UNDERSTANDING EARTH

FOURTH EDITION

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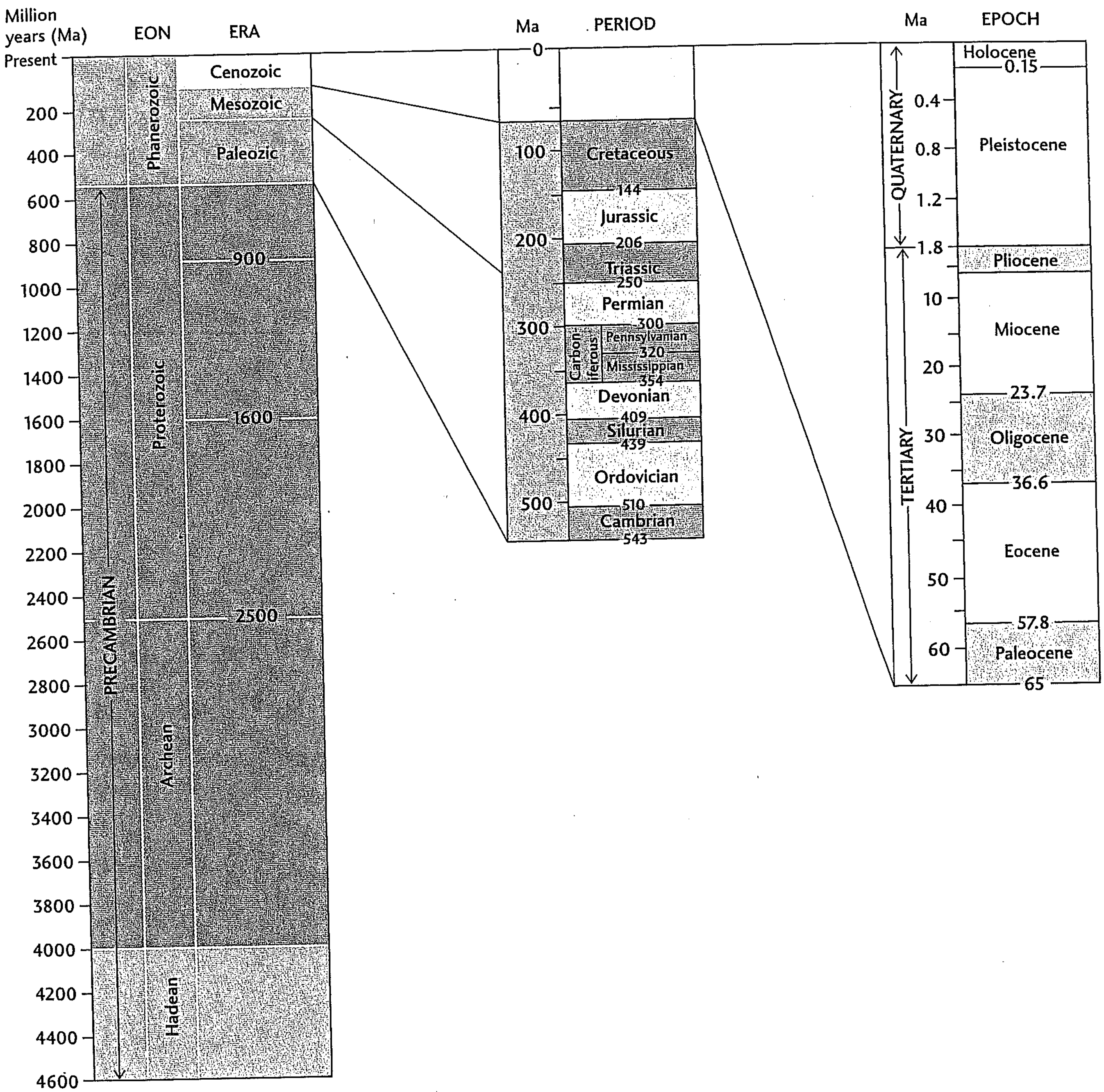
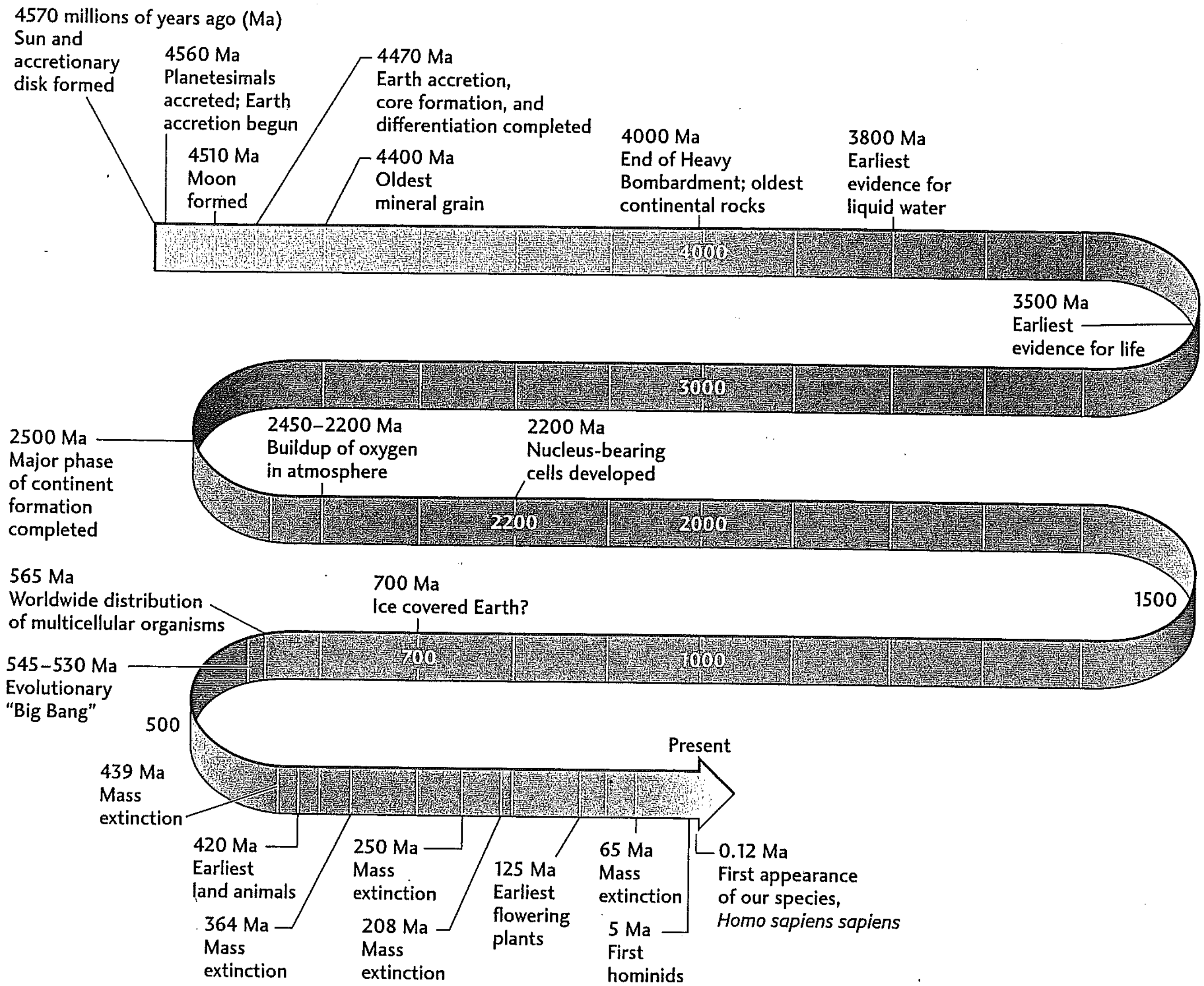
The geologic time scale



The ribbon of geologic time, from the formation of the solar system to the present



• *The Giant Outer Planets* Most of the volatile materials swept from the region of the terrestrial planets were carried to the cold outer reaches of the solar system to form the giant outer planets made up of ices and gases—Jupiter, Saturn, Uranus, and Neptune—and their satellites. The giant planets were big enough and their gravitational attraction strong enough to enable them to hold onto the lighter nebular constituents. Thus, although they have rocky cores, they (like the Sun) are composed mostly of hydrogen and helium and the other light constituents of the original nebula.

This standard model of solar system formation should be taken only for what it is: a tentative explanation that many scientists think best fits the known facts. Perhaps the model comes close to what actually happened. More important, however, this model gives us a way to think about the origin of the solar system that can be tested by observing the planets of our solar system and by studying other stars. American and Russian spacecraft carrying planetary probes have returned data about the nature and composition of the atmospheres and surfaces of Mercury, Venus, Mars, Jupiter, Saturn, Uranus, Neptune, and the Moon. A startling finding is that, in our solar system consisting of 9 planets and at least 60 satellites, no two bodies are the same!

Other Solar Systems

For ages, scientists and philosophers have speculated that there may be planets around stars other than our Sun. In the 1990s, using large telescopes, astronomers discovered planets orbiting nearby Sun-like stars. In 1999, the first family of *exoplanets*—the solar systems of another star—was found. These planets are too dim to be seen directly by telescopes, but their existence can be inferred from their slight gravitational pull on the stars that they orbit, causing to-and-fro movements of the star that can be measured. Currently, more than 90 exoplanets have been identified. Most planets found in this way are Jupiter-sized or larger and are close to their parent stars—many within scorching distance. Earth-sized planets are too small to be detected by this technique, but astronomers might be able to find such planets using other methods. For example, in about 10 years or so, spacecraft above Earth's atmosphere should be able to search for the dimming of the parent star's light as an orbiting planet passes in front of it along the line of sight to Earth.

We are fascinated by planetary systems around other stars because of what they might teach us about our own origins. Our overriding interest, though, is in the profound scientific and philosophical implications posed by the question: "Is anyone else out there?" In about 20 years, a spacecraft named *Life Finder* could be carrying instruments to analyze the atmospheres of exoplanets in our galaxy for signs of the presence of some kind of life. Based on what we know about biological processes, life on an exoplanet would probably be carbon-based and require liquid water. The benign temperatures we enjoy on Earth—not too far outside the range between the freezing and boiling points of water—appear to be essential. An atmosphere is needed to filter harmful radiation from the parent star, and so the planet must be large enough for its gravitational field to keep the atmosphere from escaping into space. For a habitable planet with advanced life *as we know it* to exist would require conditions even more limiting. For example, if the planet were too massive, delicate organisms such as humans would be too weak to withstand its larger gravitational force. Are these requirements too restrictive for life to exist elsewhere? Many scientists think not, considering the billions of Sun-like stars in our own galaxy.

Early Earth: Formation of a Layered Planet

How did Earth evolve from a rocky mass to a living planet with continents, oceans, and an atmosphere? The answer lies in **differentiation:** the transformation of random chunks of primordial matter into a body whose interior is divided into concentric layers that differ from one another both physi-

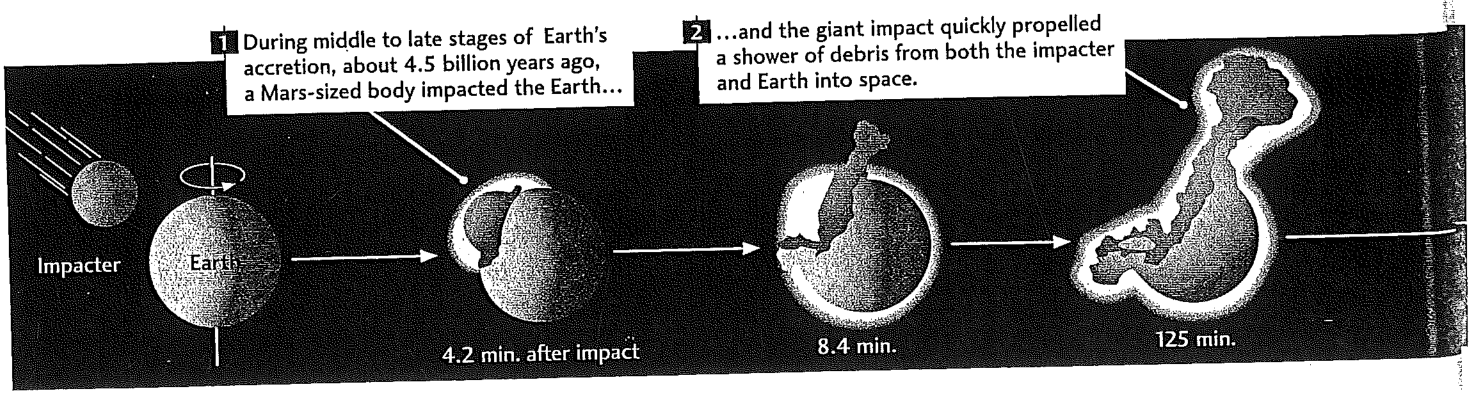


Figure 1.5 Computer simulation of the origin of the Moon by the impact of a Mars-sized body on Earth. [*Solid Earth Sciences and Society,* National Research Council, 1993.]

cally and chemically. Differentiation occurred early in Earth's history, when the planet got hot enough to melt.

