



1 Planet Earth

For hundreds of thousands of years, humans have learned to survive by adapting to the natural rhythms and cycles of the planet on which we live. Understanding our environment has always been essential. But from our beginnings, we have been able to perceive only our immediate landscape, usually only a few square kilometers. Our perspective for observing and understanding Earth and its changes was very limited—at best, a vantage point on a high hill or mountaintop.

Since the 1960s, however, we have seen our planet as it really is, a tiny blue sphere suspended in the blackness of empty space, as this photograph of the International Space Station hovering over Earth's cloud-covered oceans illustrates so dramatically. Astronaut photographs and satellite images have revealed the exquisite beauty of Earth, a planet washed in water and surrounded by a thin atmosphere with swirling white clouds. Viewed from space, our planet—our home—is a system of moving gas, liquid, and solids with numerous interconnected and interdependent components.

Our need to understand Earth as a system is one of the reasons the different views from space are so valuable and so exciting. But the exploration of space did more than



increase our understanding of Earth. We have landed on the Moon, mapped the surfaces of Mercury, Venus, and Mars, and surveyed the diverse landscapes of the moons of Jupiter, Saturn, Uranus, and Neptune. Every object in the solar system contains part of a record of planetary origin and evolution that helps us understand our own planet.

Back on Earth, we have also extended our explorations to the vast unknown of the ocean floor. We have mapped its landforms and structure, gaining insight into its origin and history. We now know that the rocks below the ocean floor are completely different from those below the surface of the continents. We also have peered into Earth's depths using indirect methods. We have traced the paths of earthquake-generated seismic waves, measured the amount of heat that escapes from inside Earth, and recorded the pulse of the magnetic field. Consequently, we have discovered how Earth's interior is churning slowly and how such movements affect processes at the very surface of the planet.

With these new perspectives of our planet, we must develop an all-encompassing view of how Earth operates as a constantly changing dynamic system. In this chapter we start to do this by comparing and contrasting other planets with Earth. We also describe the major features of continents and ocean basins and view Earth's internal structure—all features that make Planet Earth unique in the solar system.

Photograph courtesy of NASA.



MAJOR CONCEPTS

1. A comparison of Earth with other inner planets reveals the distinguishing characteristics of our planet and shows what makes it unique.
2. Earth's atmosphere is a thin shell of gas surrounding the planet. It is a fluid in constant motion. Other planets have atmospheres, but Earth's is unique because it is 78% nitrogen and 21% oxygen.
3. The hydrosphere is another feature that makes Earth unique. Water moves in a great, endless cycle from the ocean to the atmosphere, over the land surface, and back to the sea again.
4. The biosphere exists because of water. Although it is small compared with other layers of Earth, it is a major geologic force operating at the surface.
5. Continents and ocean basins are the largest-scale surface features of Earth.
6. The continents have three major components: (a) ancient shields, (b) stable platforms, and (c) belts of folded mountains. Each reveals the mobility of Earth's crust.
7. The major structural features of the ocean floor are: (a) the oceanic ridges, (b) the vast abyssal floor, (c) long, narrow, and incredibly deep trenches, (d) seamounts, and (e) continental margins.
8. Earth is a differentiated planet, with its materials segregated into layers according to density. The internal layers classified by composition are (a) crust, (b) mantle, and (c) core. The major internal layers classified by physical properties are (a) lithosphere, (b) asthenosphere, (c) mesosphere, (d) outer core, and (e) inner core. Material within each of these units is in motion, making Earth a changing, dynamic planet.

INTRODUCTION TO GEOLOGY

Geology is the science of Earth. It concerns all of Earth: its origin, its history, its materials, its processes, and the dynamics of how it changes.

Geology is an incredibly fascinating subject. It is concerned with such diverse phenomena as volcanoes and glaciers, rivers and beaches, earthquakes and landslides, and even the history of life. Geology is a study about what happened in the past and what is happening now—a study that increases our understanding of nature and our place in it.

Yet geology does much more than satisfy intellectual curiosity. We are at a point in human history when Earth scientists have a responsibility to help solve some of society's most pressing problems. These include finding sites for safe disposal of radioactive waste and toxic chemicals, determining responsible land use for an expanding population, and providing safe, plentiful water supplies. Geology is being called upon to guide civil engineers in planning buildings, highways, dams, harbors, and canals. Geology helps us recognize how devastation caused by natural hazards, such as landslides, earthquakes, floods, and beach erosion, can be avoided or mitigated. Another driving force in our attempt to understand Earth is the discovery of natural resources. All Earth materials, including water, soils, minerals, fossil fuels, and building materials, are "geologic" and are discovered, exploited, and managed with the aid of geologic science.

Geologists also offer key information about the entire global system, especially past climate change and likely causes and effects of future climate modification. Perhaps, in the end, more fully comprehending nature is as important as the discovery of oil fields and mineral deposits.

Let us begin by exploring why Earth is unique among the planetary bodies of the solar system. We will then examine some of its important characteristics: its size, composition, atmosphere, hydrosphere, and the structure of its interior.

EARTH COMPARED WITH OTHER PLANETS

Among the inner planets (Mercury, Venus, Earth, the Moon, and Mars), Earth is unique because of its size and distance from the Sun. It is large enough to develop and retain an atmosphere and a hydrosphere. Temperature ranges are moderate, such that water can exist on its surface as liquid, solid, and gas.

The Solar System

A map of the solar system (Figure 1.1) shows the Sun and the major planetary bodies. This is Earth's cosmic home, the place of its origin and development. All of the planets in the solar system were created at the same time and from the same general material. The massive Sun, a star that generates heat by nuclear fusion, is the center of the system. Because of the Sun's vast gravitational influence, all of the planets orbit around it. As seen from above their north poles, the planets move counterclockwise about the Sun in slightly elliptical orbits. Moreover, all orbit in the same plane as the Sun's equator, except Pluto (note the different inclination of its orbit).

The diagram of the solar system in Figure 1.1 is not, of course, to scale. The orbits are distorted, and the sizes of the planetary bodies are greatly exaggerated and shown in perspective. In reality, the orbits are extremely large compared with the planets' sizes. A simple analogy may help convey the size and structure of the solar system. If the Sun were the size of an orange, Earth would be roughly the size of a grain of sand orbiting 9 m (30 ft) away. Jupiter would be the size of a pea revolving 60 m (200 ft) away. Pluto would be like a grain of silt 10 city blocks away. The nearest star would be the size of another orange more than 1600 km (1000 mi) away.

Until recently, the planets and their moons were mute astronomical bodies, only small specks viewed in a telescope. But today, they are new worlds as real as our own, because we have landed on their surfaces and studied them with remotely controlled probes. One of the most fundamental facts revealed by our exploration of the solar system is that the sizes and compositions of the planets vary systematically with distance from the Sun (Figure 1.2). The **inner planets** (Figure 1.3) include Mercury and the planetlike Moon, with their cratered surfaces; Venus, with its extremely hot, thick atmosphere of carbon dioxide and numerous volcanoes; Earth, with cool blue seas, swirling clouds and multicolored lands; and Mars, with huge canyons, giant extinct volcanoes, frigid polar ice caps, and long, dry river beds. The large **outer planets**—Jupiter, Saturn, Uranus, and Neptune—are giant balls of gas, with majestic rings and dozens of small satellites composed mostly of ice. The most distant planet, Pluto, is small and similar to these icy moons. Indeed, water ice is the most common “rock” in the outer solar system. The **density** of a planet or moon reveals these dramatic differences in composition. (Density is a measure of mass per unit volume: g/cm^3). For example, the densities of the rocky inner planets are quite high (over $3 \text{ g}/\text{cm}^3$) compared to the gas- and ice-rich outer planets which have densities less than about $1.6 \text{ g}/\text{cm}^3$.

Our best evidence tells us that Earth formed, along with the rest of the solar system, about 4.6 billion years ago. Nonetheless, only the inner planets are even vaguely like Earth. The compositions (dominated by dense solids with high melting points) of the inner planets make them radically different from the outer planets, made of low-temperature ices as well as gas. Although the inner planets are roughly of the same general size, mass, and composition, they vary widely in ways that are striking and important to us as living creatures. Why is Earth so different from its neighbors? Why does it alone have abundant liquid water, a dynamic crust, an oxygen-rich atmosphere, and perhaps most unique, that intricate web of life, the biosphere?



Tour of the Solar System

How do the inner planets differ from the outer planets?

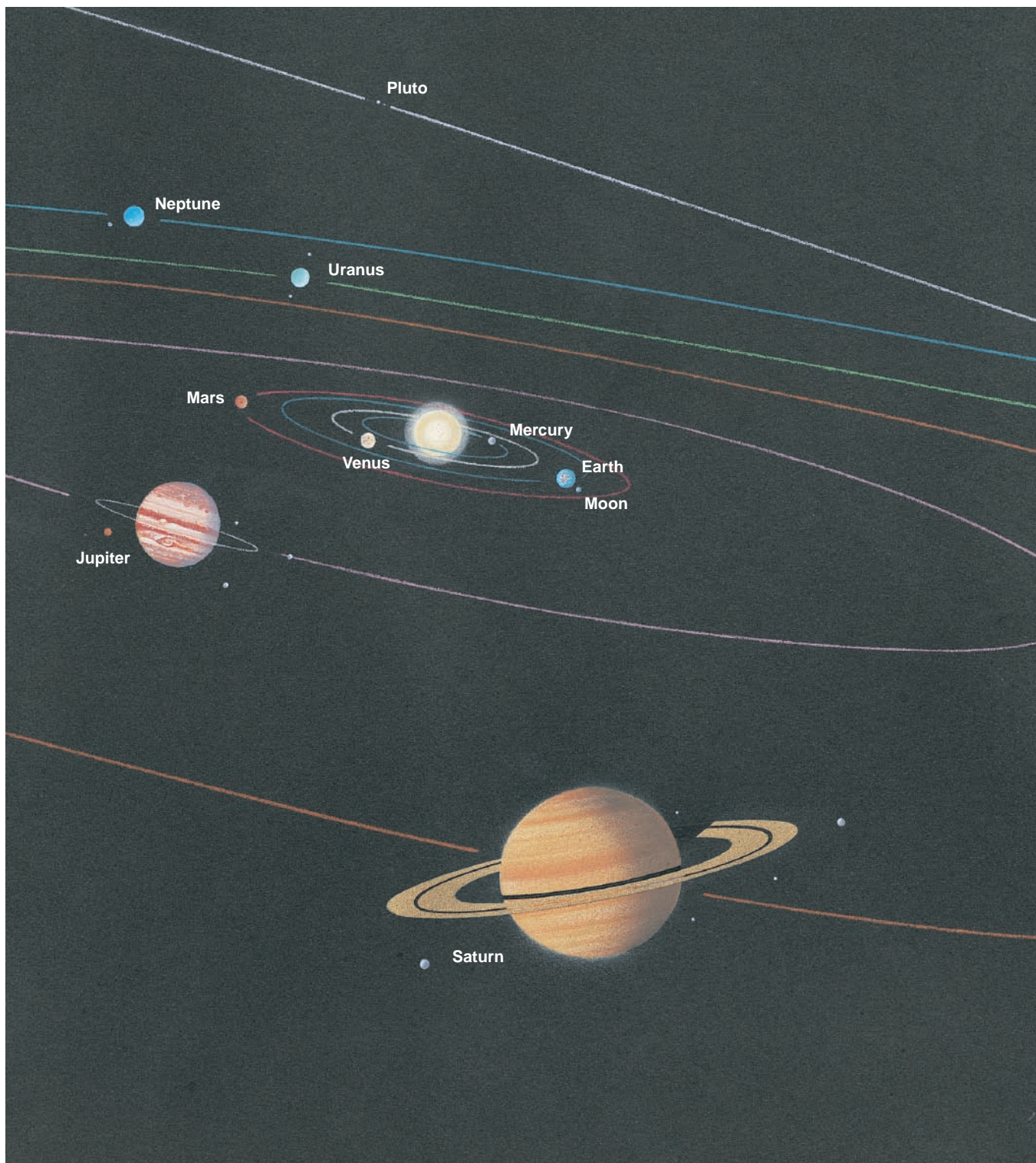


FIGURE 1.1 Our solar system consists of one star, a family of nine planets (almost 70 moons discovered so far), thousands of asteroids, and billions of meteoroids and comets (not shown here). The inner planets (Mercury, Venus, Earth with its Moon, and Mars) are composed mostly of rocky materials. The outer planets (Jupiter, Saturn, Uranus, and Neptune) are much larger, are composed mostly of gas and liquid, and have no solid surfaces. Pluto and Charon and the satellites in the outer solar system are composed mostly of water ice. Some are so cold (-230°C) that they have methane ice or nitrogen ice at their surfaces.

