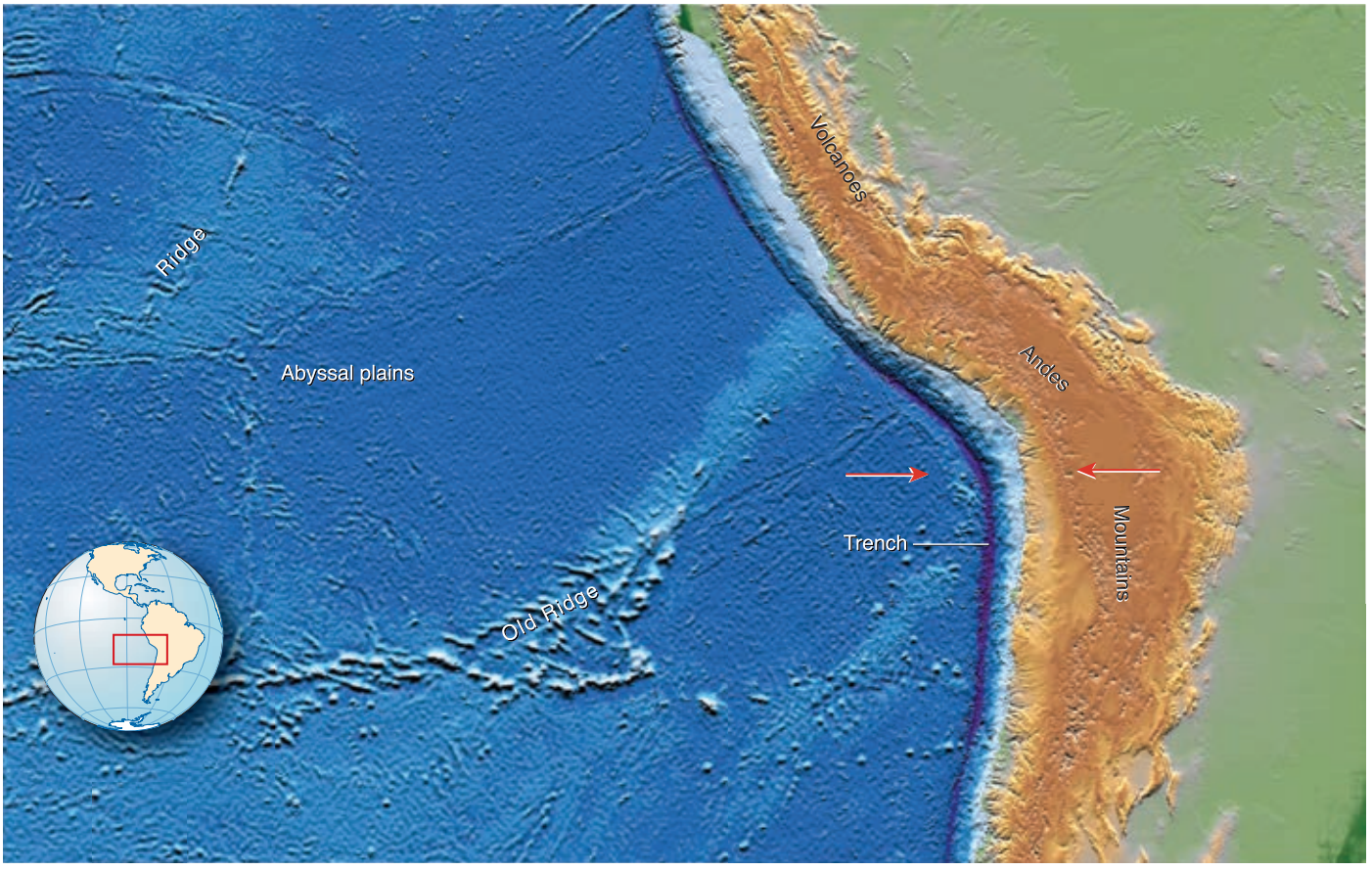
Base map by Ken Perry, Chalk Butte, Inc.