Earth Heats Up and Melts

To understand Earth's present layered structure, we must return to the time when Earth was still subject to violent impacts by planetesimals and larger bodies. A moving object carries kinetic energy, or energy of motion. (Think of how the energy of motion crushes a car in a collision.) A planetesimal colliding with Earth at a typical velocity of 15–20 km/s would deliver as much energy as 100 times its weight in TNT. When planetesimals and larger bodies crashed into the primitive Earth, most of this energy of motion was converted into heat, another form of energy. The impact energy of a body perhaps twice the size of Mars colliding with Earth would be equivalent to exploding several trillion 1-megaton nuclear bombs (a single one of these terrible weapons would destroy a large city), enough to eject a vast amount of debris into space and to generate enough heat to melt most of what remained of Earth.

Many scientists now think that such a cataclysm did indeed occur during the middle to late stages of Earth's accretion. The giant impact created a shower of debris from both Earth and the impacting body and propelled it into space. The Moon aggregated from this debris (**Figure 1.5**). Earth would have re-formed as a largely molten body. This huge impact sped up Earth's rotation and changed its spin axis, knocking it from vertical with respect to Earth's orbital plane to its present 23° inclination. All this occurred about 4.5 billion years ago, between the beginning of Earth's accretion (4.56 billion years ago) and the age of the oldest Moon rocks brought back by the *Apollo* astronauts (4.47 billion years).

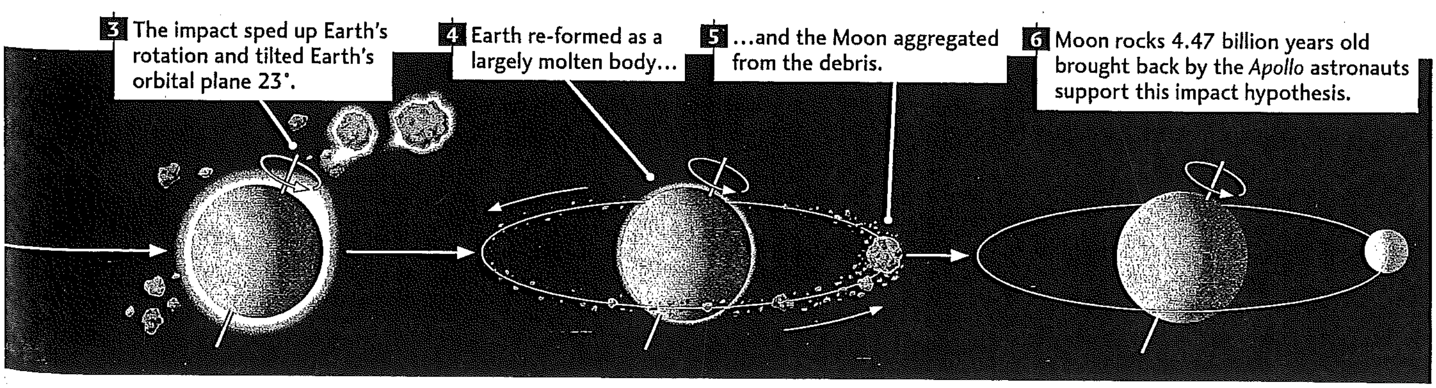
In addition to the giant impact, another source of heat would have caused melting early in Earth's history. Several elements (uranium, for example) are *radioactive,* which means that they disintegrate spontaneously by emitting subatomic particles. As these particles are absorbed by the surrounding matter, their energy of motion is transformed into heat. Radioactive heating would have contributed to heating and melting in the young Earth. Radioactive elements, though present only in small amounts, have had an enormous effect on Earth's evolution and continue to keep the interior hot.

Differentiation Begins

Although Earth probably began as an unsegregated mixture of planetesimals and other remnants of the solar nebula, it did not retain this form for long. Large-scale melting occurred as a result of the giant impact. Some workers in this field speculate that 30 to 65 percent of Earth melted, forming an outer layer hundreds of kilometers thick, which they call a "magma (molten rock) ocean." The interior, too, heated to a "soft" state in which its components could move around. Heavy material sank to the interior to become the core, and lighter material floated to the surface and formed the crust. The rising lighter matter brought interior heat to the surface, where it could radiate into space. In this way, Earth cooled and mostly solidified and was transformed into a differentiated or zoned planet with three main layers: a central core and an outer crust separated by a mantle (**Figure 1.6**). A summary of the timing of the events that describe Earth's origin and evolution into a differentiated planet is shown in Figure 1.12.

Earth's Core Iron, which is denser than most of the other elements, accounted for about a third of the primitive planet's material. The iron and other heavy elements such as nickel sank to form a central **core.** Scientists have found that the core, which begins at a depth of about 2900 km, is molten on the outside but solid in a region called the *inner core,* which extends from a depth of about 5200 km to Earth's center at about 6400 km. The inner core is solid because the pressures at the center are too high for iron to melt (the temperature at which any material melts increases with increasing pressure).

Earth's Crust Other molten materials were less dense than the parent substances from which they separated, so they floated toward the surface of the magma ocean. There



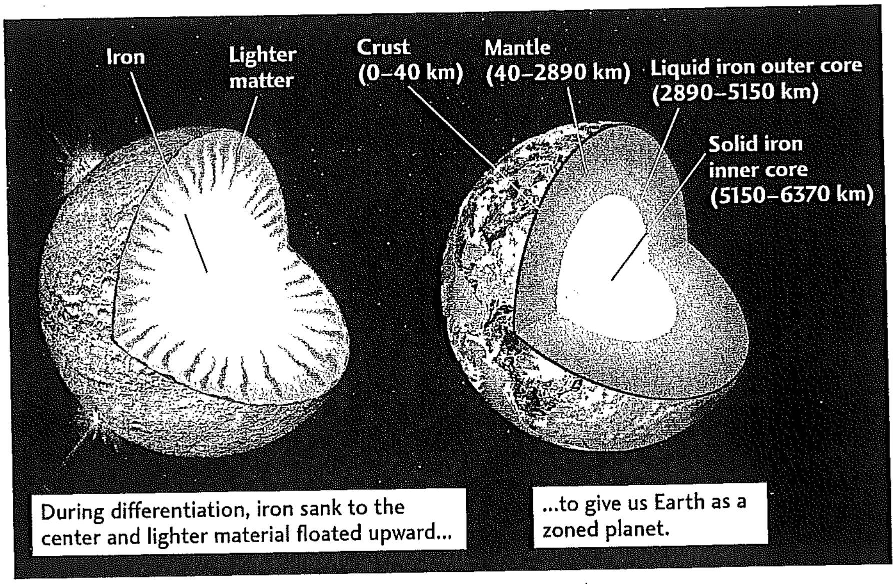


Figure 1.6 The differentiation of early Earth resulted in a zoned planet with a dense iron core, a crust of light rock, and a residual mantle between them.

they cooled to form Earth's solid **crust,** a thin outer layer about 40 km thick. The crust contains relatively light materials with low melting temperatures. Most of these materials are easily melted compounds of the elements silicon, aluminum, iron, calcium, magnesium, sodium, and potassium, combined with oxygen. All of these materials, other than iron, are among the lightest of the solid elements. (Chapter 3 discusses chemical compounds and the elements from which they form.)

Recently, in western Australia, a crystal fragment of the mineral zircon was found that is 4.3 to 4.4 billion years old, which would make it the oldest terrestrial material yet discovered. Chemical analysis indicates that the sample formed near the surface in the presence of water under relatively cool conditions. If this finding is confirmed by additional data and experiments, we can conclude that Earth may have cooled enough for a crust to form only 100 million years after the planet re-formed following the giant impact.

Earth's Mantle Between the core and the crust lies the **mantle,** a region that forms the bulk of the solid Earth. The mantle is the material left in the middle zone after most of the heavy matter sank and the light matter rose toward the surface. The mantle ranges from about 40 to 2900 km in depth. It consists of rocks of intermediate density, mostly compounds of oxygen with magnesium, iron, and silicon.

There are more than 100 elements, but chemical analysis of rocks indicates that only 8 make up 99 percent of Earth's mass (**Figure 1.7**). In fact, about 90 percent of Earth consists of only 4 elements: iron, oxygen, silicon, and magnesium. When we compare the relative abundance of elements in the crust with their abundance in the whole Earth, we find that iron accounts for a full 35 percent of Earth's mass. Because of differentiation, however, there is little iron in the crust, where the light elements predominate. As you can see in Figure 1.7, the crustal rocks on which we stand are almost 50 percent oxygen.

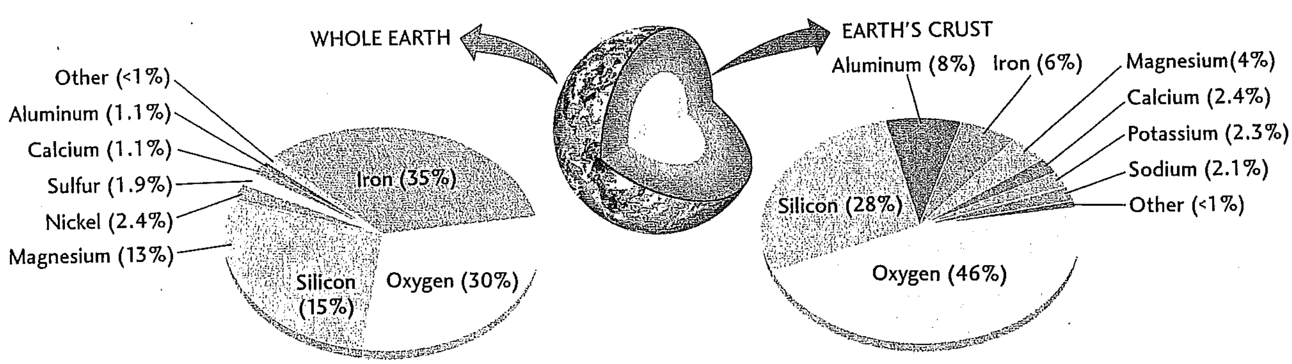


Figure 1.7 The relative abundance of elements in the whole Earth compared with that of elements in Earth's crust, given as percentages by weight. Differentiation created a light crust, depleted of iron and rich in oxygen, silicon, aluminum, calcium, potassium, and sodium. About 90 percent of Earth consists of only four elements: iron, oxygen, silicon, and magnesium. Note also that oxygen, silicon, and aluminum alone account for more than 80 percent of the crust.

Earth's Continents, Oceans, and Atmosphere Form

Early melting led to the formation of Earth's crust and eventually the continents. It brought lighter materials to Earth's outer layers and allowed even lighter gases to escape from the interior. These gases formed most of the atmosphere and oceans. Even today, trapped remnants of the original solar nebula continue to be emitted as primitive gases in volcanic eruptions.

Continents The most visible features of Earth's crust are the continents. Continental growth began soon after differentiation, and it has continued throughout geologic time. We have only the most general notion of what led to the formation of continents. We think that magma floated up from Earth's molten interior to the surface, where it cooled and solidified to form a crust of rock. This primeval crust melted and solidified repeatedly, causing the lighter materials to separate from the heavier ones and float to the top to form the primitive nucleus of the continents. Rainwater and other components of the atmosphere eroded the rocks, causing them to decompose and disintegrate. Water, wind, and ice then loosened rocky debris and moved it to low-lying places. There it accumulated in thick layers, forming beaches, deltas, and the floors of adjacent seas. Repetition of this process through many cycles built up the continents.