All planetary bodies in the solar system are important in the study of Earth because their chemical compositions, surface features, and other characteristics show how planets evolve. They provide important insight into the forces that shaped our planet's history.

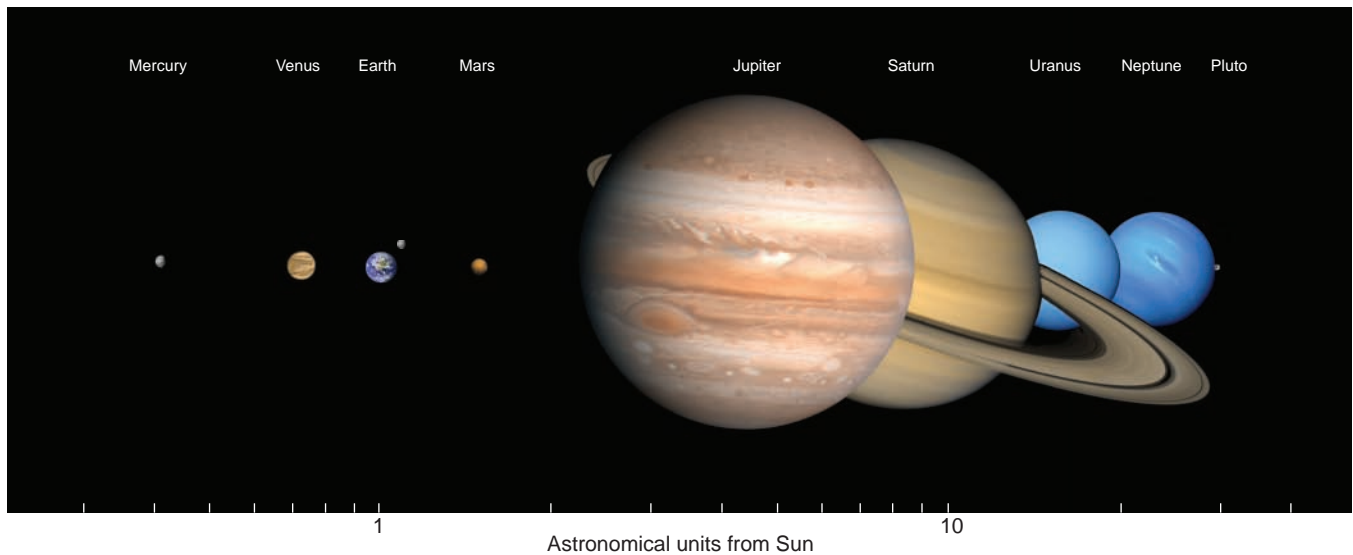


FIGURE 1.2 The planets of the solar system vary in size and composition with distance from the Sun. The inner planets are small and rocky, whereas the outer planets are much larger and composed mostly of hydrogen and helium.

Earth

From a planetary perspective, Earth is a small blue planet bathed in a film of white clouds and liquid water (Figure 1.3). In this remarkable view, we see Earth motionless, frozen in a moment of time, but there is much more action shown here than you might imagine. The blue water and swirling white clouds dominate the scene and underline the importance of moving water in the Earth system. Huge quantities of water are in constant motion, in the sea, in the air (as invisible vapor and condensed as clouds), and on land. You can see several complete cyclonic storms spiraling over thousands of square kilometers, pumping vast amounts of water into the atmosphere. When this water becomes precipitation on land, it flows back to the sea in great river systems that erode and sculpt the surface.

Large parts of Africa and Antarctica are visible in this view. The major climatic zones of our planet are clearly delineated. For example, the great Sahara Desert is visible at the top of the scene, extending across North Africa and into adjacent Saudi Arabia. Much of the vast tropical rain forest of central Africa is seen beneath the discontinuous cloud cover. Also, large portions of the south polar ice cap are clearly visible.

Earth is just the right distance from the Sun for its temperature to let water exist as a liquid, a solid, and a gas. Water in any of those forms is part of the hydrosphere. If Earth were closer to the Sun, our oceans would evaporate; if it were farther from the Sun, our oceans would freeze solid. However, there is plenty of liquid water on Earth, and it is liquid water, as much as anything else, that makes Earth unique among the planets of the solar system. Heated by the Sun, water moves on Earth in great cycles. It evaporates from the huge oceans into the atmosphere, precipitates over the landscape, collects in river systems, and ultimately flows back to the oceans. As a result, Earth's surface stays "young," being constantly changed by water and eroded into intricate systems of river valleys. This dynamism is in remarkable contrast to other planetary bodies, the surfaces of which are dominated by the craters of ancient meteorite impacts (Figure 1.3).

The presence of water as a liquid on Earth's surface throughout its long history also enabled life to evolve. And life, strange as it may seem, has profoundly changed the composition of Earth's atmosphere. Here is the mechanism: Photosynthesis by countless plants removes large quantities of carbon dioxide from the atmosphere. As part of this process, the plants "exhale" oxygen. In addition, many forms of marine life remove carbon dioxide from seawater to make their shells, which later fall to the seafloor and form limestone.

How has space photography changed our view of Earth and its geologic systems?

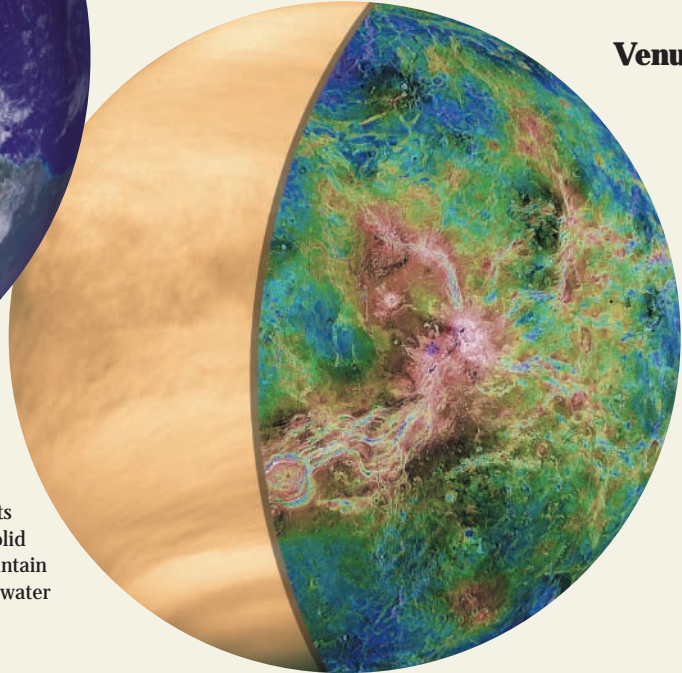
Earth



Earth is a delicate blue ball wrapped in filmy white clouds. The water and swirling clouds that dominate Earth's surface underline the importance of water in Earth's systems. The cold polar regions are buried with ice, and the warm tropics are speckled with clouds and greenery. The rocks of the high continents are strongly deformed and older than the rocks of the ocean basins. Earth has active volcanoes, a dynamic interior, and no large impact craters are visible on its surface.

Diameter 12,800 km Density 5.55 g/cm³

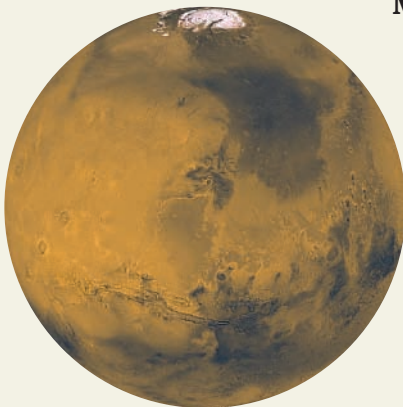
Venus



Venus is often considered Earth's twin because of its similar size and density, but the two planets are not identical. This image of Venus shows its cloudy atmosphere partially stripped away to reveal a radar map of the solid surface made by an orbiting satellite. Venus has high plateaus, folded mountain belts, many volcanoes, and relatively smooth volcanic plains, but it has no water and few meteorite impact craters.

Diameter 12,100 km. Density 5.25 g/cm³

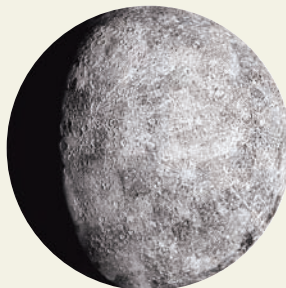
Mars



Mars is much smaller than Earth and Venus but has many fascinating geologic features—evidence that its surface has been dynamic in the past. Three huge extinct volcanoes, one more than 28 km high, can be seen in the left part of this image. An enormous canyon extends across the entire hemisphere—a distance roughly equal to that from New York to San Francisco. These features reveal that today's windy, desert Martian surface has been dynamic in the past, but ancient meteorite impact craters (visible in the upper right part of the image) have not been completely obliterated by younger events.

Diameter 6800 km Density 3.9 g/cm³

Mercury



Mercury is similar to the Moon, with a surface dominated by ancient impact craters and younger smooth plains presumably made from floods of lava. Like the Moon, Mercury lacks an atmosphere and hydrosphere.

Diameter 4900 km Density 5.44 g/cm³

Moon



The Moon has two contrasting provinces: bright, densely cratered highlands and dark, smooth lava plains. We know from rock samples brought back by the *Apollo* astronauts that the dark smooth plains are ancient floods of lava that filled many large meteorite impact craters and spread out over the surrounding area. The volcanic activity thus occurred after the formation of the heavily cratered terrain, but was not sufficient to obliterate all of the impact craters. Today the Moon is a geologically quiet body with no atmosphere or liquid water. Diameter 3500 km Density 3.3 g/cm³

FIGURE 1.3 The surfaces of the inner planets, shown at the same scale, provide insight into planetary dynamics. (Courtesy of NASA/JPL/Caltech)

Another characteristic of Earth is that it is dynamic. Its interior and surface continually change as a result of its **internal heat**. In marked contrast, many other planetary bodies have changed little since they formed because they are no longer hot inside. Most of Earth's heat comes from natural **radioactivity**. The breakdown of three elements—potassium, uranium, and thorium—is the principal source of this heat. Once generated, this heat flows to the surface and is lost to space. Another source of heat has been inherited from the formation of the planets. Heat was generated in each of the planets by the infall of countless meteorites to form a larger and larger planet. This **accretionary heat** may have melted the early planets, including Earth. Larger planets have more internal heat and retain it longer than smaller planets.