Figure 2.13 **The San Andreas Fault system** in California is part of a long transform plate boundary that separates the North America plate from the Pacific plate. It connects a divergent boundary in the Gulf of California with the Mendocino transform fault and the Juan de Fuca ridge. At least a dozen major fault systems can be seen as linear mountain trends. Movement along the San Andreas Fault is horizontal; that is, one block of Earth's slides laterally past another.

year, relative to the North America plate. As stress builds between the plates, the rock bodies deform until they break. This sudden release along the fault causes earthquakes like those so common in California. Another transform boundary cuts the Asian continent from the Gulf of Aqaba to the Dead Sea and creates a valley obvious from space (Figure 2.2).

Convergent Plate Boundaries Plates move toward one another along **convergent plate boundaries**. Along such plate margins, geologic activity is far more varied and complicated than at transform plate boundaries (**Figure 2.14**). Intense compression ultimately rumples the lithosphere and builds high folded mountain belts. Preexisting rocks become altered by heat and pressure. The net result is the growth of continents. Where two plates converge, one tips down and slides beneath the other in a process known as *subduction*.

It is clear that earthquakes and volcanoes dramatically outline convergent plate margins (Figure 2.11). The simplest form of convergence involves two plates with oceanic crust. Such subduction zones in the western and northern Pacific region lie along the volcanic islands of Tonga, the Marianas, and the Aleutians. Trenches form where the downgoing plate plunges into the mantle. These are long, narrow troughs, normally 5 to 8 km deep, and are the lowest features on Earth. As a plate of lithosphere slips into the mantle, it becomes heated and dehydrated. Some rock material melts, becomes less dense, and rises, and some erupts to form a string of volcanic islands called an island arc.



Base map by Ken Perry, Chalk Butte, Inc.

Figure 2.14 **The Andes Mountains** were formed by the subduction of the Nazca plate beneath South America at a convergent plate margin. Layers of sedimentary rock, which were originally horizontal, have been elevated and compressed into folds that were subsequently eroded. The resistant layers appear as ridges in the eastern Andes. Folded mountain belts such as the Andes are one of the most significant results of converging plates, but if you look carefully you can also see the relatively smooth volcanic plains and isolated volcanic cones that show the role played by volcanism at convergent plate margins.