Oceans and Atmosphere Some geologists think that most of the air and water on Earth today came from volatile-rich matter of the outer solar system that impacted the planet after it was formed. For example, the comets we see are composed largely of water ice plus frozen carbon dioxide and other gases. Countless comets may have bombarded Earth early in its history, bringing water and gases that subsequently gave rise to the early oceans and atmosphere.

Many other geologists believe that the oceans and atmosphere can be traced back to the "wet birth" of Earth itself. According to this hypothesis, the planetesimals that aggregated into our planet contained ice, water, and other volatiles. Originally, the water was locked up (chemically bound as oxygen and hydrogen) in certain minerals carried by the aggregating planetesimals. Similarly, nitrogen and carbon were chemically bound in minerals. As Earth heated and its materials partially melted, water vapor and other gases were freed, carried to the surface by magmas, and released through volcanic activity.

The gases released from volcanoes some 4 billion years ago probably consisted of the same substances that are expelled from present-day volcanoes (though not necessarily in the same relative abundances): primarily hydrogen, carbon dioxide, nitrogen, water vapor, and a few other gases (**Figure 1.8**). Almost all of the hydrogen escaped to outer space, while the heavier gases enveloped the planet. This early atmosphere lacked the oxygen that makes up 21 percent of the atmosphere today. Oxygen did not enter the atmosphere until photosynthetic organisms evolved, as described later in this chapter.

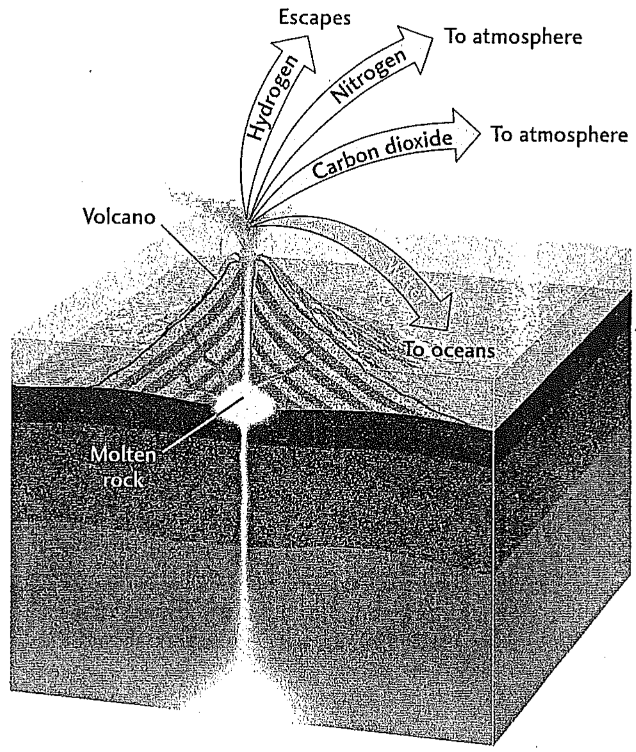


Figure 1.8 Early volcanic activity contributed enormous amounts of water vapor, carbon dioxide, and other gases to the atmosphere and oceans and solid materials to the continents. Photosynthesis by microorganisms removed carbon dioxide and added oxygen to the primitive atmosphere. Hydrogen, because it is light, escaped into space.

Diversity of the Planets

By about 4 billion years ago, Earth had become a fully differentiated planet. The core was still hot and mostly molten, but the mantle was fairly well solidified, and a primitive crust and continents had developed. The oceans and atmosphere had formed, probably from substances released from Earth's interior, and the geologic processes that we observe today were set in motion.

But what of the other planets? Did they go through the same early history? Information transmitted from our planetary spacecraft indicates that all the terrestrial planets have undergone differentiation, but their evolutionary paths have varied.

Mercury has a faint atmosphere, mostly helium. Atmospheric pressure at the surface is less than a trillionth that of Earth. There is no surface wind or water to erode and smooth its ancient surface. It looks like the Moon: intensely cratered and covered by a layer of rock debris, the fractured remnants of billions of years of meteorite impacts. Because it has essentially no atmosphere and is located close to the Sun, the planet warms to a surface temperature of 467°C during the day and cools to –173°C at night. This is the largest temperature range known in the solar system (other impacts of various sizes on our planet and its life. The poet Robert Frost may have had in mind the vulnerability of life on Earth when he wrote

> Some say the world will end in fire,
> Some say in ice.
> From what I've tasted of desire
> I hold with those who favor fire.
> But if I had to perish twice,
> I think I know enough of hate
> To say that for destruction ice
> Is also great
> And would suffice.

Earth as a System of Interacting Components

Although Earth has cooled down from its fiery beginnings, it remains a restless planet, continually changing through such geologic activity as earthquakes, volcanoes, and glaciation. This activity is powered by two heat engines: one internal, the other external. A heat engine—for example, the gasoline engine of an automobile—transforms heat into mechanical motion or work. Earth's internal engine is powered by the heat energy trapped during the planet's violent origin and generated by radioactivity in its deep interior. The internal heat drives motions in the mantle and core, supplying the energy to melt rock, move continents, and lift up mountains. Earth's external engine is driven by solar energy—heat supplied to Earth's surface by the Sun. Heat from the Sun energizes the atmosphere and oceans and is responsible for our climate and weather. Rain, wind, and ice erode mountains and shape the landscape, and the shape of the landscape, in turn, changes the climate.

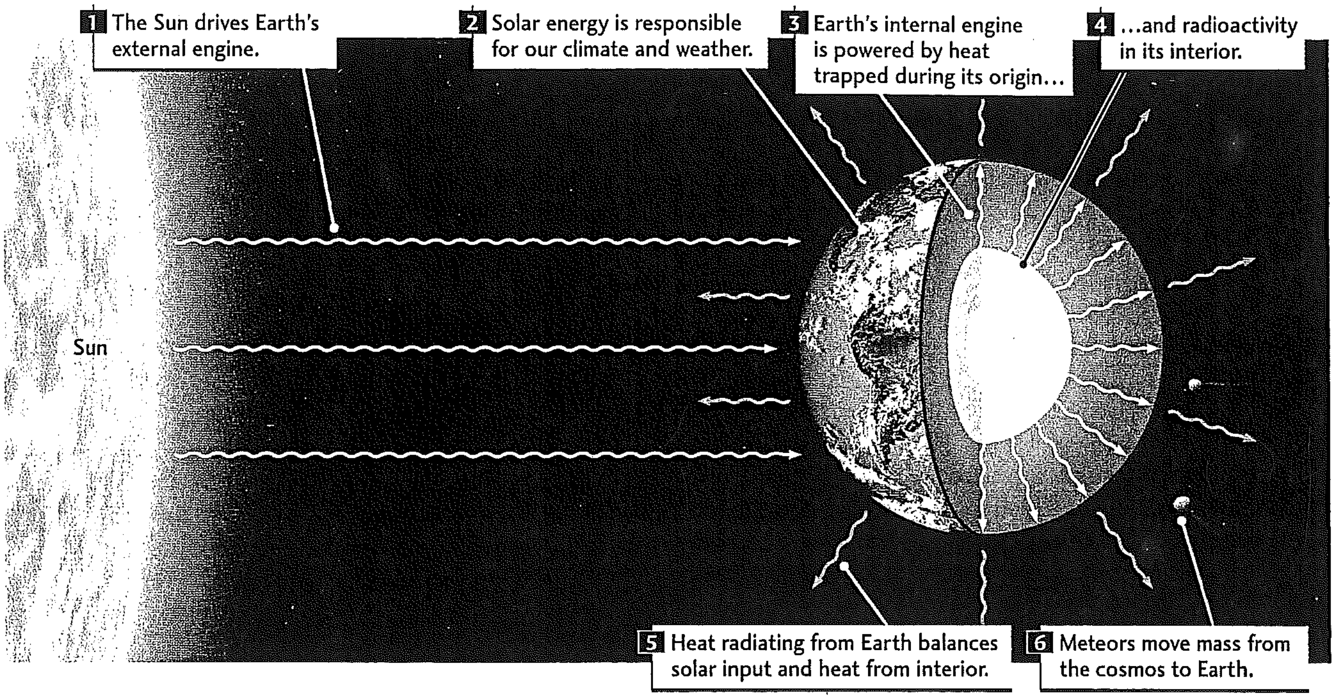
All the parts of our planet and all their interactions, taken together, constitute the **Earth system.** Although Earth scientists have long thought in terms of natural systems, it was not until the latter part of the twentieth century that they were equipped with the tools needed to investigate how the Earth system actually works. Principal among these were networks of instruments and Earth-orbiting satellites to collect information about the Earth system on a global scale and electronic computers powerful enough to calculate the mass and energy transfers within the system. The major components of the Earth system are described in Table 1.2 and depicted in **Figure Story 1.10**. We have discussed some of them already; we will define the others below.

We will talk about many facets of the Earth system in later chapters. Let's get started by thinking about some of its basic features. Earth is an *open system* in the sense that it exchanges mass and energy with the rest of the cosmos. Radiant energy from the Sun energizes the weathering and erosion of Earth's surface, as well as the growth of plants, which feed almost all living things. Our climate is controlled by the balance between the solar energy coming into the Earth system and the energy Earth radiates back into

Table 1.2 Major Components of the Earth System

	Solar Energy Energizes These Components
Atmosphere	Gaseous envelope extending from Earth's surface to an altitude of about 100 km
Hydrosphere	Surface waters comprising all oceans, lakes, rivers, and groundwaters
Biosphere	All organic matter related to life near Earth's surface
	Earth's Internal Heat Energizes These Components
Lithosphere	Strong, rocky outer shell of the solid Earth that comprises the crust and uppermost mantle down to an average depth of about 100 km; forms the tectonic plates
Asthenosphere	Weak, ductile layer of mantle beneath the lithosphere that deforms to accommodate the horizontal and vertical motions of plate tectonics
Deep mantle	Mantle beneath the asthenosphere, extending from about 400 km deep to the core-mantle boundary (about 2900 km deep)
Outer core	Liquid shell composed primarily of molten iron, extending from about 2900 km to 5150 km in depth
Inner core	Inner sphere composed primarily of solid iron, extending from about 5150 km deep to Earth's center (about 6400 km deep)

EARTH IS AN OPEN SYSTEM THAT EXCHANGES ENERGY AND MASS WITH ITS SURROUNDINGS



THE EARTH SYSTEM IS ALL PARTS OF OUR PLANET AND THEIR INTERACTIONS

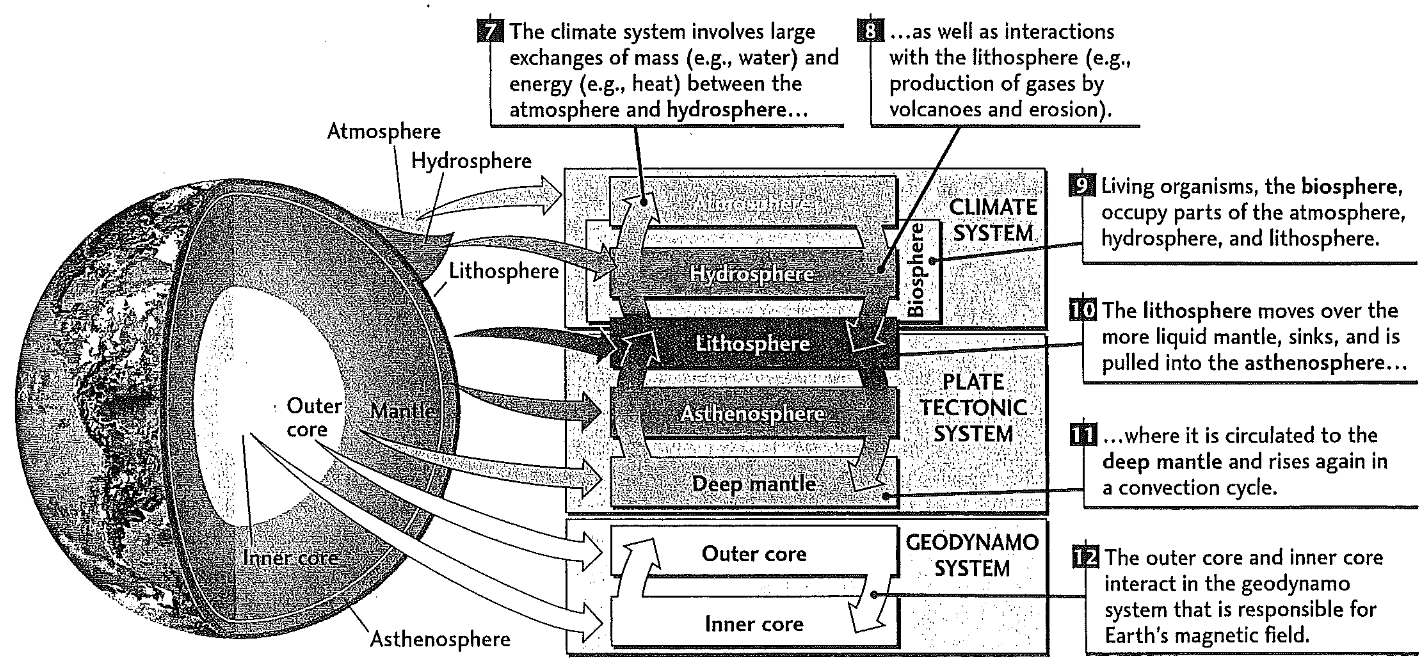


Figure Story 1.10 Major components and subsystems of the Earth system (see Table 1.2). Interactions among the components are powered by energy from the Sun and the planetary interior and organized into three global geosystems: the climate system, the plate tectonic system, and the geodynamo system.

space. The mass transfers between Earth and space decreased markedly after the Heavy Bombardment period, but they still play an active role in the Earth system—just ask the dinosaurs!