Earth's internal heat creates slow movements within the planet. Its rigid outer layer (the lithosphere) breaks into huge fragments, or plates, that move. Over billions of years, these moving plates have created ocean basins and continents. The heat-driven internal movement also has deformed Earth's solid outer layers, creating earthquakes, mountain belts, and volcanic activity. Thus, Earth has always been a dynamic planet, continuously changing as a result of its internal heat and the circulation of its surface water.

Look again at the view of Earth from space (Figure 1.3). Of particular interest in this view is the rift system of East Africa. The continent is slowly being ripped apart along this extensive fracture system. Where this great rift separates the Arabian Peninsula from Africa, it has filled with water, forming the Red Sea. The rift extends from there southward across most of the continent (it is mostly obscured by clouds in the equatorial region). Some animals that evolved in the East African rift valleys spread from there and learned to live in all of the varied landscapes of the planet. This was their first home, but they have since walked on the Moon.

The Other Inner Planets

In stark contrast to the dynamic Earth, some of the other inner planets are completely inactive and unchanging. For example, the Moon and Mercury (Figure 1.3) are pockmarked with thousands of craters that record the birth of the planets about 4.55 billion years ago. This was a period when planetary bodies swept up what remained of the cosmic debris that formed the Sun and its planets. As the debris struck each body, **impact craters** formed.

The Moon and Mercury are so small that they were unable to generate and retain enough internal heat to sustain prolonged geologic activity. They rapidly cooled and lost the ability to make volcanoes. Their smooth lava plains are ancient by comparison with those on Earth. Consequently, their surfaces have changed little in billions of years. They retain many meteorite impact craters formed during the birth of the solar system. Neither planet has a hydrosphere or an atmosphere to modify them. Thus, these small planets remain as “fossils” of the early stages in planetary development. The footprints left on the Moon by the *Apollo* astronauts will remain fresh and unaltered for millions of years. Mars is larger and has more internal heat and a thin atmosphere (Figure 1.3). Its originally cratered surface has been modified by volcanic eruptions, huge rifts, and erosion by wind and, in its distant past, running water. Today, Mars is too cold and the atmospheric pressure too low for water to exist as a liquid. Large polar ice caps mark both poles. In many ways, Mars is a frozen wasteland with a nearly immobile crust. Consequently, its ancient impact craters were never completely obliterated.

Venus is larger still and has more internal energy, which moves the crust and continually reshapes its surfaces (Figure 1.3). Venus is only slightly smaller than Earth and closer to the Sun. A thick carbon dioxide-rich atmosphere holds in the solar energy that reaches the surface and makes the temperature rise high enough to melt lead (around 500°C). The atmospheric pressure is 90 times that on Earth. Unlike the smaller planets, Venus has no heavily cratered areas. Its ancient impact

What can the surface features tell us about planetary dynamics?

craters must have been destroyed by deformation or by burial below lava flows. Its surface is apparently young. Because of its large size, it has cooled quite slowly, so that volcanoes may even be active today. On the other hand, no evidence of water has been found on Venus; it has no oceans, no rivers, no ice caps, and only a very little water vapor. Only Earth has large amounts of liquid water that have influenced its development throughout history.

This, then, is Planet Earth in its cosmic setting—only a pale blue dot in space, part of a family of planets and moons that revolve about the Sun. It is a minor planet bound to an ordinary star in the outskirts of one galaxy among billions. Yet, from a human perspective, it is a vast and complex system that has evolved over billions of years, a home we are just beginning to understand. Learning about Earth and the forces that change it—the intellectual journey upon which you are about to embark—is a journey we hope you will never forget. Our study of the diverse compositions and conditions of the planets should remind us of the delicate balance that allows us to exist at all. Are we intelligent enough to understand how our world functions as a planet and to live wisely within those limits?

EARTH'S OUTERMOST LAYERS

The outermost layers of Earth are the atmosphere, hydrosphere, and biosphere. Their dynamics are especially spectacular when seen from space.

Views of Earth from space like the one in Figure 1.3 reveal many features that make Earth unique, and they provide insight into our planet's history of change. The atmosphere is the thin, gaseous envelope that surrounds Earth. The hydrosphere, the planet's discontinuous water layer, is seen in the vast oceans. Even parts of the biosphere—the organic realm, which includes all of Earth's living things—can be seen from space, such as the dark green tropical forest of equatorial Africa. The lithosphere—the outer, solid part of Earth—is visible in continents and islands.

One of the unique features of Earth is that each of the planet's major realms is in constant motion and continual change. The atmosphere and the hydrosphere move in dramatic and obvious ways. Movement, growth, and change in the biosphere can be readily appreciated—people are part of it. But Earth's seemingly immobile lithosphere is also in motion, and it has been so throughout most of the planet's history.

The Atmosphere

Perhaps Earth's most conspicuous features, as seen from space, are the **atmosphere** and its brilliant white swirling clouds (Figure 1.3). Although this envelope of gas forms an insignificantly small fraction of the planet's mass (less than 0.01%), it is particularly significant because it moves easily and is constantly interacting with the ocean and land. It plays a part in the evolution of most features of the landscape and is essential for life. On the scale of the illustration in Figure 1.3, most of the atmosphere would be concentrated in a layer as thin as the ink with which the photo is printed.

The atmosphere's circulation patterns are clearly seen in Figure 1.3 by the shape and orientation of the clouds. At first glance, the patterns may appear confusing, but upon close examination we find that they are well organized. If we ignore the details of local weather systems, the global atmospheric circulation becomes apparent. Solar heat, the driving force of atmospheric circulation, is greatest in the equatorial regions. The heat causes water in the oceans to evaporate, and the heat makes the moist air less dense, causing it to rise. The warm, humid air forms an equatorial belt of spotty clouds, bordered on the north and south by zones that are cloud-free, where air descends. To the north and south, cyclonic storm systems develop where warm air from low latitudes confronts cold air around the poles.

Our atmosphere is unique in the solar system. It is composed of 78% nitrogen, 21% oxygen, and minor amounts of other gases, such as carbon dioxide (only 0.035%) and water vapor. The earliest atmosphere was much different. It was essentially oxygen-free and consisted largely of carbon dioxide and water vapor. The present carbon dioxide-poor atmosphere developed as soon as limestone began to form in the oceans, tying up the carbon dioxide. Oxygen was added to the atmosphere later, when plants evolved. As a result of photosynthesis, plants extracted carbon dioxide from the primitive atmosphere and expelled oxygen into it. Thus, the oxygen in the atmosphere is and was produced by life.

The Hydrosphere

The **hydrosphere** is the total mass of water on the surface of our planet. Water covers about 71% of the surface. About 98% of this water is in the oceans. Only 2% is in streams, lakes, groundwater, and glaciers. Thus, it is for good reason that Earth has been called “the water planet.” It has been estimated that if all the irregularities of Earth’s surface were smoothed out to form a perfect sphere, a global ocean would cover Earth to a depth of 2.25 km.

Again, it is this great mass of water that makes Earth unique. Water permitted life to evolve and flourish; every inhabitant on Earth is directly or indirectly controlled by it. All of Earth’s weather patterns, climate, rainfall, and even the amount of carbon dioxide in the atmosphere are influenced by the water in the oceans. The hydrosphere is in constant motion; water evaporates from the oceans and moves through the atmosphere, precipitating as rain and snow, and returning to the sea in rivers, glaciers, and groundwater. As water moves over Earth’s surface, it erodes and transports weathered rock material and deposits it. These actions constantly modify Earth’s landscape. Many of Earth’s distinctive surface features are formed by action of the hydrosphere.

The Biosphere

The **biosphere** is the part of Earth where life exists. It includes the forests, grasslands, and familiar animals of the land, together with the numerous creatures that inhabit the sea and atmosphere. Microorganisms such as bacteria are too small to be seen, but they are probably the most common form of life in the biosphere. As a terrestrial covering, the biosphere is discontinuous and irregular; it is an interwoven web of life existing within and reacting with the atmosphere, hydrosphere, and lithosphere. It consists of more than 1.6 million described species and perhaps as many as 3 million more not yet described. Each species lives within its own limited environmental setting (Figure 1.4).

Almost the entire biosphere exists in a narrow zone extending from the depth to which sunlight penetrates the oceans (about 200 m) to the snow line in the tropical and subtropical mountain ranges (about 6000 m above sea level). At the scale of the photograph in Figure 1.3, the biosphere—all of the known life in the solar system—would be in a thin layer no thicker than the paper on which the image is printed.

Certainly one of the most interesting questions about the biosphere concerns the number and variety of organisms that compose it. Surprisingly, the truth is that no one knows the answer. Despite more than 250 years of systematic research, estimates of the total number of plant and animal species vary from 3 million to more than 30 million. Of this number, only 1.6 million species have been recorded. The diversity is stranger than you may think. Insects account for more than one-half of all known species, whereas there are only 4000 species of mammals, or about 0.025% of all species. Observation shows that there are more species of small animals than of large ones. The smallest living creatures—those invisible to the unaided eye, such as protozoa, bacteria, and viruses—contribute greatly to the variety of species. The biosphere is a truly remarkable part of Earth’s systems.

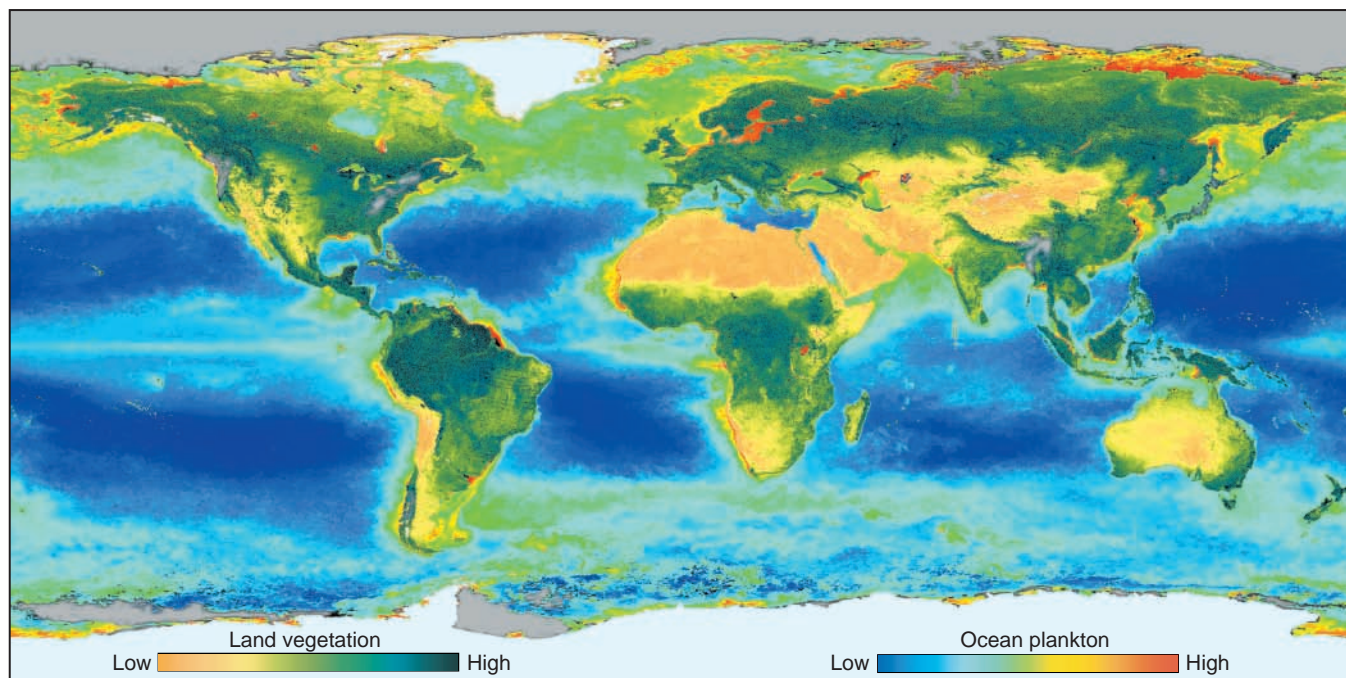
The main factors controlling the distribution of life on our planet are temperature, pressure, and chemistry of the local environment. However, the range of

How are Earth’s atmosphere and hydrosphere different from those on other planets?