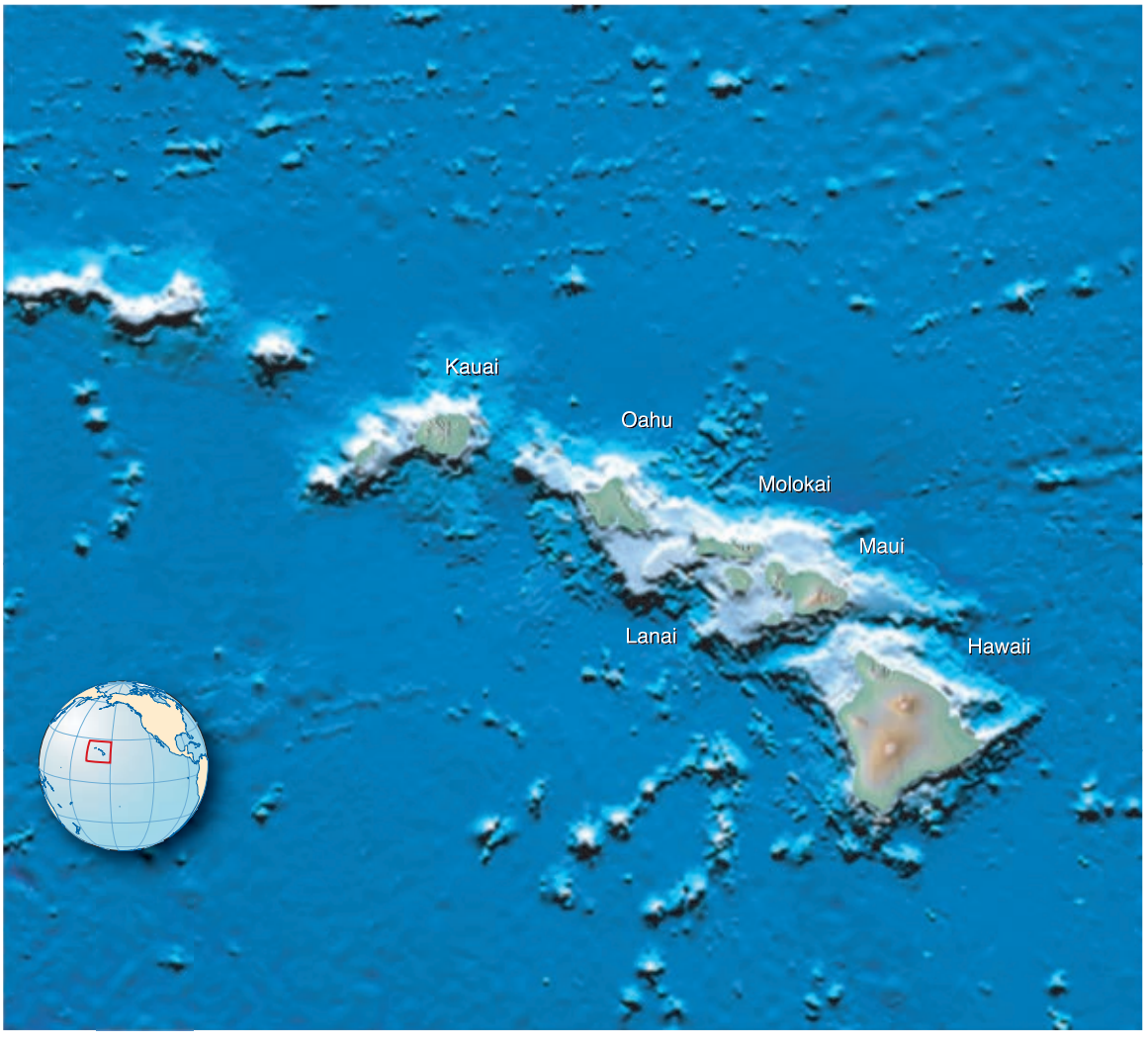
If the oceanic plate dives beneath a continent, the molten rock may form a chain of volcanoes on the continental margin; the Cascades of California-Oregon-Washington are an example. The remarkable series of deep-sea trenches and associated volcanic arcs make the "ring of fire" that almost surrounds the Pacific Ocean (Figure 2.11).

As each subducting plate grinds its way downward, earthquakes are produced. The deepest of all earthquakes, almost 700 km deep, occur at convergent plate boundaries. Plate tectonics can thus readily explain why the Andes mountains of South America are tormented by repeated volcanic eruptions and earthquakes (Figure 2.14). They are forming where two tectonic plates converge. The same is true for the western coasts of Central America. It is equally clear that the earthquakes and volcanic eruptions in the Mediterranean area occur at a convergent plate margin.

Where moving plates converge, the rocks in the crust may also become deformed. The crust in continents and in island arcs is buoyant (it is less dense than oceanic crust) and resists subduction back into the dense mantle. Consequently, this kind of crust becomes intensely compressed and folded at some convergent plate margins. The structures of the Andes Mountains (Figure 2.14) of South America vividly express this type of deformation. The complex system of ridges and valleys in the eastern Andes is produced by folded sedimentary rock layers deformed by the collision of two plates. The folded layers now appear like wrinkles in a rug. The Appalachians were formed in a similar manner.

A younger mountain belt that extends from Alaska through the Rockies and Central America and into the Andes of South America was produced by the encounter of the American plates with the Pacific, Cocos, and Nazca plates. This is a geologically young mountain system, with many parts still being deformed as the plates continue to move.

Within-Plate Tectonics and Mantle Plumes Within the moving plates, the continental and oceanic crust experience little tectonic or volcanic activity as they move away from mid-oceanic ridges. However, **plumes** of hot rock rising from the deep mantle (Figure 2.8) may create isolated volcanoes and gently warp the interior of a plate. An excellent example is the Hawaiian Island chain in the Pacific Ocean (**Figure 2.15**). The huge volcanoes and geysers of Yellowstone National Park in western North America may also overlie a mantle plume. Earthquakes related to the volcanoes in these areas are also common (Figure 2.11), but large deep earthquakes are rarely felt in such within-plate regions.



Base map by Ken Perry, Chalk Butte, Inc.