Although we think of Earth as a single system, it is a challenge to study the whole thing all at once. Instead, we will focus our attention on parts of the system we are trying to understand. For instance, in the discussion of recent climate changes, we will primarily consider interactions among the atmosphere, hydrosphere, and biosphere that are driven by solar energy. Our coverage of how the continents formed will focus on interactions between the crust and the deeper mantle that are driven by Earth's internal energy. Specialized subsystems that encompass interesting types of terrestrial behavior are called **geosystems**. The Earth system can be thought of as the collection of all these open, interacting (and often overlapping) geosystems.

In this section, we will introduce two important geosystems that operate on a global scale: the climate system and the plate tectonic system. A third global system is the geodynamo, which is responsible for Earth's magnetic field. It is an important part of how Earth works as a planet and a key tool for exploring the interior. The geodynamo is discussed in Chapter 21. Its importance to understanding plate tectonics is discussed in Chapter 2. Later in the book, we will have occasion to discuss a number of smaller geosystems. Here are three examples: volcanoes that erupt hot lava (Chapter 6), hydrologic systems that give us our drinking water (Chapter 13), and petroleum reservoirs that produce oil and gas (Chapter 22).

The Climate System

Weather is the term we use to describe the temperature, precipitation, cloud cover, and winds observed at a point on Earth's surface. We all know how variable the weather can be—hot and rainy one day, cool and dry the next—depending on the movements of storm systems, warm and cold fronts, and other rapidly changing atmospheric disturbances. Because the atmosphere is so complex, even the best forecasters have a hard time predicting the weather more than four or five days in advance. However, we can guess in rough terms what our weather will be much farther into the future, because the prevailing weather is governed primarily by the changes in solar energy input on seasonal and daily cycles: summers are hot, winters cold; days are warmer, nights cooler. *Climate* is a description of these weather cycles obtained by averaging temperature and other variables over many years of observation. In addition to mean values, a complete description of climate also includes measures of how variable the weather has been, such as the highest and lowest temperatures ever recorded on a given day.

The **climate system** includes all the properties and interactions of components within the Earth system needed to determine the climate on a global scale and discover how the climate changes with time. The problem is incredibly complicated because climate is not a behavior of the atmosphere alone. It is sensitive to many processes involving the hydrosphere, biosphere, and solid Earth (see Figure Story 1.10). To understand these interactions, scientists build numerical models—virtual climate systems—on big computers, and they compare the results of their computer simulations with observed data. (In March 2002, Japan unveiled the world's largest and fastest computer, the Earth Simulator, dedicated to modeling Earth's climate and other geosystems.)

Scientists gain confidence in their models if there is good agreement with the observed data. They use the disagreements to figure out where the models are wrong or incomplete. They hope to improve the models enough through testing with many types of observations that they can accurately predict how climate will change in the future. A particularly urgent problem is to understand the global warming that might be caused by human-generated emissions of carbon dioxide and other "greenhouse" gases. Part of the public debate about global warming centers on the accuracy of computer predictions. Skeptics argue that even the most sophisticated computer models are unreliable because they lack many features of the real Earth system. In Chapter 23, we will discuss some aspects of how the climate system works and the practical problems of climate change caused by human activities.

The Plate Tectonic System

Some of Earth's more dramatic geologic events—volcanic eruptions and earthquakes, for example—also result from interactions within the Earth system. These phenomena are driven by Earth's internal heat, which escapes through the circulation of material in Earth's solid mantle, a process known as *convection.*

We have seen that Earth is zoned by chemistry: its crust, mantle, and core are chemically distinct layers that segregated during early differentiation. Earth is also zoned by strength, a property that measures how much an Earth material can resist being deformed. Material strength depends on chemical composition (bricks are strong, soap bars are weak) and temperature (cold wax is strong, hot wax is weak). In some ways, the outer part of the solid Earth behaves like a ball of hot wax. Cooling of the surface forms the strong outer shell or **lithosphere** (from the Greek *lithos,* meaning "stone") that encases a hot, weak **asthenosphere** (from the Greek *asthenes,* meaning "weak"). The lithosphere includes the crust and the top part of the mantle down to an average depth of about 100 km. When subjected to force, the lithosphere tends to behave as a rigid and brittle shell, whereas the underlying asthenosphere flows as a moldable, or ductile, solid.

According to the remarkable theory of **plate tectonics,** the lithosphere is not a continuous shell; it is broken into about a dozen large "plates" that move over Earth's surface at rates of a few centimeters per year. Each plate acts as a

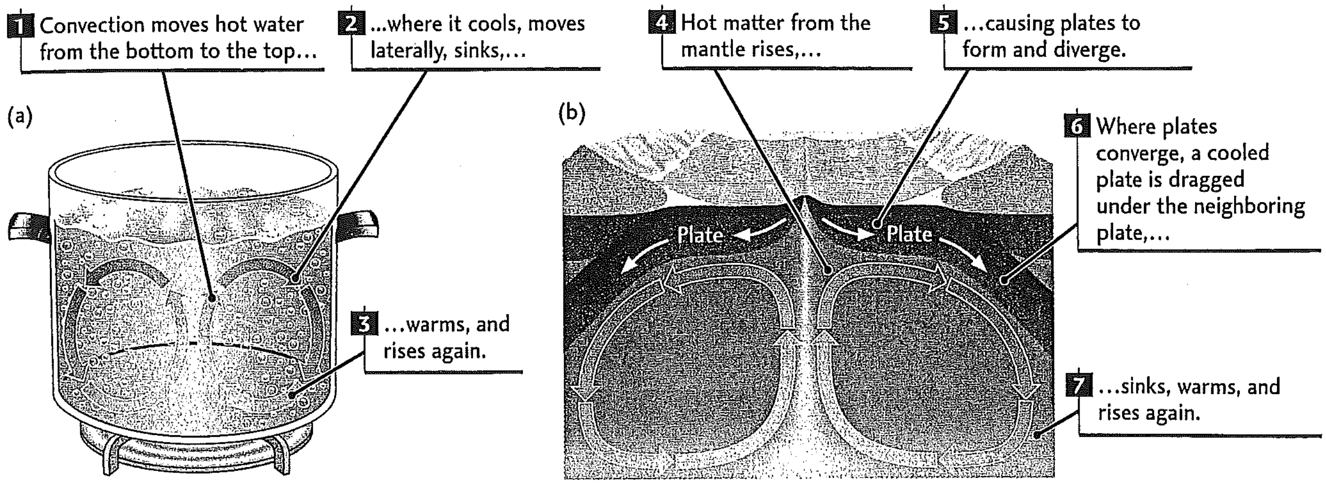


Figure 1.11 (a) Boiling water is a familiar instance of convection. (b) A simplified view of convection currents in Earth's interior.

distinct rigid unit that rides on the asthenosphere, which also is in motion. The lithosphere that forms a plate may be just a few kilometers thick in volcanically active areas and perhaps 200 km thick or more beneath the older, colder parts of the continents. The discovery of plate tectonics in the 1960s furnished scientists with the first unified theory to explain the worldwide distribution of earthquakes and volcanoes, continental drift, mountain building, and many other geologic phenomena. Chapter 2 will be devoted to a detailed description of plate tectonics.

Why do the plates move across Earth's surface instead of locking up into a completely rigid shell? The forces that push and pull the plates around the surface come from the heat engine in Earth's solid mantle, which causes convection. In general terms, convection is a mechanism of energy and mass transfer in which hotter material rises and cooler material sinks. We tend to think of convection as a process involving fluids and gases—circulating currents of water boiling in a pot, smoke rising from a chimney, or heated air floating up to the ceiling as cooled air sinks to the floor—but it can also occur in solids that are at high enough temperatures to be weak and ductile. We note that the flow in ductile solids is usually slower than fluid flow, because even "weak" solids (say, wax or taffy) are more resistant to deformation than ordinary fluids (say, water or mercury).

Convection can occur in a flowing material, either a liquid or a ductile solid, that is heated from below and cooled from above. The heated matter rises under the force of buoyancy because it has become less dense than the matter above it. When it reaches the surface, it gives up heat and cools as it moves sideways, becoming denser. When it gets heavier than the underlying material, it sinks under the pull of gravity, as depicted in **Figure 1.11**. The circulation continues as long as enough heat remains to be transferred from the hot interior to the cool surface.

The movement of the plates is the surface manifestation of convection in the mantle, and we refer to this entire system as the **plate tectonic system.** Driven by Earth's internal heat, hot mantle material rises where plates separate and begins to gel the lithosphere. The lithosphere cools and becomes more rigid as it moves away from this divergent boundary. Eventually, it sinks into the asthenosphere, dragging material back into the mantle at boundaries where plates converge (Figure 1.11b). As with the climate system (which involves a wide range of convective processes in the atmosphere and oceans), scientists study plate tectonics using computer simulations to represent what they think are the most important components and interactions. They revise the models when their implications disagree with actual data.

Earth Through Geologic Time

So far, we have discussed two major topics: how Earth formed from the early solar system, and how two global geosystems work today. What happened during the intervening 4.5 billion years? To answer this question, we begin with an overview of geologic time from the birth of the planet to the present. Later chapters will fill in the details.

An Overview of Geologic Time

Comprehending the immensity of geologic time can be a challenge for the uninitiated. The popular writer John McPhee has eloquently noted that geologists look into the

CHAPTER 2

Plate Tectonics: The Unifying Theory

"What is now proved was once only imagin'd."

WILLIAM BLAKE

The lithosphere—Earth's strong, rigid outer shell of rock—is broken into about a dozen plates, which slide by, converge with, or separate from each other as they move over the weaker, ductile asthenosphere. Plates are created where they separate and are recycled where they converge, in a continuous process of creation and destruction. Continents, embedded in the lithosphere, drift along with the moving plates. The theory of **plate tectonics** describes the movement of plates and the forces acting between them. It also explains the distribution of many large-scale geologic features that result from movements at plate boundaries: mountain chains, rock assemblages, structures on the seafloor, volcanoes, and earthquakes. Plate tectonics provides a conceptual framework for a large part of this book and, indeed, for much of geology. **This chapter lays out the plate tectonics theory and examines how the forces that drive plate motions are related to the mantle convection system.**

The Discovery of Plate Tectonics

In the 1960s, a great revolution in thinking shook the world of geology. For almost 200 years, geologists had developed various theories of *tectonics* (from the Greek *tekton,* meaning "builder")—the general term they used to describe mountain building, volcanism, and other processes that construct geologic features on Earth's surface. It was not until the discovery of plate tectonics, however, that a single theory could satisfactorily explain the whole range of geologic processes. Not only is plate tectonics all-encompassing, it is also elegant: many observations can be explained by a few simple principles. In the history of science, simple theories that explain many observations usually turn out to be the most enduring. Physics had a comparable revolution at the beginning of the twentieth century, when the theory of relativity unified the physical laws that govern space, time, mass, and motion. Biology had a comparable revolution in the middle of the twentieth century, when the discovery of DNA allowed biologists to explain how organisms transmit the information that controls their growth, development, and functioning from generation to generation.