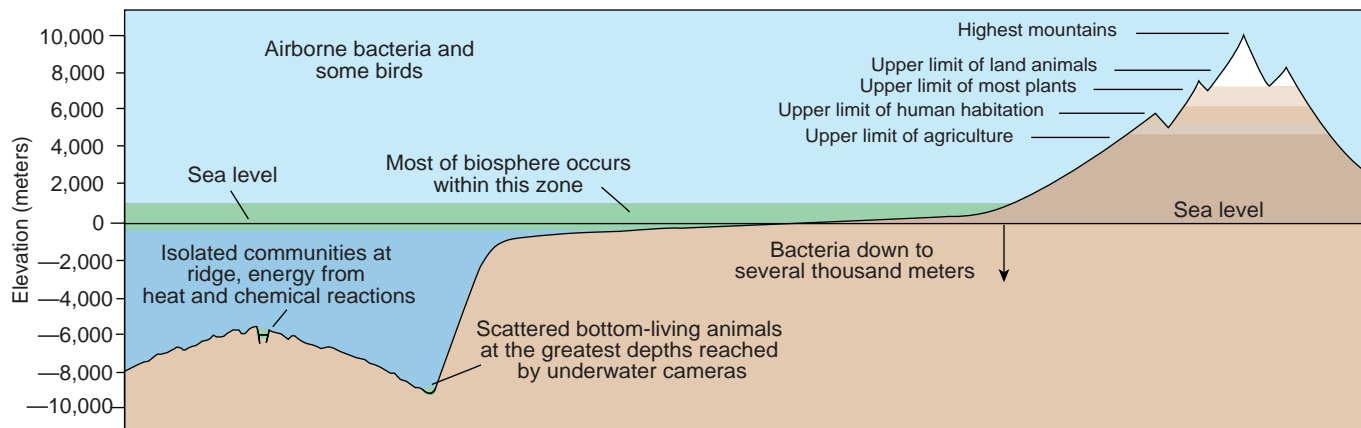
What is the biosphere? How does it affect Earth dynamics?

environmental conditions in which life is possible is truly amazing, especially the range of environments in which microorganisms can exist (Figure 1.4B).

Although the biosphere is small compared with Earth's other major layers (atmosphere, hydrosphere, and lithosphere), it has been a major geologic force. Essentially all of the present atmosphere has been produced by the chemical activity of the biosphere. The composition of the oceans is similarly affected by living things; many marine organisms extract calcium carbonate from seawater to make their shells and hard parts. When the organisms die, their shells settle to the seafloor and accumulate as beds of limestone. In addition, the biosphere formed all of Earth's coal, oil, and natural gas. Thus, much of the rock in Earth's crust originated in some way from biological activity.



(A) This map of the biosphere was produced from data derived from satellite sensors. Land vegetation increases from tan to yellow to green to black. Escalating concentrations of ocean phytoplankton are shown by colors ranging from purple to red. Phytoplankton are microscopic plants that live in the surface layer of the ocean and form the foundation of the marine food chain. Note the particularly high concentrations of phytoplankton in polar waters (red and yellow) and the very low concentrations (purple and blue) in the mid-latitudes. (Courtesy of SeaWiFS Project, NASA/Goddard Space Flight Center and Orbimage)



(B) Most of the biosphere exists within a very thin zone from 100 m below sea level to about 2000 m above sea level.

FIGURE 1.4 These global views of Earth's biosphere emphasize that life is widespread and has become a powerful geologic force.

A historical record of the biosphere is preserved, sometimes in remarkable detail, by fossils that occur in rocks. Indeed, the number of living species today represents less than 10% of the number of species that have existed since life first developed on Earth.

EARTH'S INTERNAL STRUCTURE

The solid materials of Earth are separated into layers according to composition and mechanical properties. From outside in, the compositional layers are (1) crust, (2) mantle, and (3) core. Layers based on physical properties are (1) lithosphere, (2) asthenosphere, (3) mesosphere, (4) outer core, and (5) inner core.

Why is it important to distinguish between the physical and chemical layers of Earth's interior?

Studies of earthquake waves, meteorites that fall to Earth, magnetic fields, and other physical properties show that Earth's interior consists of a series of shells of different compositions and mechanical properties. Earth is called a **differentiated planet** because of this separation into layers. How did Earth become differentiated? First, recall that the density of liquid water is 1 g/cm^3 . The density of most rocks at the surface is about three times as great, just under 3 g/cm^3 . But the overall density of Earth is about 5.5 g/cm^3 . Clearly, Earth consists of internal layers of increasing density toward the center. The internal layers were produced as different materials rose or sank so that the least-dense materials were at the surface and the most dense were in the center of the planet. Thus, gravity is the motive force behind Earth's differentiated structure.

In the discussion below we take you on a brief tour to the very center of Earth, which lies at a depth of about 6400 km. Chemical properties define one set of layers, and mechanical behavior defines a different set. Figure 1.5 shows the layers based on chemical properties on the left and those based on mechanical properties on the right. An understanding of both types of layers is vital.

Internal Structure Based on Chemical Composition

Geologists use the term **crust** for the outermost compositional layer (Figure 1.5, left). The base of the crust heralds a definite change in the proportions of the various elements that compose the rock but not a strong change in its mechanical behavior or physical properties.

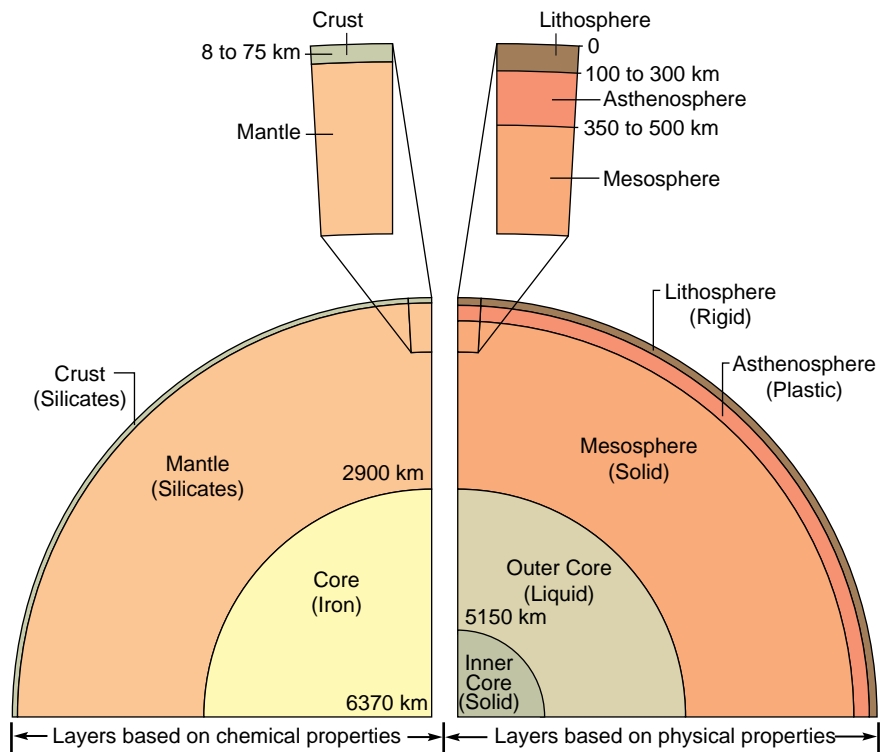
Moreover, the crust of the **continents** is distinctly different from the crust beneath the **ocean basins** (Figure 1.6). Continental crust is much thicker (as much as 75 km), is composed of less-dense "granitic" rock (about 2.7 g/cm^3), is strongly deformed, and includes the planet's oldest rocks (billions of years in age). By contrast, the oceanic crust is only about 8 km thick, is composed of denser volcanic rock called basalt (about 3.0 g/cm^3), is comparatively undeformed by folding, and is geologically young (200 million years or less in age). These differences between the continental and oceanic crusts, as you shall see, are fundamental to understanding Earth.

The next major compositional layer of Earth, the **mantle**, surrounds or covers the core (Figure 1.5, left). This zone is about 2900 km thick and constitutes the great bulk of Earth (82% of its volume and 68% of its mass). The mantle is composed of silicate rocks (compounds of silicon and oxygen) that also contain abundant iron and magnesium. Fragments of the mantle have been brought to the surface by volcanic eruptions. Because of the pressure of overlying rocks, the mantle's density increases with depth from about 3.2 g/cm^3 in its upper part to nearly 5 g/cm^3 near its contact with the core.

Earth's **core** is a central mass about 7000 km in diameter. Its density increases with depth but averages about 10.8 g/cm^3 . The core makes up only 16% of Earth's volume, but, because of its high density, it accounts for 32% of Earth's mass.

FIGURE 1.5 The internal structure of Earth consists of layers of different composition and layers of different physical properties. The left side shows the layering based on chemical composition. These consist of a crust, mantle, and core.

The right side shows the layering based on physical properties such as rigidity, plasticity, and whether it is solid or liquid. (Note that the two divisions, chemical and physical, do not coincide except at the core mantle boundary.)



Indirect evidence indicates that the core is mostly metallic iron, making it distinctly different from the silicate material of the mantle.

Internal Structure Based on Physical Properties

The mechanical (or physical) properties of a material tell us how it responds to force, how weak or strong it is, and whether it is a liquid or a solid. The solid, strong, and rigid outer layer of a planet is the **lithosphere** (“rock sphere”). The lithosphere includes the crust and the uppermost part of the mantle (Figure 1.5, right). Earth’s lithosphere varies greatly in thickness, from as little as 10 km in some oceanic areas to as much as 300 km in some continental areas. Figure 1.6 shows how the major internal layers of Earth are related.

Within the upper mantle, there is a major zone where temperature and pressure are just right so that part of the material melts, or nearly melts. Under these conditions, rocks lose much of their strength and become soft and plastic and flow slowly. This zone of easily deformed mantle is known as the **asthenosphere** (“weak sphere”). The boundary between the asthenosphere and the overlying lithosphere is mechanically distinct but does not correspond to a fundamental change in chemical composition. The boundary is simply a major change in the rock’s mechanical properties.