Figure 2.15 **The Hawaiian Islands** formed far from any plate boundary and are thought to lie above a plume of hot material rising through the mantle. As the lithosphere slowly moves northeast, it carries the older volcanoes away from the hot spot. Volcanoes are still active on the large southern island of Hawaii, but not on the more eroded Maui, and other islands to the northeast where the action of the hydrologic system is dominant.

STATE OF THE ART Heat Flow Measurements and Plate Tectonics

Earth is a giant heat engine. Not only does it create its own heat, but its tectonic system is driven by the flow of this heat. The outer core is molten and convects vigorously. Portions of the mantle melt. Volcanoes erupt hot lava. Hot springs bubble and boil. Metallic ore deposits form from hot fluids. These facts underscore the importance of understanding Earth's internal heat. To do this, geologists evaluate *heat flow* by measuring the amount of thermal energy released through a given area (in milliwatts/m^2). Heat flow is usually measured by lowering a sensitive thermometer down a deep drill hole and recording the temperature—sometimes called the *geothermal gradient*.

The map summarizes decades of careful measurements and shows fundamental relationships between heat flow and global tectonic setting (compare with Figure 2.11). It is obvious that heat flow is not distributed uniformly across the planet. But why do these patterns emerge? Where is Earth's internal heat coming from anyway?

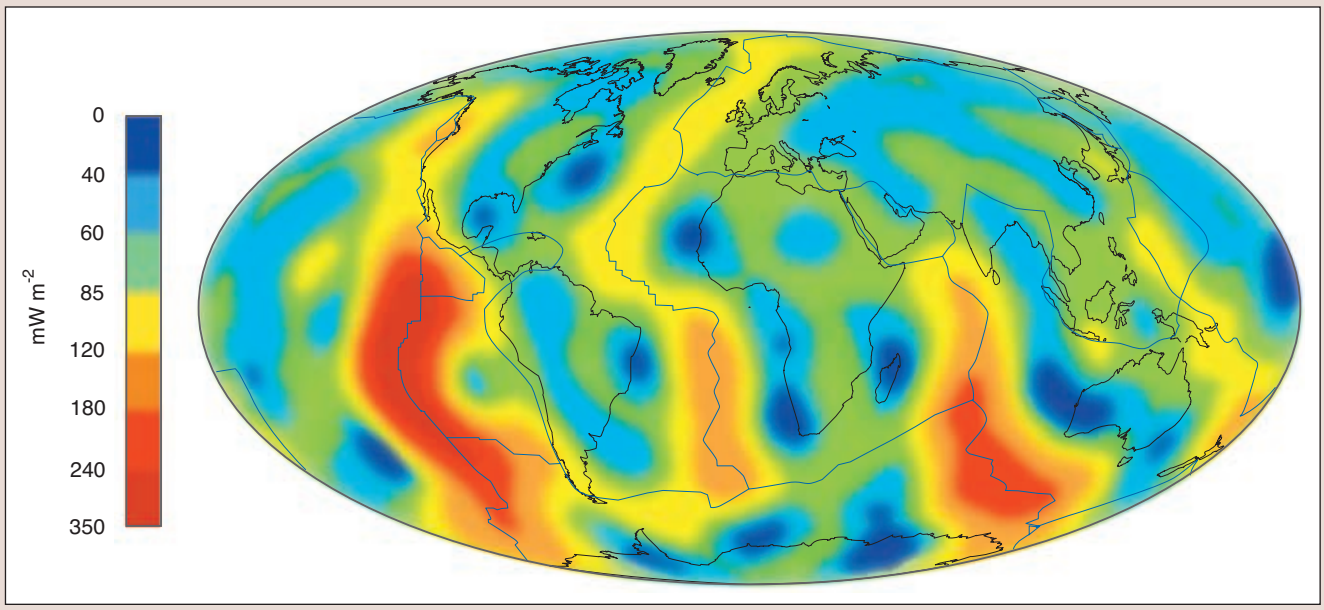
Let us answer the last question first. Today, most of the heat released from Earth is generated by radioactive decay of three elements found in small quantities in almost all rocks—potassium, uranium, and thorium. The heat is created when small quantities of matter are converted to energy. Even though the mantle contains very low concentrations of these radioactive elements, it is so thick and massive that the mantle is the dominant source of Earth's thermal energy. Therefore, heat flow (and the temperature gradient) is high where the hot mantle is near the surface.