The basic ideas of plate tectonics were put together as a unified theory of geology less than 40 years ago. The scientific synthesis that led to plate tectonics, however, really began much earlier in the twentieth century, with the recognition of evidence for continental drift.

Continental Drift

Such changes in the superficial parts of the globe seemed to me unlikely to happen if the earth were solid to the center. I therefore imagined that the internal parts might be a fluid more dense, and of greater specific gravity than any of the solids we are acquainted with, which therefore might swim in or upon that fluid. Thus the surface of the earth would be a shell, capable of being broken and disordered by the violent movements of the fluid on which it rested.

(Benjamin Franklin, 1782, in a letter to French geologist Abbé J. L. Giraud-Soulavie)

The concept of **continental drift**—large-scale movements of continents over the globe—has been around for a long time. In the late sixteenth century and in the seventeenth century, European scientists noticed the jigsaw-puzzle fit of the coasts on both sides of the Atlantic, as if the Americas, Europe, and Africa were at one time assembled together and had subsequently drifted apart. By the close of the nineteenth century, the Austrian geologist Eduard Suess put some of the pieces of the puzzle together and postulated that the combined present-day southern continents had once formed a single giant continent called *Gondwanaland* (or *Gondwana*). In 1915, Alfred Wegener, a German meteorologist who was recovering from wounds suffered in World War I, wrote a book on the breakup and drift of continents. In it, he laid out the remarkable similarity of rocks, geologic structures, and fossils on opposite sides of the Atlantic. In the years that followed, Wegener postulated a supercontinent, which he called **Pangaea** (Greek for "all lands"), that broke up into the continents as we know them today (**Figure 2.1**).

Although Wegener was correct in asserting that the continents had drifted apart, his hypotheses about how fast the continents were moving and what forces were pushing them across Earth's surface turned out to be wrong, which reduced his credibility among other scientists. After about a decade of spirited debate, physicists convinced geologists that Earth's outer layers were too rigid for continental drift to occur, and Wegener's ideas fell into disrepute except among a few geologists in Europe, South Africa, and Australia.

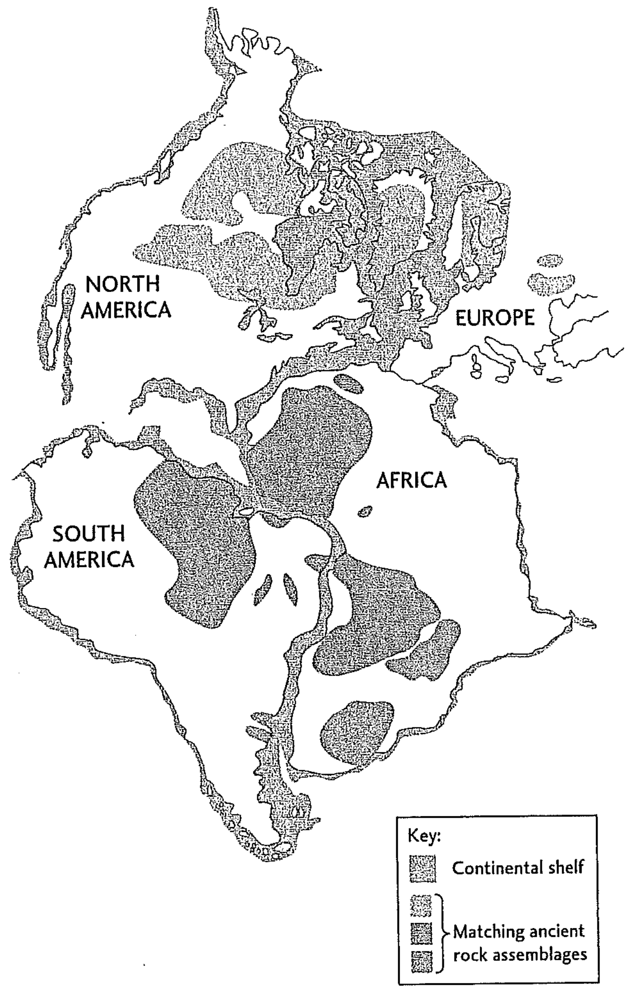


Figure 2.1 The jigsaw-puzzle fit of continents bordering the Atlantic Ocean formed the basis of Alfred Wegener's theory of continental drift. In his book *The Origin of Continents and Oceans,* Wegener cited as additional evidence the similarity of geologic features on opposite sides of the Atlantic. The matchup of ancient crystalline rocks is shown in adjacent regions of South America and Africa and of North America and Europe. [Geographic fit from data of E. C. Bullard; geological data from P. M. Hurley.]

The advocates of the drift hypothesis pointed not only to geographic matching but also to geologic similarities in rock ages and trends in geologic structures on opposite sides of the Atlantic (see Figure 2.1). They also offered arguments, accepted now as good evidence of drift, based on fossil and climatological data. Identical fossils of a reptile 300 million years old, for example, are found only in Africa and South America, suggesting that the two continents were joined at the time (**Figure 2.2**). The animals and plants on different continents showed similarities in evolution until the postulated breakup time. After that, they followed divergent evo-

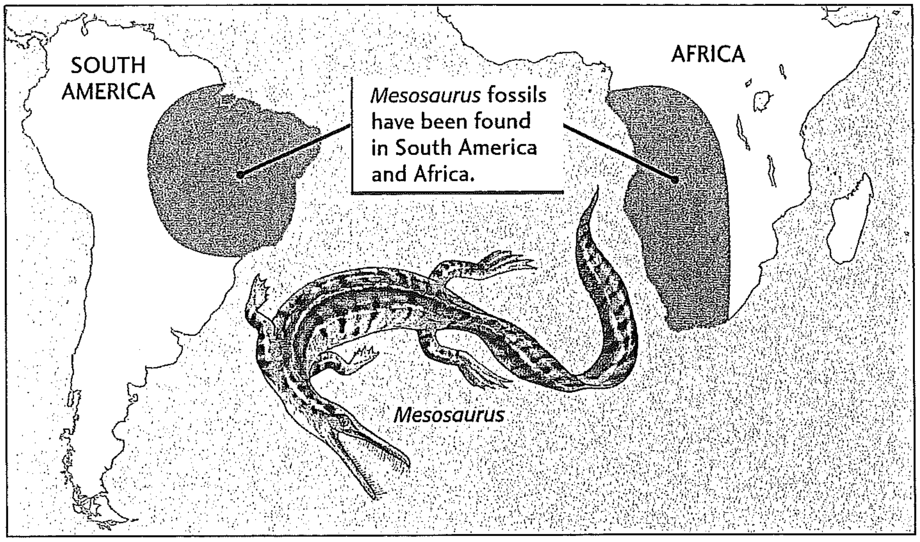


Figure 2.2 Fossils of the reptile *Mesosaurus,* 300 million years old, are found in South America and Africa and nowhere else in the world. If *Mesosaurus* could swim across the South Atlantic Ocean, it could have crossed other oceans and should have spread more widely. The observation that it did not suggests that South America and Africa must have been joined at that time. [After A. Hallam, "Continental Drift and the Fossil Record," *Scientific American* (November 1972): 57–66.]

lutionary paths, presumably because of the isolation and changing environments of the separating continental masses. In addition, rock deposits associated with glaciers that existed some 300 million years ago are now distributed across South America, Africa, India, and Australia. If the southern continents are reassembled into Gondwanaland near the South Pole, a single continental glacier could account for all the glacial deposits.

Seafloor Spreading

The geologic evidence did not convince the skeptics who maintained that continental drift was physically impossible. No one had yet come up with a plausible driving force that could have split Pangaea and moved the continents apart. Wegener, for example, thought the continents floated like boats across the solid oceanic crust, dragged along by the tidal forces of the Sun and Moon!

The breakthrough came when scientists realized that convection in Earth's mantle (discussed in Chapter 1) could push and pull the continents apart, creating new oceanic crust through the process of **seafloor spreading.** In 1928, the British geologist Arthur Holmes came close to expressing the modern notions of continental drift and seafloor spreading when he proposed that convection currents "dragged the two halves of the original continent apart, with consequent mountain building in the front where the currents are descending, and the ocean floor development on the site of the gap, where the currents are ascending." Given the physicists' arguments that Earth's crust and mantle are rigid and immobile, Holmes conceded that "purely speculative ideas of this kind, specially invented to match the requirements, can have no scientific value until they acquire support from independent evidence."

Convincing evidence began to emerge as a result of extensive exploration of the seafloor after World War II. The mapping of the undersea Mid-Atlantic Ridge and the discovery of the deep, cracklike valley, or rift, running down its center sparked much speculation (**Figure 2.3**). Geologists found that almost all of the earthquakes in the Atlantic Ocean occurred near this rift valley. Because most earthquakes are generated by tectonic faulting, these results indicated that the rift was a tectonically active feature. Other mid-ocean ridges with similar shapes and earthquake activity were found in the Pacific and Indian oceans.

In the early 1960s, Harry Hess of Princeton University and Robert Dietz of the Scripps Institution of Oceanography proposed that the crust separates along the rifts in mid-ocean ridges and that new seafloor forms by upwelling of hot new crust into these cracks. The new seafloor—actually the top of newly created lithosphere—spreads laterally away from the rift and is replaced by even newer crust in a continuing process of plate creation.

The Great Synthesis: 1963–1968

The seafloor spreading hypothesis put forward by Hess and Dietz in 1962 explained how the continents could drift apart

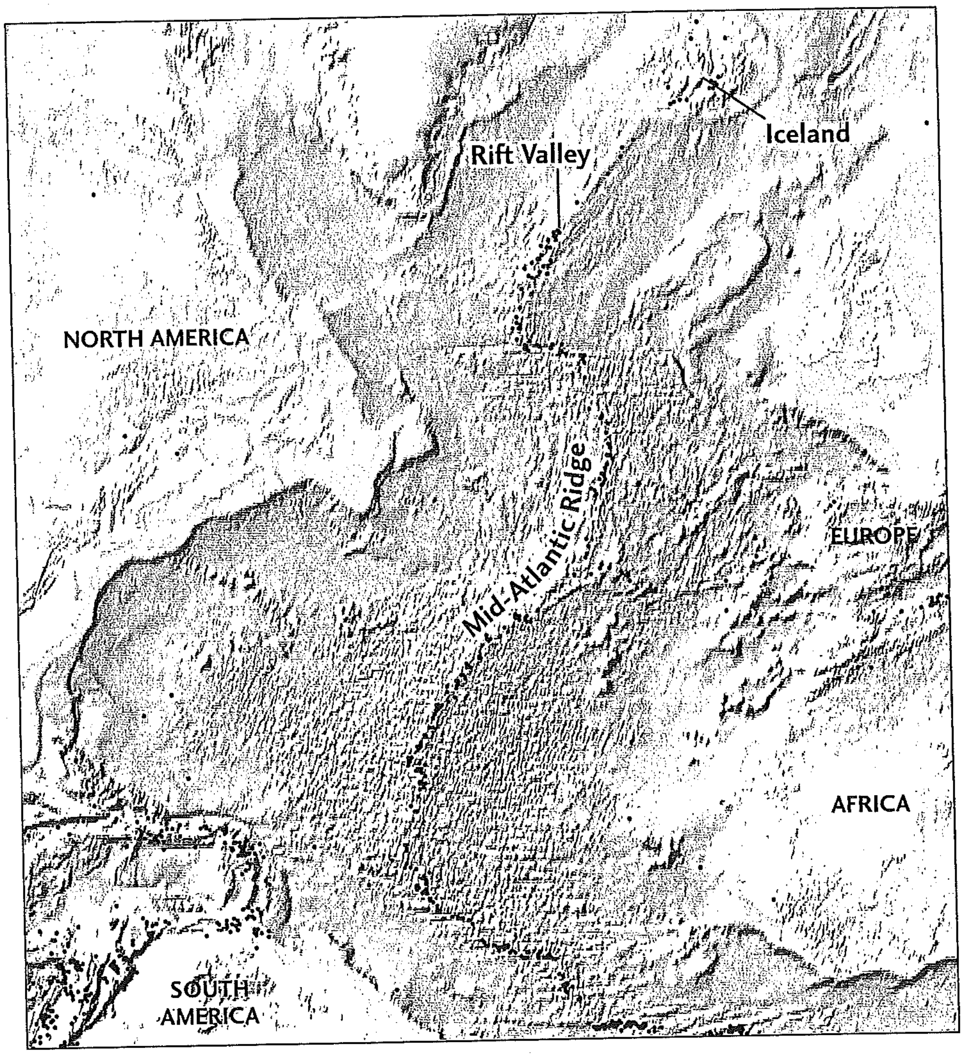


Figure 2.3 The North Atlantic Ocean floor, showing the cracklike rift valley running down the center of the Mid-Atlantic Ridge and associated earthquakes (black dots).

through the creation of new lithosphere at mid-ocean rifts. Could the seafloor and its underlying lithosphere be destroyed by recycling back into Earth's interior? If not, Earth's surface area would have to increase over time, so our planet would have to get bigger and bigger. For a period in the early 1960s, some physicists and geologists actually believed in this idea of an expanding Earth, based on a now-discredited modification of Einstein's theory of gravitation. Other geologists recognized that the seafloor was indeed being recycled in the regions of intense volcanic and earthquake activity around the margins of the Pacific Ocean basin, known collectively as the Ring of Fire (**Figure 2.4**). The details of this process, however, remained obscure.