The rock below the asthenosphere is stronger and more rigid than in the asthenosphere. It is so because the high pressure at this depth offsets the effect of high temperature, forcing the rock to be stronger than the overlying asthenosphere. The region between the asthenosphere and the core is the **mesosphere** (“middle sphere”).

Earth’s core marks a change in both chemical composition and mechanical properties. On the basis of mechanical behavior alone, the core has two distinct parts: a solid **inner core** and a liquid **outer core**. The outer core has a thickness of about 2270 km compared with the much smaller inner core, with a radius of only about 1200 km. The core is extremely hot, and heat loss from the core and the rotation of Earth probably cause the liquid outer core to flow. This circulation generates Earth’s magnetic field.

What layers of Earth are most significant to planetary dynamics?

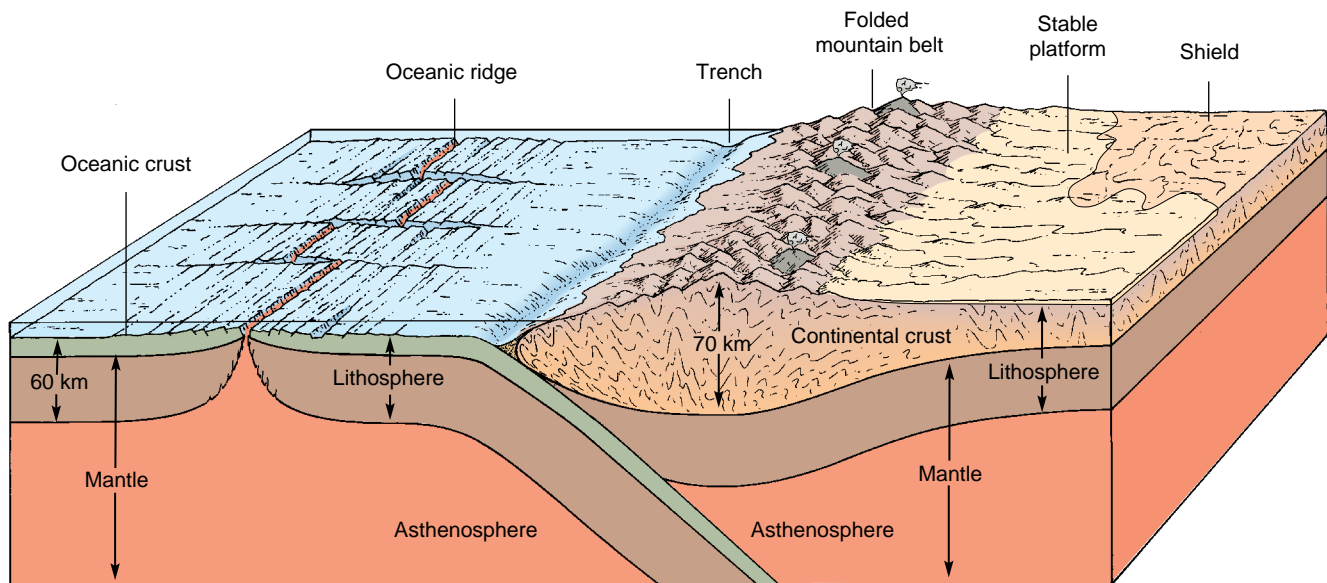


FIGURE 1.6 The outermost layers of the solid Earth, based on physical characteristics, are the asthenosphere and the lithosphere. The asthenosphere is hot, close to its melting point, and is capable of plastic flow. The lithosphere above it is cooler and rigid. It includes the uppermost part of the mantle and two types of crust: thin, dense oceanic crust and thick, buoyant continental crust.

MAJOR FEATURES OF THE CONTINENTS

Continents consist of three major structural components: (1) shields; (2) stable platforms; and (3) folded mountain belts. Continental crust is less dense, thicker, older, and more deformed than oceanic crust.

If Earth had neither an atmosphere nor a hydrosphere, two principal regions would stand as its dominant features: ocean basins and continents. The ocean basins, which occupy about two-thirds of Earth's surface, have a remarkable topography, most of which originated from extensive volcanic activity and Earth movements that continue today. The continents rise above the ocean basins as large platforms. The ocean waters more than fill the ocean basins and rise high enough to flood a large part of the continents. The present shoreline, so important to us geographically and so carefully mapped, has no simple relation to the structural boundary between continents and ocean basins.

In our daily lives, the position of the ocean shoreline is very important. But from a geologic viewpoint, the elevation of the continents with respect to the ocean floor is much more significant than the position of the shore. The difference in elevation of continents and ocean basins reflects their fundamental difference in composition and density. Continental "granitic" rocks are less dense (about 2.7 g/cm^3) than the basaltic rocks of the ocean basins (about 3.0 g/cm^3). That is, a given volume of continental rock weighs less than the same volume of oceanic rock. This difference causes the **continental crust** to be more buoyant—to rise higher—than the denser **oceanic crust** in much the same way that ice cubes float in a glass of water because ice is less dense than water. Moreover, the rocks of the continental crust are older (some as old as 4.0 billion years old) than the rocks of the oceanic crust.

The elevation and area of the continents and ocean basins now have been mapped with precision. These data can be summarized in various forms. Figure 1.7 shows that the average elevation of the continents is 0.8 km above sea level, and the average elevation of the seafloor (depth of the ocean) is about 3.7 km below sea level. Only a relatively small percentage of Earth's surface rises significantly above the average elevation of the continents or drops below the average depth

What are the fundamental structural features of continents?

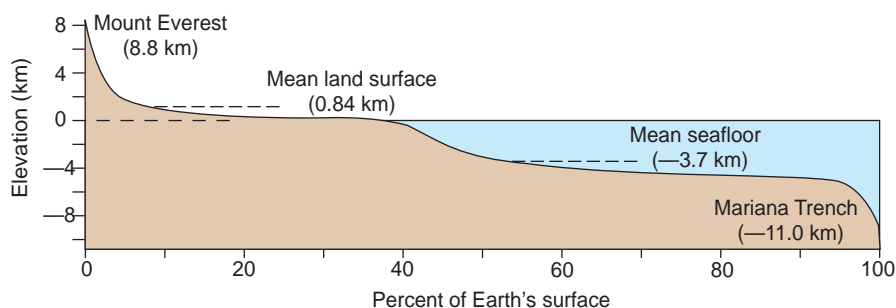


FIGURE 1.7 A graph of the elevation of the continents and ocean basins shows that the average height of the continents is only 0.8 km above sea level. Only a small percentage of Earth's surface rises above the average elevation of the continents or drops below the average elevation of the ocean floor.

of the ocean. If the continents did not rise quite so high above the ocean floor, the entire surface of Earth would be covered with water.

What are the most significant features of continental shields?

Shields. The extensive flat region of a continent, in which complexly deformed ancient crystalline rocks are exposed, is known as a **shield** (Figure 1.8). All of the rocks in the shield formed long ago—most more than 1 billion years ago. Moreover, these regions have been relatively undisturbed for more than a half-billion years except for broad, gentle warping. The rocks of the shields are highly deformed igneous and metamorphic rock; they are also called the **basement complex**.

Without some firsthand knowledge of a shield, visualizing the nature and significance of this important part of the continental crust is difficult. Figure 1.9 shows part of the Canadian shield of the North American continent as seen from space. It will help you to comprehend the extent, the complexity, and some of the typical features of shields. First, a shield is a regional surface of low relief that generally has an elevation within a few hundred meters of sea level. (**Relief** is the elevation difference between the low and the high spots.) Resistant rocks may rise 50 to 100 m above their surroundings.

A second characteristic of shields is their complex internal structure and complex arrangements of rock types. Many rock bodies in a shield once were molten, and others have been compressed and extensively deformed while still solid. Much of the rock in shields was formed several kilometers below the surface. They are now exposed only because the shields have been subjected to extensive uplift and erosion.

What are the most significant features of stable platforms?

Stable Platforms. When the basement complex is covered with a veneer of sedimentary rocks, a **stable platform** is created. The layered sedimentary rocks are nearly horizontal and commonly etched by dendritic (treelike) river patterns (Figure 1.10). These broad areas have been relatively stable throughout the last 500 million or 600 million years; that is, they have not been uplifted a great distance above sea level or submerged far below it—hence the term stable platform. In North America, the stable platform lies between the Appalachian Mountains and the Rocky Mountains and extends northward to the Lake Superior region and into western Canada. Throughout most of this area, the sedimentary rocks are nearly horizontal, but locally they have been warped into broad domes and basins (Figure 1.8). Sometimes it is useful to group the shield and stable platform together in what is called a **craton**.

Folded Mountains. Some of the most impressive features of the continents are the young **folded mountain belts** that typically occur along their margins. Most people think of a mountain as simply a high, rugged landform, standing in contrast to flat plains and lowlands. Mountains, however, are much more than high country. To a geologist, the term mountain belt means a long, linear zone in Earth's crust where the rocks have been intensely deformed by horizontal stress during the slow

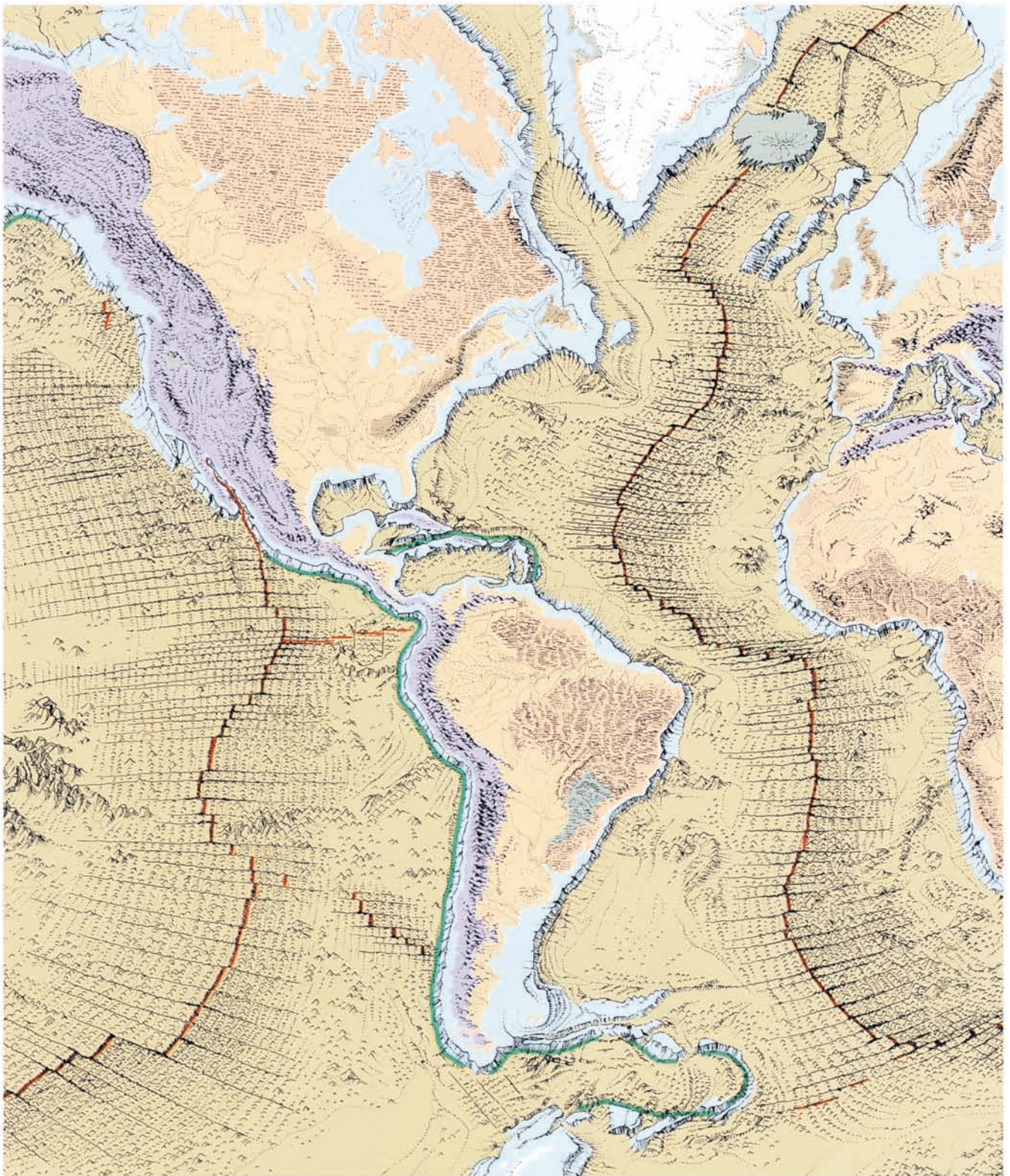


FIGURE 1.8 The major surface features of Earth reflect the structure of the lithosphere. The continental crust rises above the ocean basins and forms continents. They have as their major structural features shields, stable platforms, and folded mountain belts. The continents are formed mostly of granitic rock. The oceanic crust forms the ocean floor. Its major features include the oceanic ridge, the abyssal floor, seamounts, and trenches. It is composed primarily of basalt.