This principle helps us understand why heat flow is so high below oceanic regions where the cold lithosphere is thin compared to that beneath the continents. Another way of thinking about this oceanic thermal anomaly is to remember that oceanic lithosphere is hot when it forms by igneous processes at ocean ridges. It is also much younger than most continental lithosphere and has not yet lost all of its heat. Moreover, the highest heat flow regions are the mid-ocean ridges—especially the East Pacific rise and the ridge in the Indian Ocean. At the ridge, the lithosphere is young, thin, and the site of active volcanism.

Courtesy of H.N. Pollack

The zones of lowest heat flow correspond to ancient central parts of the continents—the shields (compare with the map on the inside front cover). Apparently, the lithosphere is cool and thick under the ancient shields.

Another interesting pattern is visible upon careful examination of the heat flow over trenches (or subduction zones). Note that heat flow is low over the subduction zones near Indonesia and the west coast of South America. Why is heat flow low near these zones of active volcanoes? Probably because the subduction of cold oceanic lithosphere refrigerates the mantle and reduces the heat flow.



Data from H.N. Pollack and D.S. Chapman

What are the major plates and how are they moving?

Plates and Plate Motion

Take a moment to study Figure 2.9 again. You will want to become very familiar with this map because it shows a new geography—the geography of tectonic plates. As you have seen, most of Earth's major features can be understood from the interactions of these plates in the tectonic system.

In Figure 2.9, you can see that seven major lithospheric plates are recognized—the North America, South America, Pacific, Australia, Africa, Eurasia, and Antarctica plates—together with several smaller ones. Let us take a brief tour, so you will know what to look for.

1. The divergent plate boundaries are marked by oceanic ridges, which extend from the Arctic south through the central Atlantic and into the Indian and Pacific oceans. Movement of the plates is away from the crest of the oceanic ridge.
2. The North America and South America plates are moving westward and interacting with the Pacific, Juan de Fuca, Cocos, and Nazca plates along the west coast of the Americas.
3. The Pacific plate is moving northwestward away from the oceanic ridge toward a system of deep trenches in the western Pacific basin.
4. The Australia plate includes Australia, India, and the northeastern Indian Ocean. It is moving northward, causing India to collide with the rest of Asia to produce the high Himalaya Mountain ranges and the volcanic arc of Indonesia.
5. The Africa plate includes the continent of Africa, plus the southeastern Atlantic and western Indian oceans. It is moving northward and colliding with the Eurasia plate.
6. The Eurasia plate, which consists of Europe and most of Asia, moves eastward.
7. The Antarctica plate includes the continent of Antarctica, plus the floor of the Antarctic Ocean. It is unique in that it is nearly surrounded by oceanic ridges.

Gravity and Isostasy

Gravity plays a fundamental role in Earth's dynamics. It is intimately involved with differentiation of the planet's interior, isostatic adjustments of the crust's elevation, plate tectonics, and downward flow of water in the hydrologic system.

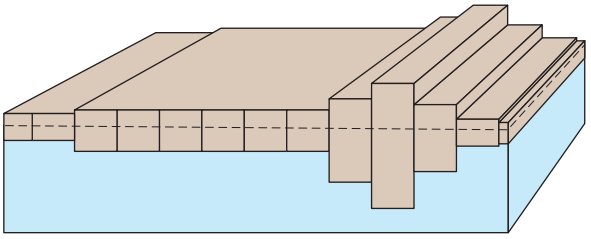
How is isostasy a reflection of an equilibrium state?

Gravity is one of the great fundamental forces in the universe. It played a vital role in the formation of the solar system, the origin of the planets, and the impact of meteorites that dominated their early history. Since then, gravity has been a constant force in every phase of planetary dynamics, and it is a dominant factor in all geologic processes operating on and within Earth—glaciers, rivers, wind, and even volcanoes.