In 1965, the Canadian geologist J. Tuzo Wilson first described tectonics around the globe in terms of rigid "plates" moving over Earth's surface. He characterized the three basic types of boundaries where plates move apart, come together, or slide past each other. In a quick succession of discoveries and theoretical advances, other scientists showed that almost all current tectonic deformations are concentrated at these boundaries. They measured the rates and directions of the tectonic motions, and they demonstrated that these motions are mathematically consistent with a system of rigid plates moving on the planet's spherical surface. The basic elements of the plate tectonics theory were established by the end of 1968. By 1970, the evidence for plate tectonics had become so persuasive in its abundance that almost all Earth scientists embraced the theory. Textbooks were revised, and specialists began to consider the implications of the new concept for their own fields. For a timeline of the landmark events leading to the theory of plate tectonics, see Appendix 3.

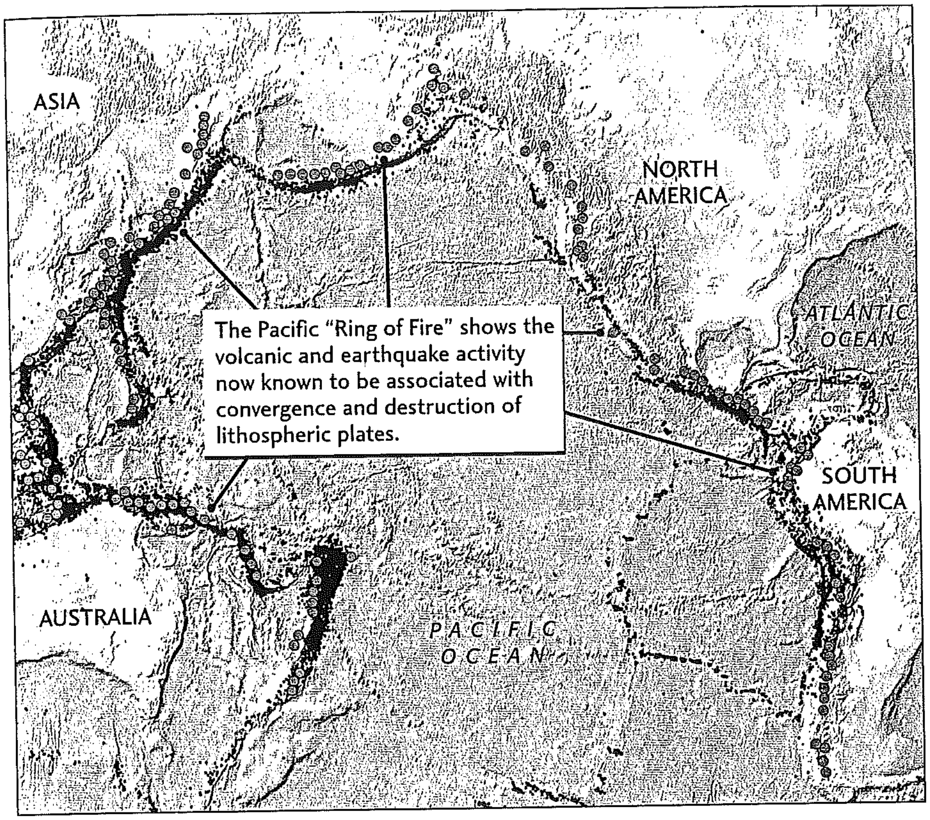


Figure 2.4 The Pacific Ring of Fire, showing active volcanoes (large red circles) and earthquakes (small black dots).

The Mosaic of Plates

According to the theory of plate tectonics, the rigid lithosphere is not a continuous shell but is broken into a mosaic of about a dozen large, rigid plates that are in motion over Earth's surface. Each plate moves as a distinct rigid unit, riding on the asthenosphere, which is also in motion. The major plates and their present-day motions are represented in **Figure 2.5**. The largest is the Pacific Plate, which comprises much (though not all) of the Pacific Ocean basin. Some of the plates are named after the continents they contain, but in no case is a plate identical with a continent. The North American Plate, for instance, extends from the Pacific coast of the continent of North America to the middle of the Atlantic Ocean, where it meets the Eurasian and African plates.

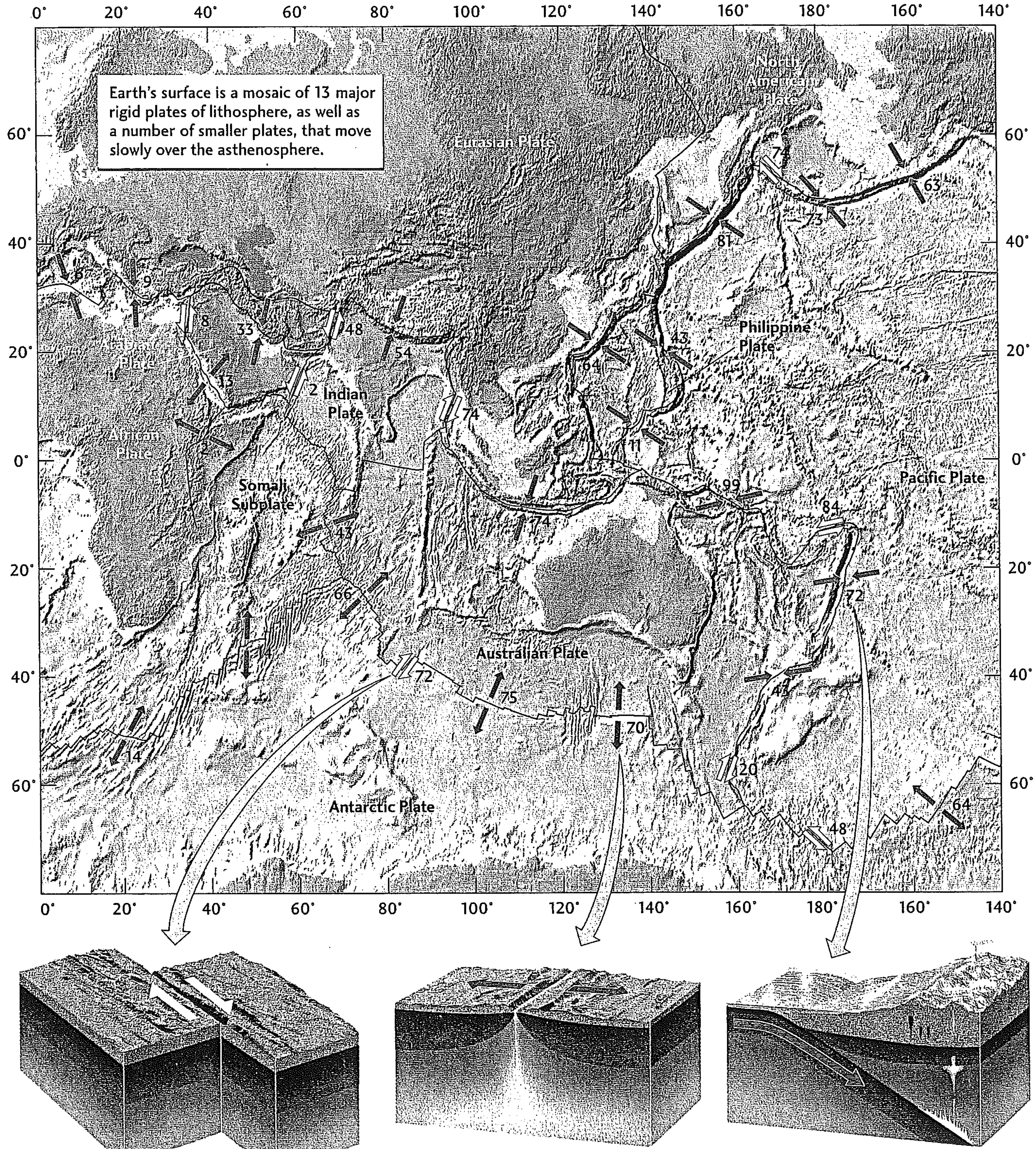
In addition to the major plates, there are a number of smaller ones. An example is the tiny Juan de Fuca Plate, a piece of oceanic lithosphere trapped between the giant Pacific and North American plates just offshore of the northwestern United States. Others are continental fragments, such as the small Anatolian Plate, which includes much of Turkey. (Not all of the smaller plates are shown in Figure 2.5.)

If you want to see geology in action, go to a plate boundary. Depending on which boundary you visit, you will find earthquakes; volcanoes; mountains; long, narrow rifts; and more. Many geologic features develop through the interactions of plates at their boundaries. The three basic types of plate boundaries are depicted in Figure 2.5 and discussed in the following pages.

- At *divergent boundaries,* plates move apart and new lithosphere is created (plate area increases).
- At *convergent boundaries,* plates come together and one is recycled back into the mantle (plate area decreases).
- At *transform-fault boundaries,* plates slide horizontally past each other (plate area remains constant).

Like many models of nature, the three types of plates shown in Figure 2.5 are idealized. Besides these basic types, there are "oblique boundaries" that combine divergence or convergence with some amount of transform faulting. Moreover, what actually goes on at a plate boundary depends on the type of lithosphere involved, because continental and oceanic lithosphere behave rather differently. The continental crust is made of rocks that are both lighter and weaker than either the oceanic crust or the mantle beneath the crust. Later chapters will examine this compositional difference in more detail, but for now you need only to keep in mind two consequences: (1) because it is lighter, continental crust is not as

EARTH'S LITHOSPHERE IS MADE OF MOVING PLATES



At transform-fault boundaries, plates slide horizontally past each other.

At divergent boundaries, plates move apart and create new lithosphere.

At convergent boundaries, plates collide and one is pulled into the mantle and recycled.