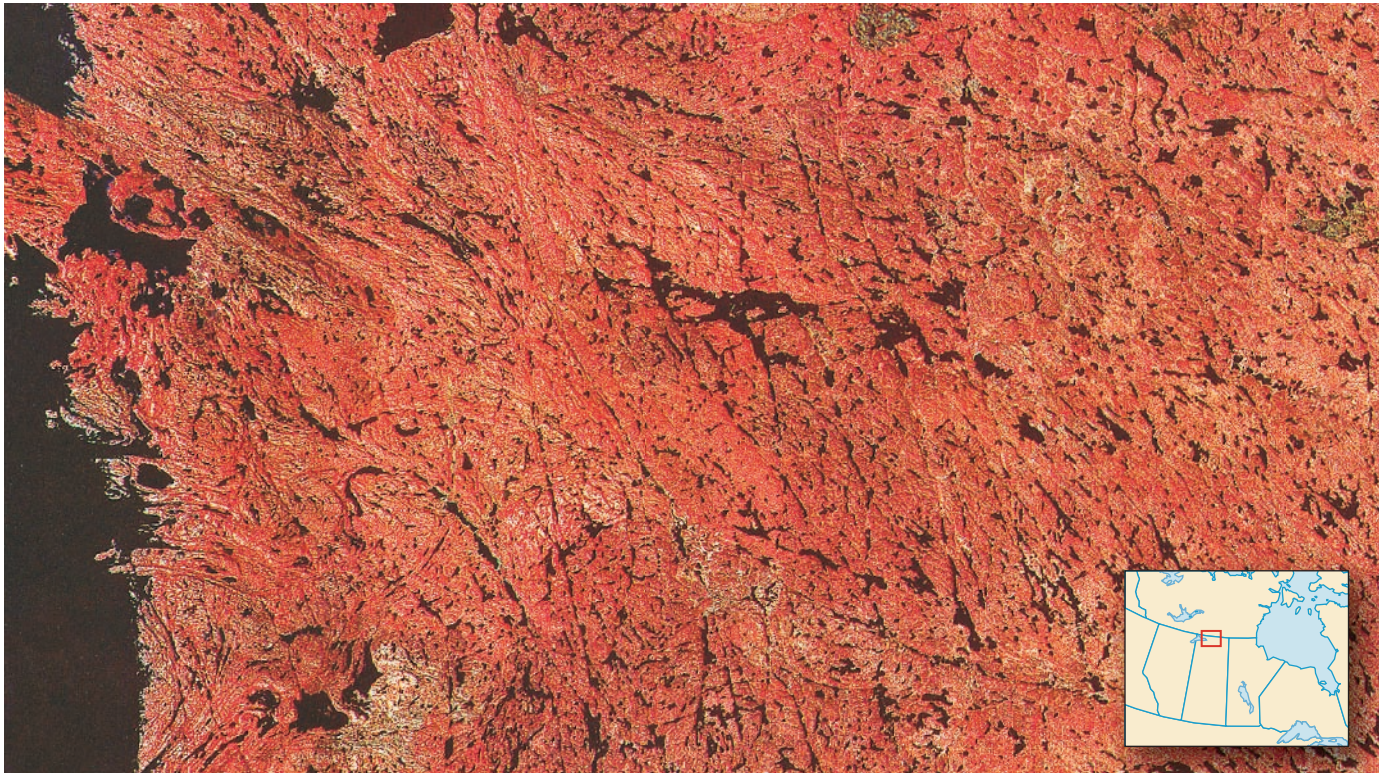


FIGURE 1.9 The Canadian shield is a fundamental structural component of North America. It is composed of complexly deformed crystalline rock bodies, eroded to an almost flat surface near sea level, as shown in this false-color satellite image. Throughout much of the Canadian shield, the topsoil has been removed by glaciers, and different rock bodies are etched in relief by erosion. The resulting depressions commonly are filled with water, forming lakes and bogs that emphasize the structure of the rock bodies. Dark tones show areas of metamorphic rock. Light pink tones show areas of granitic rock. (Courtesy of NASA)

collision between two lithospheric plates. In addition, they generally have been intruded by molten rock. The topography can be high and rugged, or it can be worn down to a surface of low relief. To a sightseer, the topography of a mountain belt is everything, but to a geologist, it is not as important as the extent and style of its internal deformation. The great folds and fractures in mountain belts provide evidence that Earth's lithosphere is, and has been, in motion.

Figure 1.10 illustrates some characteristics of folded mountains and the extent to which the margins of continents have been deformed. On this map of the Appalachian Mountains, the once horizontal layers of rock have been deformed by compression and are folded like wrinkles in a rug. Erosion has removed the upper parts of the folds, so the resistant layers form zigzag patterns similar to those that would be produced if the crest of the wrinkles in a rug were sheared off.

The crusts of the Moon, Mars, and Mercury lack this type of deformation. All of their impact craters, regardless of age, are circular—proof that the crusts of these planets have not been strongly deformed by compressive forces. Their crusts, unlike that of Earth, appear to have been fixed and immovable throughout their histories. However, Venus is like Earth in this respect and has long belts of folded mountains.

Summary of the Continents. The broad, flat continental masses that rise above the ocean basins have an almost endless variety of hills and valleys, plains and plateaus, and mountains. Yet from a regional perspective, the geologic differences between continents are mostly in size and shape and in the proportions of shields, stable platforms, and folded mountain belts.

Can a folded mountain belt be a lowland?

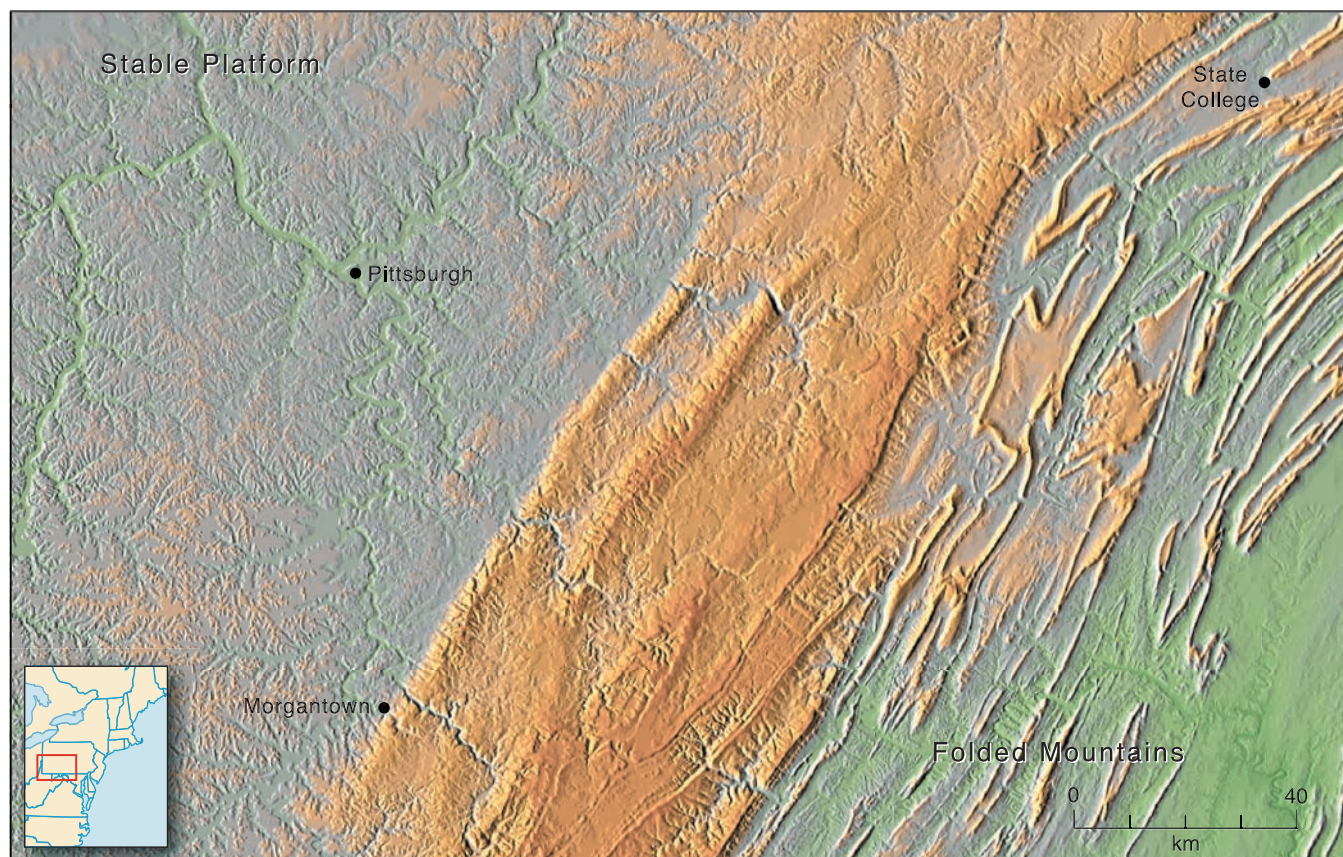


FIGURE 1.10 The stable platform and folded mountain belt in the eastern United States are clearly shown on this topographic map. The layered rocks of the stable platform are nearly horizontal, but on a regional scale, they are warped into a large structural basin that has been highly dissected by intricate networks of river valleys (upper left). The rocks of the Appalachian Mountains, in contrast, have been compressed and folded (center and lower right). The folded layers are expressed by long, narrow ridges of resistant sandstone that rise about 300 m above the surrounding area (lower right). Erosion has removed the upper parts of many folds, so their resistant limbs (which form the ridges) are exposed in elliptical or zigzag outcrop patterns. (Courtesy of Ken Perry, Chalk Butte, Inc.)