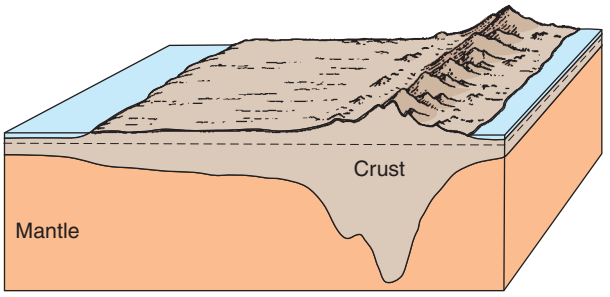
Gravity also operates on a much grander scale within Earth's crust. It causes "lighter" (less dense) portions, such as continents, to stand higher than the rocks of the "heavier," denser ocean floor. Similarly, the loading of Earth's crust at one place with thick sediment in a river delta, or with glacial ice, or with water in a deep lake will cause that region to subside. Conversely, the removal of rock from a mountain range by erosion will lighten the load, causing the deep crust to move upward to take its place. This gravitational adjustment of Earth's crust is **isostasy** (Greek *isos*, "equal"; *stasis*, "standing"). Earth's lithosphere therefore continuously responds to the force of gravity as it tries to maintain a gravitational balance.

Isostasy occurs because the crust is more buoyant than the denser mantle beneath it. Each portion of the crust displaces the mantle according to its thickness and density (**Figure 2.16**). Denser crustal material sinks deeper into the mantle than does less-dense crustal material. Alternatively, thicker crustal material will extend to greater depth than thin crust of the same density. Isostatic adjustments in Earth's crust can be compared to adjustments in a sheet of ice floating on a lake as you skate on it. The layer of ice bends down beneath you, displacing a volume of water with a weight equal to your weight. As you move ahead, the ice rebounds behind you, and the displaced water flows back.

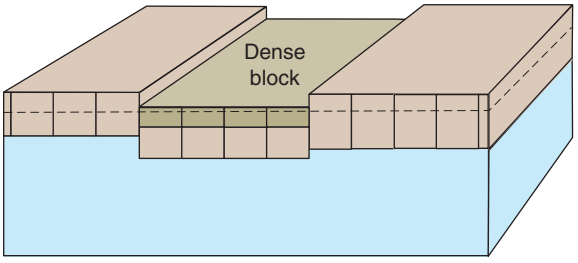
As a result of isostatic adjustment, high mountain belts and plateaus are commonly underlain by thicker crust that extends deeper into the mantle than do



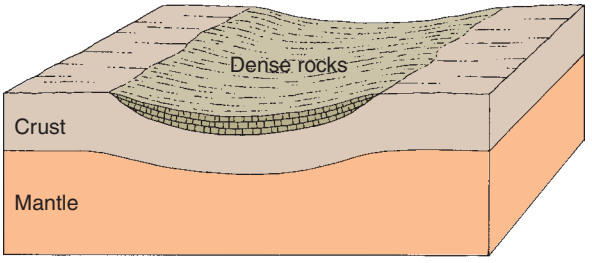
(A) Low-density blocks float on a denser liquid. If the blocks have equal densities, the thicker blocks rise higher and sink deeper than the thinner blocks.



(B) High mountains in low-density crust are balanced by a deep root that extends into the mantle.



(C) Floating blocks of unequal density. The block with denser (green) portions sinks and the surface is lower than the adjacent blocks, even though the thickness is the same.



(D) A deep basin may form if the rocks beneath it are denser (green) than surrounding rocks (brown).

Figure 2.16 **Isostasy** is the universal tendency of segments of Earth's crust to establish a condition of gravitational balance. Differences in both thickness and density can cause isostatic adjustments in Earth's crust.

areas of low elevation. Any thickness change in an area of the crust—such as the removal of material by erosion or the addition of material by sedimentation, volcanic eruption, or accumulations of large continental glaciers—causes an isostatic adjustment.