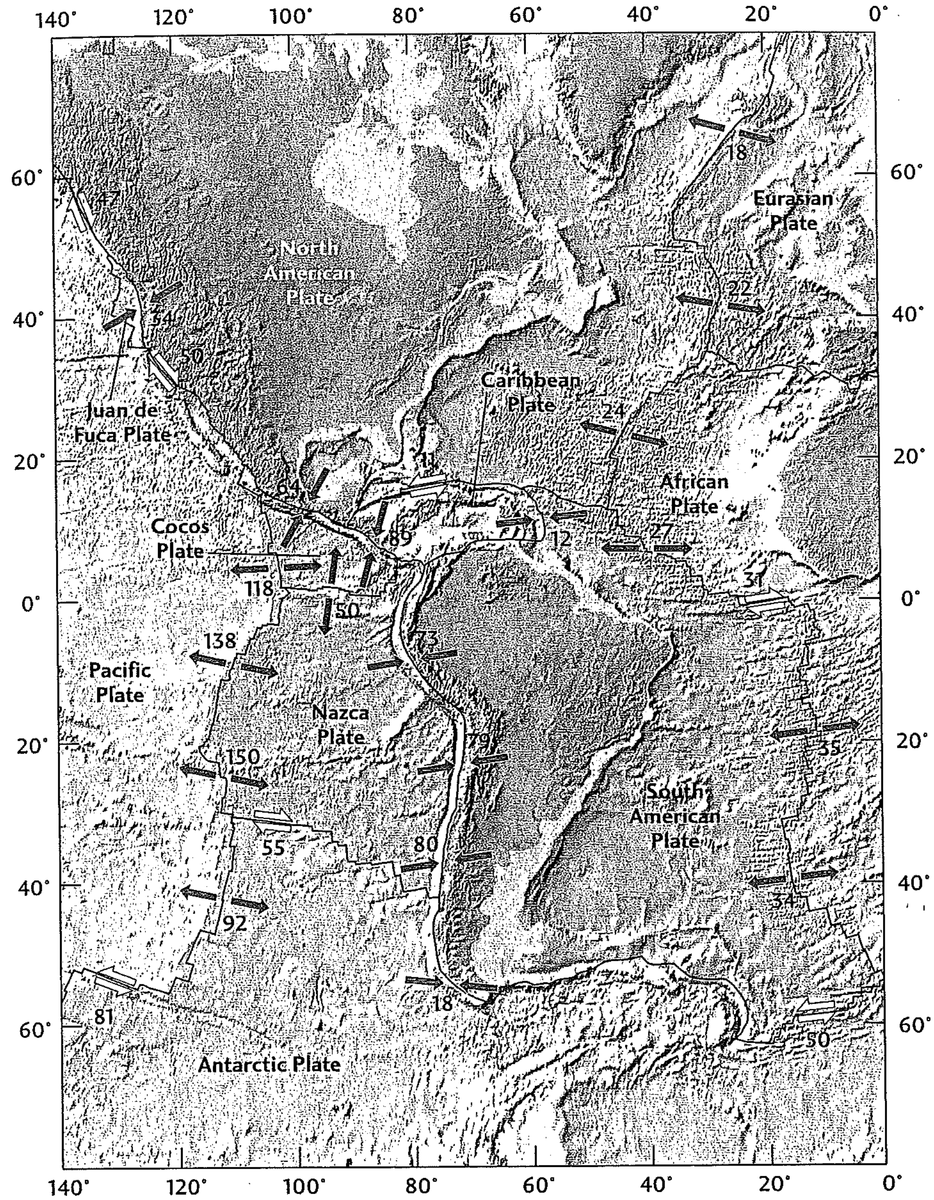


Figure 2.5 Earth's plates today, showing the plate boundaries. This flattened view of Earth's land and undersea topography shows the three basic types of plate boundaries: divergent boundaries, where plates separate (←—→); convergent boundaries, where plates come together (→←); and transform-fault boundaries, where plates slide past each other (⇄). These arrows show in what directions the plates are moving with respect to each other at their common boundaries. The numbers next to the arrows indicate the relative plate speeds in millimeters per year. [Plate boundaries by Peter Bird, UCLA.]

easily recycled as oceanic crust, and (2) because continental crust is weaker, plate boundaries that involve continental crust tend to be more spread out and more complicated than oceanic plate boundaries.

Divergent Boundaries

Divergent boundaries within the ocean basins are narrow rifts that approximate the idealization of plate tectonics. Divergence within the continents is usually more complicated and distributed over a wider area. This difference is illustrated in **Figure 2.6**.

Oceanic Plate Separation On the seafloor, the boundary between separating plates is marked by a mid-ocean ridge that exhibits active volcanism, earthquakes, and rifting caused by tensional (stretching) forces that are pulling the two plates apart. Figure 2.6a shows what happens in one example, the Mid-Atlantic Ridge. Here seafloor spreading is at work as the North American and Eurasian plates sepa-

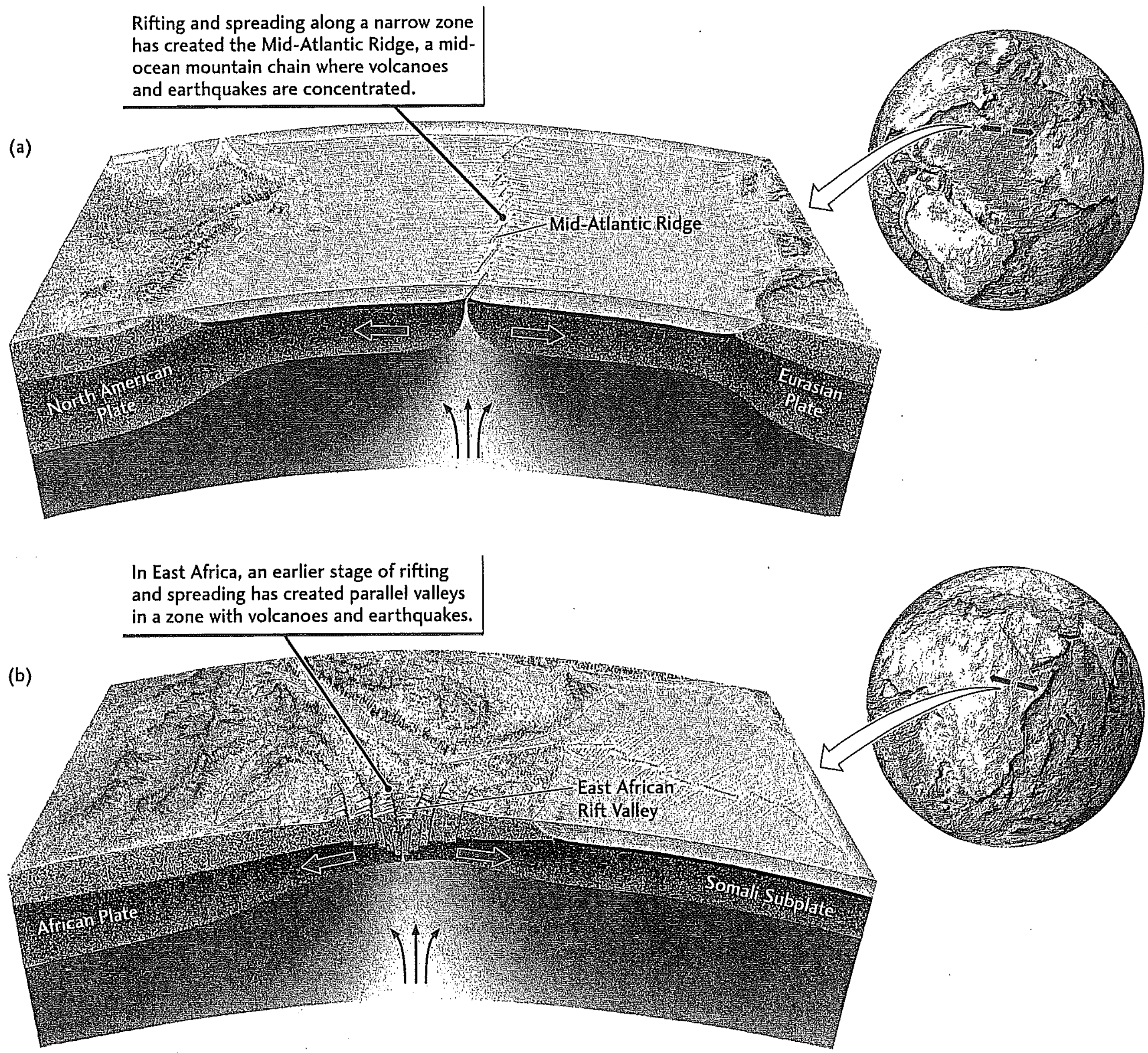


Figure 2.6 (a) Rifting and seafloor spreading along the Mid-Atlantic Ridge create a mid-ocean volcanic mountain chain where volcanism, faulting, and earthquakes are concentrated along a narrow spreading center. (b) Early stages of rifting and plate separation now occurring within eastern Africa, where multiple rift valleys with their associated faulting, volcanism, and earthquakes are distributed over a wider zone.

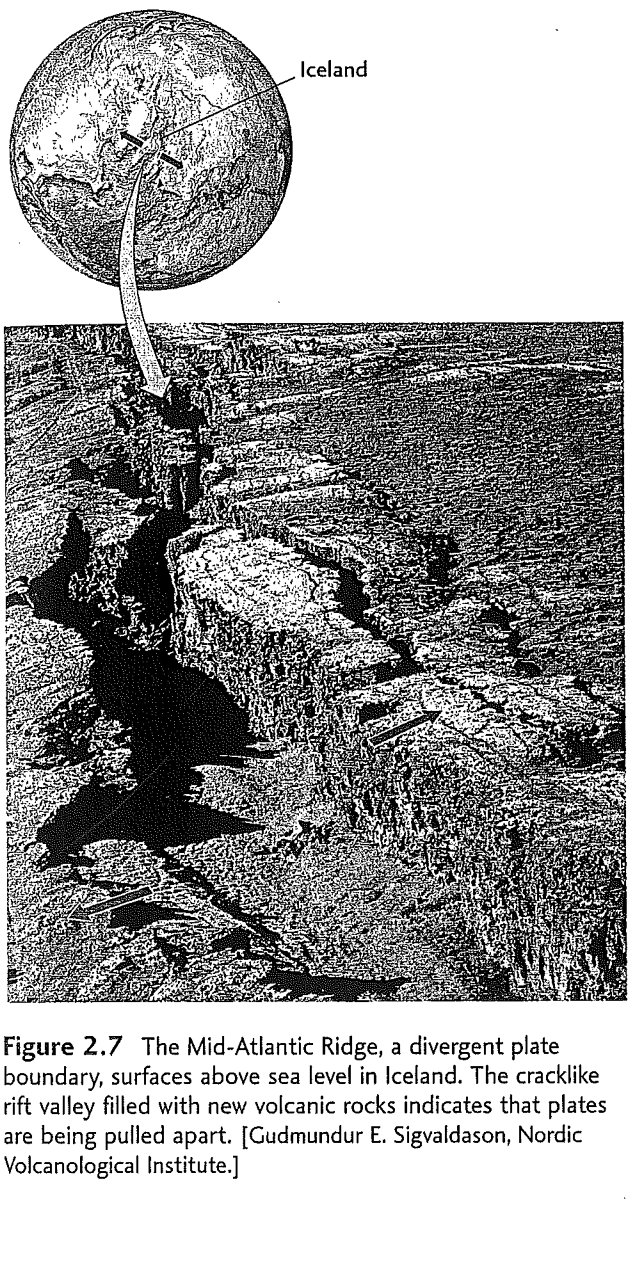


Figure 2.7 The Mid-Atlantic Ridge, a divergent plate boundary, surfaces above sea level in Iceland. The cracklike rift valley filled with new volcanic rocks indicates that plates are being pulled apart. [Gudmundur E. Sigvaldason, Nordic Volcanological Institute.]

rate and new Atlantic seafloor is created by mantle upwelling. (A more detailed portrait of the Mid-Atlantic Ridge was shown in Figure 2.3.) The island of Iceland exposes a segment of the otherwise submerged Mid-Atlantic Ridge, providing geologists with an opportunity to view the process of plate separation and seafloor spreading directly (**Figure 2.7**). The Mid-Atlantic Ridge is discernible in the Arctic Ocean north of Iceland and connects to a nearly globe-encircling system of mid-ocean ridges that winds through the Indian and Pacific oceans, ending along the western coast of North America. These **spreading centers** have created the millions of square kilometers of oceanic crust that now floor the world's oceans.