Let us now briefly review the major structural components of the continents by examining North and South America (Figure 1.8). North America has a large shield, most of which is in Canada. Most of the Canadian shield is less than 300 m above sea level. The rocks in the Canadian shield formed between 1 and 4 billion years ago. The stable platform extends through the central United States and western Canada and is underlain by sedimentary rocks, slightly warped into broad domes and basins. The Appalachians are an old folded mountain belt that formed about 250 million years ago. The Rocky Mountains form part of another folded mountain belt (the Cordillera) that dominates western North America and extends into South America. The Rockies started forming about 60 million years ago, and parts of this belt are still active.

In many ways, the structure of South America (Figure 1.8) is similar to that of North America. The continent consists of a broad shield in Brazil and Venezuela, and stable platforms in the Amazon basin and along the eastern flanks of the Andes Mountains. The Andes Mountains are part of the Cordilleran folded mountain belt that extends from Alaska to the southern tip of South America. The continent has no mountain belt along the eastern margin like the Appalachian Mountains in North America. More than 90% of South America drains into the Atlantic Ocean by way of the Amazon River system.

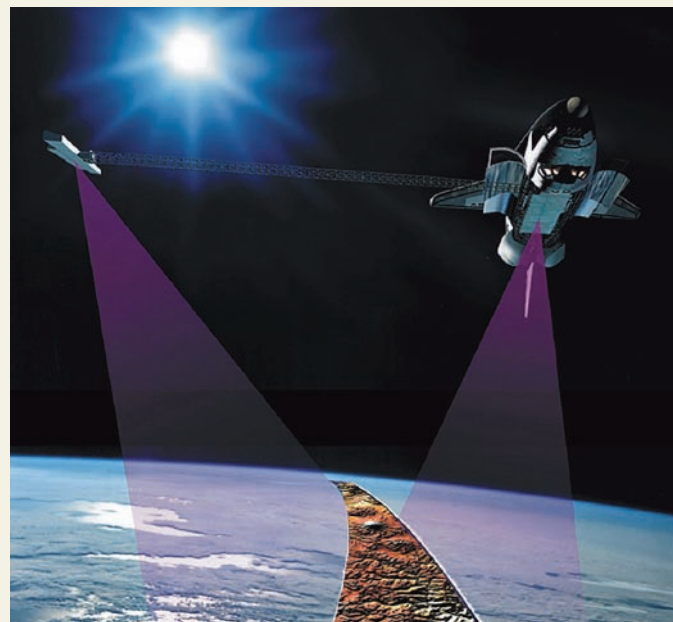
Before going on, you should briefly review the major structural features of each of the other continents and examine how they are similar and how they are different (see the shaded relief map inside the back cover).

Topographic maps that show elevations have always been important to geologists studying the continents. Until the mid-1900s, such maps were painstakingly constructed by careful fieldwork using survey instruments. It might take weeks to cover an area of 100 km², assuming access was good. Later in the 1930s and 1940s, aerial photographs replaced or supplemented these field techniques, but some fieldwork was still necessary. However, many remote areas and less-developed countries remained largely unmapped.

In February 2000, astronauts on the space shuttle using imaging radar revolutionized mapmaking. In just nine days, they collected the data for the most accurate topographic map ever made of much of the planet. Radar signals were bounced off Earth's surface and then received by two different antennas, one inside the spacecraft and the other on a 60-m-long boom extended from the shuttle. A computer then combined these separate images to prepare a three-dimensional topographic map, just as your brain combines two separate images, one from each eye, to construct a 3-D image of your surroundings.

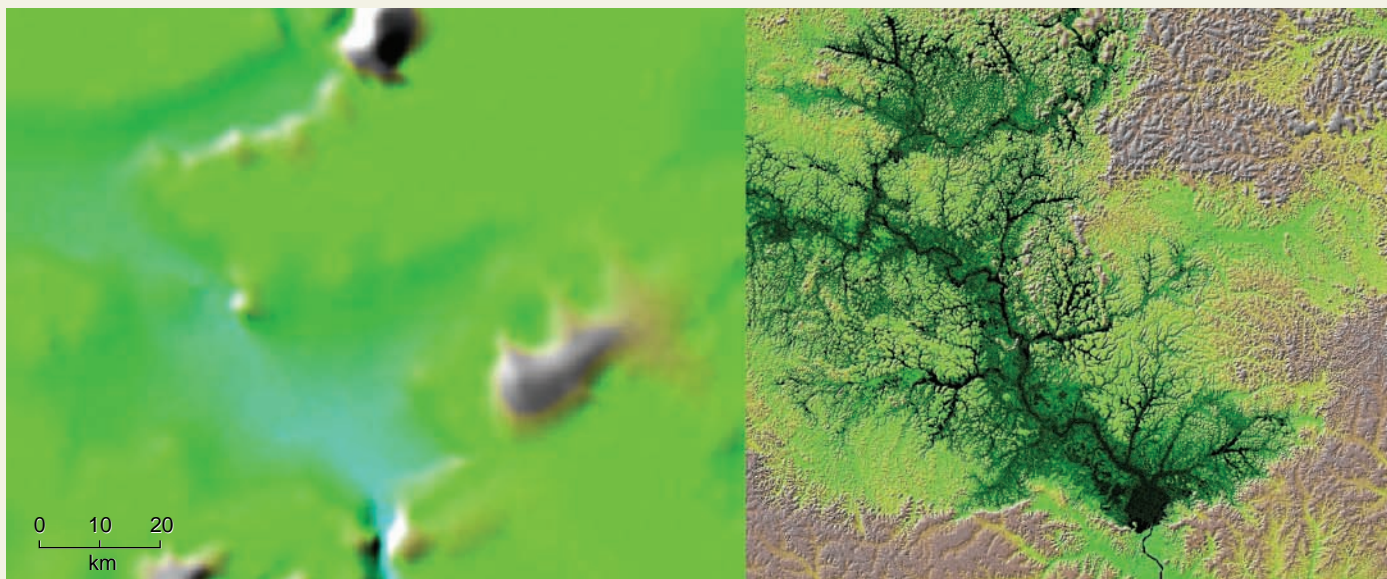
A key advantage to radar is that it can "see" the surface through clouds and in darkness. Another major advantage is speed. Shuttle radar can capture the topographic data for an area the equivalent of Rhode Island in only two seconds and for an area 100,000 km² in a minute. In nine days, the shuttle mapped nearly 80% of Earth's land surface. In many areas these will be the highest resolution maps available. Before the shuttle mission, less than 5% of Earth's surface had been mapped at a comparable scale.

NASA, the U.S. Department of Defense, and the German and Italian space agencies are supporting the project. The most detailed maps, showing objects just 3 m across, may only be available to the U.S. military. Such data will be used, for example, to guide cruise missiles through complex



terrains and assist in troop deployment. Lower resolution maps (10 to 30 m resolution) will be used to study Earth on a global scale in a way never before possible, including topics such as tectonics, flooding, erosion rates, volcanic and landslide hazards, earthquakes, and climate change.

The shuttle radar topographic map below shows the dramatic difference between the new data (30 m resolution on the left) and the best existing data (on the right) for the tropical rain forests of central Brazil. This region is centered near the city of Manaus on the great Amazon River. With the new map, you can see the delicate branching patterns of a multitude of stream valleys. The dark, smooth areas are reservoirs behind large dams. Most of the small valleys are not visible on the earlier topographic map.



(Courtesy of NASA)

MAJOR FEATURES OF THE OCEAN BASINS

Oceanic crust differs strikingly from continental crust in rock types, structure, landforms, age, and origin. The major features of the ocean floor are (1) the oceanic ridge, (2) the abyssal floor, (3) seamounts, (4) trenches, and (5) continental margins.

The ocean floor, not the continents, is the typical surface of the solid Earth. If we could drain the oceans completely, this fact would be obvious. The seafloor holds the key to the evolution of Earth's crust, but not until the 1960s did we recognize that fact and obtain enough seafloor data to see clearly its regional characteristics. This new knowledge caused a revolution in geologists' ideas about the nature and evolution of the crust, a revolution as profound as Darwin's theory of evolution.

Until about the 1940s, most geologists believed that the ocean floor was simply a submerged version of the continents, with huge areas of flat abyssal plains covered with sediment eroded from the land mass. Since then, great advances in technology and exploration have been used to map the ocean basins in remarkable detail, as clearly as if the water had been removed (see the inside cover of this book). These maps show that submarine topography is as varied as that of the continents and in some respects is more spectacular.

Along with this kind of mapping, we have collected samples of the oceanic crust with drill rigs, dredges, and submarines. We have learned that the oceanic crust is mostly basalt, a dense volcanic rock, and that its major topographic features are somehow related to volcanic activity. These features make the oceanic crust entirely different from the continental crust. Moreover, the rocks of the ocean floor are young, in geologic terms. Most are fewer than 150 million years old, whereas the ancient rocks of the continental shields are more than 600 million years old. We have discovered that the rocks of the ocean floor have not been deformed into folded mountain belts—in marked contrast to the complexly deformed rocks in the mountains and basement complex of the continents.

The Oceanic Ridge. The **oceanic ridge** is perhaps the most striking and important feature on the ocean floor. It extends continuously from the Arctic Basin, down the center of the Atlantic Ocean, into the Indian Ocean, and across the South Pacific. You can see it clearly in Figure 1.8 and on the map inside the back cover. The oceanic ridge is essentially a broad, fractured rise, generally more than 1400 km wide. Its higher peaks rise as much as 3000 m above their surroundings. A huge, cracklike **rift valley** runs along the axis of the ridge throughout much of its length, which totals about 70,000 km. In addition, great fracture systems, some as long as 4000 km, trend perpendicular to the ridge.

The Abyssal Floor. The oceanic ridge divides the Atlantic and Indian oceans roughly in half and traverses the southern and eastern parts of the Pacific. On both sides of the ridge are vast areas of broad, relatively smooth deep-ocean basins known as the **abyssal floor**. This surface extends from the flanks of the oceanic ridge to the continental margins and generally lies at depths of about 4000 m.

The abyssal floor can be subdivided into two sections: the abyssal hills and the abyssal plains. The **abyssal hills** are relatively small ridges or hills, rising as much as 900 m above the surrounding ocean floor. They cover from 80% to 85% of the seafloor, and thus, they are the most widespread landforms on Earth. Near the continental margins, land-derived sediment completely covers the abyssal hills, forming flat, smooth **abyssal plains**.

Trenches. The deep-sea **trenches** are the lowest areas on Earth's surface. The Mariana Trench, in the Pacific Ocean, is the deepest part of the world's oceans—

How do the landforms on the ocean floor differ from those on continents?

What are the highest and lowest parts of the ocean floor?