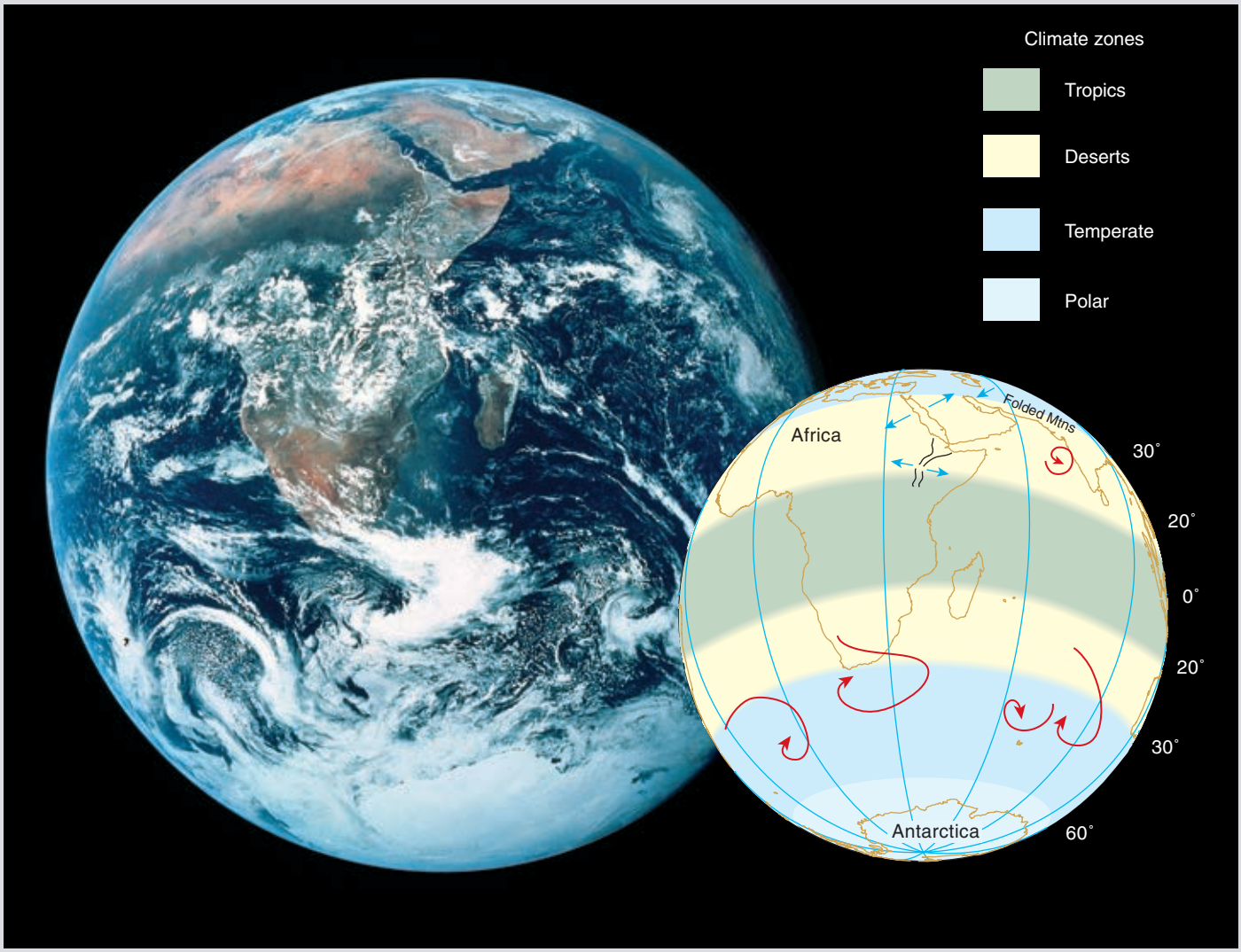
How do we know that isostatic adjustments occur?

The construction of Hoover Dam, on the Colorado River, is a well-documented illustration of isostatic adjustment. The added weight of water and sediment in the reservoir was sufficient to cause measurable subsidence. From the time of the dam's construction in 1935, 24 billion metric tons of water, plus an unknown amount of sediment, accumulated in Lake Mead, behind the dam. In a matter of years, this added weight caused the crust to subside in a roughly circular area around the lake. Continental glaciers are another clear example of isostatic adjustment of the crust. The weight of an ice sheet several thousand meters thick disrupts the crustal balance and depresses the crust beneath. In both Antarctica and Greenland, the weight of the ice has depressed the central part of the land masses below sea level. A similar isostatic adjustment occurred in Europe and North America during the last ice age, when continental glaciers existed there. Parts of both continents, such as Hudson Bay and the Baltic Sea, are still below sea level. Now that the ice is gone, however, the crust is rebounding at a rate of 5 to 10 m/1000 yr.