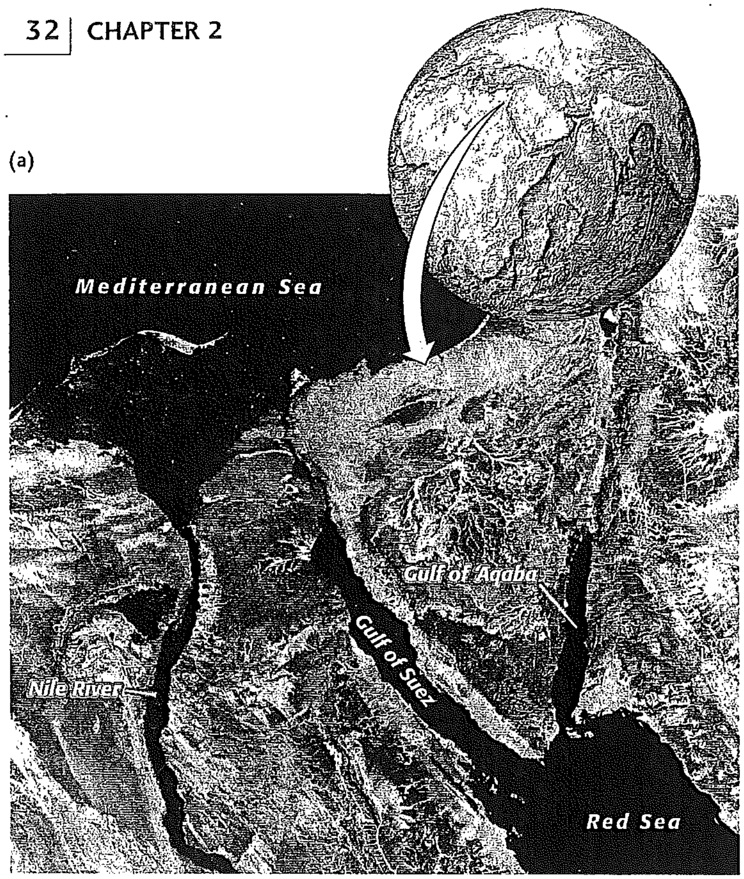
Continental Plate Separation Early stages of plate separation, such as the Great Rift Valley of East Africa (Figure 2.6b), can be found on some continents. These divergent boundaries are characterized by rift valleys, volcanic activity, and earthquakes distributed over a wider zone than oceanic spreading centers. The Red Sea and the Gulf of California are rifts that are further along in the spreading process (**Figure 2.8**). In these cases, the continents have separated enough for new seafloor to form along the spreading axis, and the rift valleys have been flooded by the ocean. Sometimes continental rifting may slow down or stop before the continent splits apart and a new ocean basin opens. The Rhine Valley along the border of Germany and France is a weakly active continental rift that may be this type of "failed spreading center." Will the East African Rift continue to open up, causing the Somali Subplate to split away from Africa completely and form a new ocean basin, as happened between Africa and the island of Madagascar? Or will the spreading slow down and eventually stop, as appears to be happening in western Europe? Geologists don't know the answers.

Convergent Boundaries

Plates cover the globe, so if they separate in one place, they must converge somewhere else, to conserve Earth's surface area. (As far as we can tell, our planet is not expanding!) Where plates collide head-on, they form convergent boundaries. The profusion of geologic events resulting from plate collisions makes convergent boundaries the most complex type observed in plate tectonics.

Ocean-Ocean Convergence If the two plates involved are oceanic, one descends beneath the other in a process known as **subduction (Figure 2.9**a). The oceanic lithosphere of the subducting plate sinks into the asthenosphere and is eventually recycled by the mantle convection system. This downbuckling produces a long, narrow deep-sea trench. In the Marianas Trench of the western Pacific, the ocean reaches its greatest depth, about 10 km—deeper than the height of Mount Everest. As the cold lithospheric slab descends, the pressure increases; the water trapped in the rocks of subducted oceanic crust is "squeezed out" and rises into the asthenosphere above the slab. This fluid causes the mantle to melt, producing a chain of volcanoes, called an **island arc,** on the seafloor behind the trench. The subduction of the Pacific Plate has formed the volcanically active Aleutian Islands west of Alaska, as well as the abundant island arcs of the western Pacific. Earthquakes that occur as deep as 600 km beneath these island arcs delineate the cold slabs of lithosphere as they descend into the mantle.

Ocean-Continent Convergence If one plate has a continental edge, it overrides the oceanic plate, because continental crust is lighter and much less easily subducted than oceanic crust (Figure 2.9b). The continental ledge crumples and is uplifted into a mountain chain roughly parallel to the deep-sea trench. The enormous forces of collision and subduction produce great earthquakes along the subduction interface. Over time, materials are scraped off the descending slab and incorporated into the adjacent mountains, leaving geologists



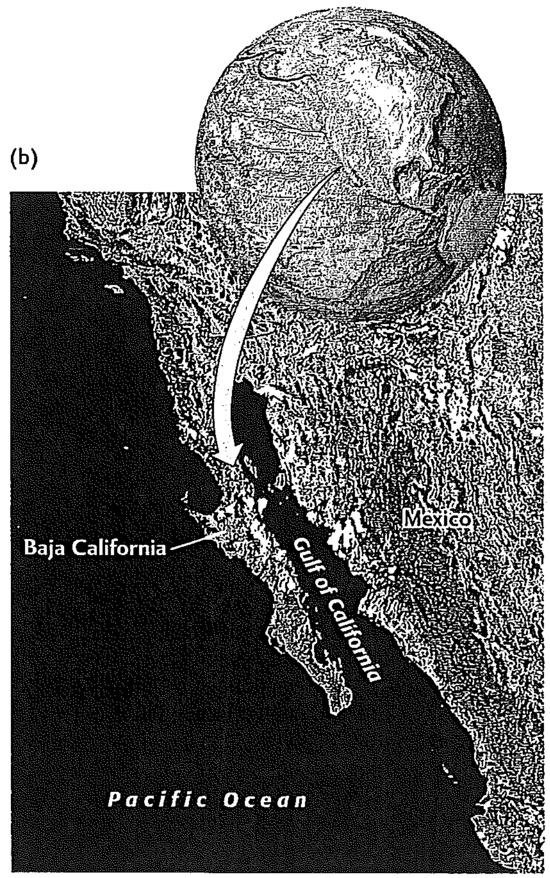


Figure 2.8 (a) The Red Sea (*lower right*) divides to form the Gulf of Suez on the left and the Gulf of 'Aqaba on the right. The Arabian Peninsula, on the right, splitting away from Africa on the left, has opened these great rifts, which are now flooded by the sea. The Nile River (*far left*) flows north into the Mediterranean Sea (*top*). [Earth Satellite Corporation.] (b) The Gulf of California, an opening ocean resulting from plate motions, marks a widening rift between Baja California and the Mexican mainland. [Worldsat International/Photo Researchers.]

with a complex (and often confusing) record of the subduction process. As in the case of ocean-ocean convergence, the water carried down by the subducting oceanic plate causes melting in the mantle wedge and the formation of volcanoes in the mountain belts behind the trench.

The west coast of South America, where the South American Plate collides with the oceanic Nazca Plate, is a subduction zone of this type. A great chain of high mountains, the Andes, rises on the continental side of the collision boundary, and a deep-sea trench lies just off the coast. The volcanoes here are active and deadly. One of them, Nevado del Ruiz in Colombia, killed 25,000 people when it erupted in 1985. Some of the world's greatest earthquakes also have been recorded along this boundary. Another example occurs where the small Juan de Fuca Plate subducts beneath the North American Plate off the coast of western North America. This convergent boundary gives rise to the dangerous volcanoes of the Cascade Range, which produced the Mount St. Helens eruption of 1980. As our understanding of the Cascadia subduction zone grows, scientists are increasingly worried that a great earthquake could occur there and cause considerable damage along the coasts of Oregon, Washington, and British Columbia.

Continent-Continent Convergence Where plate convergence involves two continents (Figure 2.9c), oceanic-type subduction cannot occur. The geologic consequences of such a collision are considerable. The collision of the Indian and Eurasian plates, both with continents at their leading edges, provides the best example. The Eurasian Plate overrides the Indian Plate, but India and Asia remain afloat, creating a double thickness of crust and forming the highest mountain range in the world, the Himalaya, as well as the vast, high plateau of Tibet. Severe earthquakes occur in the crumpling crust of this and other continent-continent collision zones.

Transform-Fault Boundaries

At boundaries where plates slide past each other, lithosphere is neither created nor destroyed. Such boundaries are **transform faults:** fractures along which relative displacement occurs as horizontal slip between the adjacent blocks. Transform-fault boundaries are typically found along mid-ocean ridges where the continuity of a divergent boundary is broken and the boundary is offset in a steplike pattern. The San Andreas fault in California, where the Pacific Plate slides by the North American Plate, is a

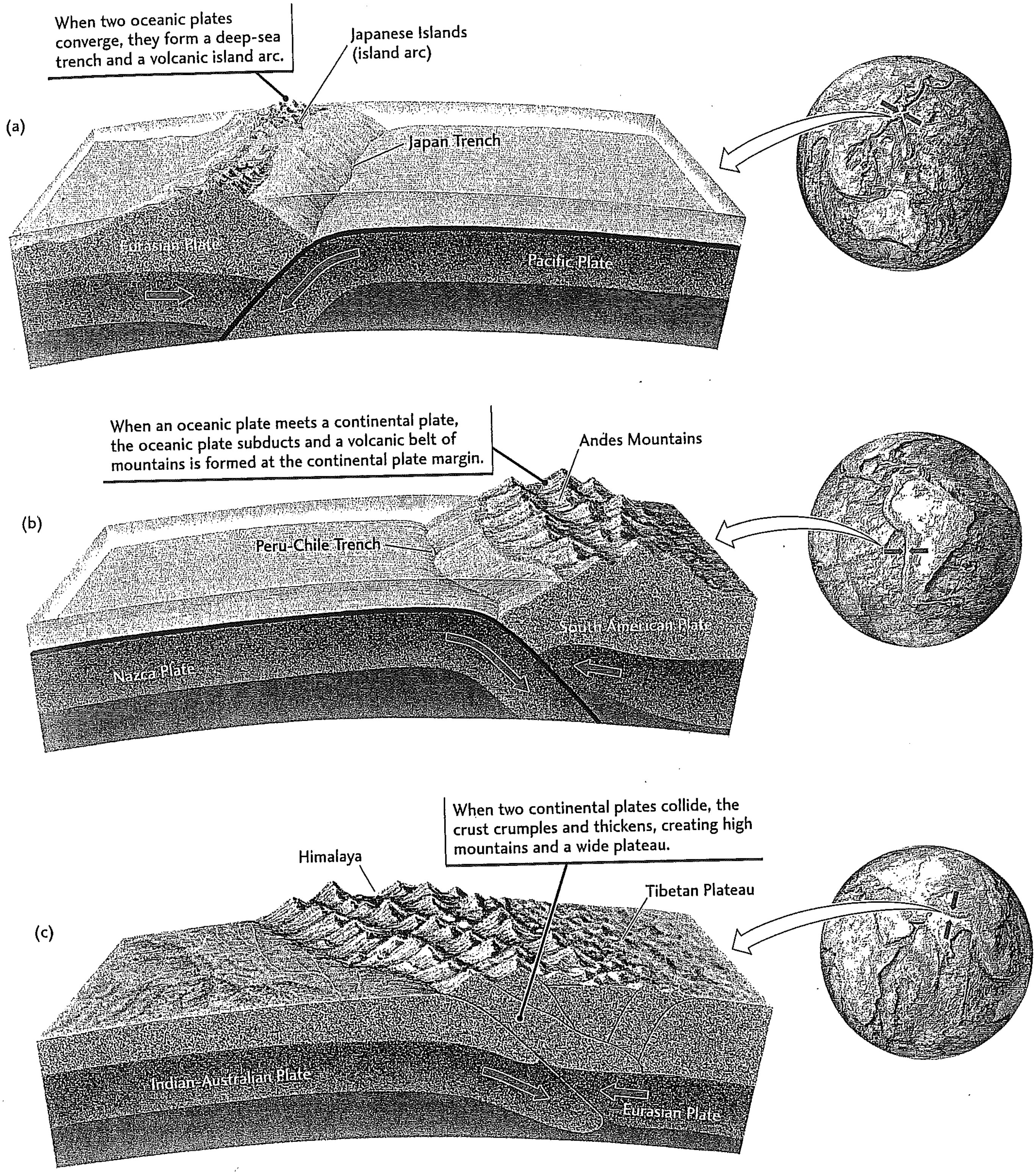


Figure 2.9 Three types of convergent boundaries. (a) Subduction of an oceanic plate beneath another oceanic plate, which forms a deep-sea trench and a volcanic island arc. (b) Subduction of an oceanic plate at a continental margin, which forms a mountainous volcanic belt within the deforming margin of the continent instead of an island arc. (c) A continent-continent plate collision, which crumples and thickens the continental crust, creating high mountains and a wide plateau.