Tilted shorelines of ancient lakes provide another means of documenting isostatic rebound. Lake Bonneville, for example, was a large lake in Utah and Nevada during the ice age but has since dried up, leaving such small remnants as Utah Lake and Great Salt Lake. Shorelines of Lake Bonneville were level when they were formed but have been tilted in response to unloading as the water was removed.

The concept of isostasy, therefore, is fundamental to studies of the crust's major features—continents, ocean basins, and mountain ranges. It also is fundamental to understanding the response of the crust to erosion, sedimentation, glaciation, and the tectonic system.

GeoLogic Earth's Systems from Space



Courtesy of NASA

A view of planet Earth from space gives us a truly global view of the geologic systems that shape the planet.

Observations

1. The continents and ocean basins are Earth's most prominent features.
2. The planet's water is seen in the vast blue oceans and the white polar ice caps. Water cycles through the atmosphere as shown by the bright swirling clouds.
3. Climate zones are expressed as regular patterns in the distribution of green vegetation on land, of the amount and shapes of clouds in the atmosphere, and ice at the poles.

Interpretations

Two major geologic systems shape the Earth—the hydrologic system and the tectonic system. The tectonic system created the lithosphere with its huge ocean basins and high continental platforms, which are underlain by rocks of different compositions, structures, and ages. Locally, new ocean basins are forming where continents are rifting apart as shown by the separation of Africa from Arabia. Elsewhere, plates are colliding to form new continents and mountain belts like the one barely visible in southern Iran.

The hydrologic system endlessly modifies the surface features of the lithosphere with rain, wind, waves, flowing water, and ice. The role played by the climate in the operation of the hydrologic system is clear. In the cloud-spotted tropics, air heated by the Sun rises in vertical convection cells making abundant rainfall and fueling the growth of vegetation in the biosphere. Cloud-free deserts lie north and south of the tropics. At the South Pole, the cold climate has created the vast Antarctic glacier. Cyclonic storms, which appear as clouds resembling huge commas, show the prevailing wind patterns generated by solar radiation and by Earth's rotation.

Key Terms

climate system (p. 38)
closed system (p. 33)
convection (p. 43)
convergent plate boundary (p. 46)
divergent plate boundary (p. 44)
dynamic system (p. 33)
eolian system (p. 41)
equilibrium (p. 34)
glacier system (p. 40)
groundwater system (p. 40)
hydrologic system (p. 36)
isostasy (p. 50)
metastable (p. 35)
open system (p. 33)
plate (p. 42)
plate tectonics (p. 42)
plume (p. 48)
river system (p. 39)
shoreline system (p. 41)
subduction (p. 43)
system (p. 32)
transform plate boundary (p. 44)

Review Questions

1. Consider the gravitational interactions among Earth, the Sun, and the Moon. Does this constitute a system? If so, what are its boundaries? Is it open or closed? What forms of energy are involved?
2. Diagram the paths by which water circulates in the hydrologic system.
3. What energy drives the hydrologic system?
4. Approximately how much water evaporates from the ocean each year?
5. Describe the major landforms resulting from (a) rivers, (b) groundwater, (c) glaciers, and (d) wind.
6. Draw a diagram (cross section) showing (a) converging plates and (b) diverging plates.
7. On a map such as the one in Figure 2.9, identify the three fundamental kinds of plate boundaries.
8. What surface features distinguish each kind of plate boundary?
9. Explain how the Alps, mid-ocean ridges, deep-sea trenches, island arcs, and volcanoes are related to plate tectonics.
10. Describe the geologic processes that occur above a mantle plume.
11. Why do the materials inside Earth convect?
12. Make a list of the many roles played by gravity in geologic systems.
13. Explain isostasy, and give two examples of isostatic adjustment of Earth's crust in recent geologic time.