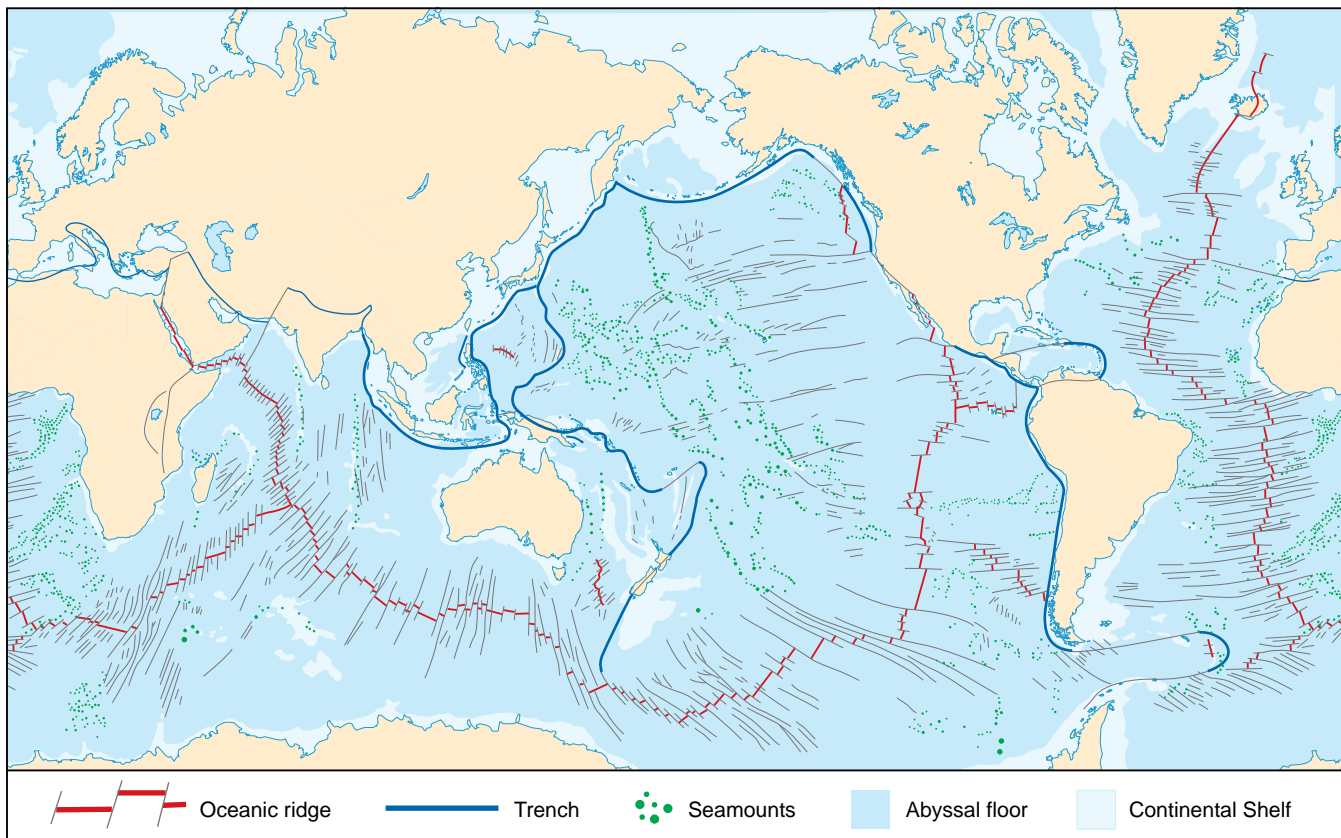


FIGURE 1.11 The major features of the ocean floor include the oceanic ridge, the deep-sea trenches, and the abyssal floor. Seamounts rise above the deep-ocean floor and are formed by volcanic eruptions.

11,000 m below sea level—and many other trenches are more than 8000 m deep. Trenches have attracted the attention of geologists for years, not only because of their depth, but also because they represent fundamental structural features of Earth's crust. As illustrated in Figure 1.11, the trenches are invariably adjacent to chains of volcanoes called **island arcs** or to coastal mountain ranges of the continents. Why? We will see in subsequent chapters how the trenches are involved in the planet's most intense volcanic and seismic (earthquake) activity, and how the movement of Earth's lithospheric plates causes it all.

Seamounts. Isolated peaks of submarine volcanoes are known as **seamounts**. Some seamounts rise above sea level and form islands, but most are submerged and are known only from oceanographic soundings. Although many may seem to occur at random, most, such as the Hawaiian Islands, form chains along well-defined lines. Islands and seamounts testify to the extensive volcanic activity that is ongoing throughout the ocean basins. They also provide important insight into the dynamics of the inner Earth.

How are continental margins different from the rest of the seafloor?

Continental Margins. The zone of transition between a continent and an ocean basin is a **continental margin**. The submerged part of a continent is called a **continental shelf**, essentially a shallow sea that extends around a continent for many kilometers. You can clearly see the continental shelf around the continents in Figure 1.8 and on the map inside the back cover. Geologically, the continental shelf is part of the continent, not part of the ocean basin. At present, continental shelves form 11% of the continental surface, but at times in the geologic past, these shallow seas were much more extensive.

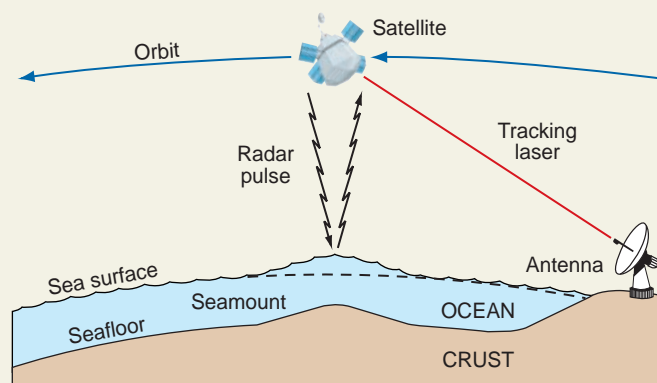
The seafloor descends in a long, continuous slope from the outer edge of the continental shelf to the deep-ocean basin. This **continental slope** marks the edge of the

Earth's uncharted frontiers lie at the floor of the oceans, and for most of human history they were as inaccessible as the stars. Thanks to several new techniques, geologists are now seeing the topography of the ocean floor.

The technique that is easiest to understand involves echo sounding. This is a special type of sonar—sound waves are timed while they travel to the ocean bottom and bounce back. Research ships tow long trails of “hydrophones” behind them to detect the signals. The result is a narrow strip map showing the elevation of the seafloor directly beneath the ship. Multiple traverses are necessary to accumulate enough data to compile a good topographic map. It would take about 125 years to map all of the ocean basins using this method.

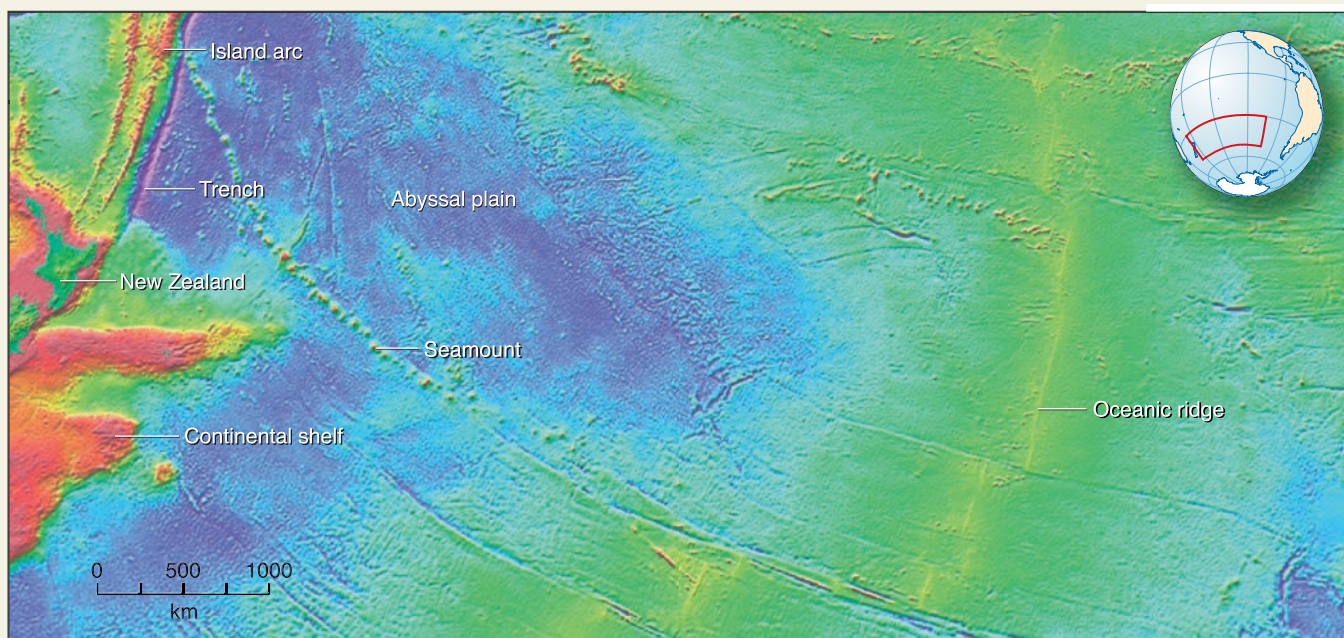
A completely new way to make global maps of the seafloor is carried out by an orbiting spacecraft instead of a ship. The satellites use radar to carefully map the elevation of the sea surface. These maps show that the surface of the ocean bulges upward and downward, mimicking the topography of the underlying ocean floor. Although these bumps are too small to be seen with your eyes, they can be measured by a radar altimeter on the satellite. The satellite emits a pulse of radar at the ocean surface, and the time for its reflection back to the satellite is measured. The width of the pulse is several kilometers wide and averages out local irregularities caused by ocean waves. To make accurate elevation measurements, the satellite itself is tracked from ground stations using lasers.

The data are then processed with a computer to calculate the topography of the underlying seafloor. The maps pro-



vide the first view of the ocean-floor structures in many remote areas of the Earth. The map shown here of a swath across the Pacific Ocean with New Zealand on the west, and the map on the inside back cover were constructed in this way.

Why does the sea surface bulge? It bulges because Earth's gravitational field is not constant everywhere. The gravitational acceleration at any spot on Earth's surface is proportional to the mass that lies directly beneath it. Thus, if a high seamount or ridge lies on the ocean floor, it has enough mass to pull water toward it, piling up the water immediately above it. Such a bulge may be several meters high. On the other hand, because water has a density less than that of rock, a point above a deep trough in the ocean floor has less mass directly below it and shows up as a shallow trough on the sea surface.



(Courtesy of D. T. Sandwell, Scripps Institution of Oceanography, University of California at San Diego)

continental rock mass. Continental slopes are found around the margins of every continent and around smaller fragments of continental crust, such as Madagascar and New Zealand. Look at Figure 1.8 and study the continental slopes, especially those surrounding North America, South America, and Africa. You can see that they form one of Earth's major topographic features. On a regional scale, they are by far the longest and highest slopes on Earth. Within this zone, from 20 to 40 km wide, the average relief above the seafloor is 4000 m. In the trenches that run along the edges of some continents, relief on the continental slope is as great as 10,000 m. In contrast to the shorelines of the continents, the continental slopes are remarkably straight over distances of thousands of kilometers.

To ensure that you understand the basic features of the oceans, refer again to Figure 1.11 and the map inside the back cover and study the regional relationships of the oceanic ridges, abyssal plains, trenches, and seamounts of each of the major oceans. For example, the topography of the Atlantic Ocean floor shows remarkable symmetry in the distribution of the major features (Figure 1.11). It is dominated by the Mid-Atlantic Ridge, a broad rise in the center of the basin. Iceland is a part of the Mid-Atlantic Ridge that reaches above sea level. South of Iceland, the ridge separates the ocean floor into two long, parallel sub-basins that are cut by fracture zones stretching across the entire basin. Abyssal hills lie on either side the ridge, and abyssal plains occur along the margins of the continental platforms. In the South Atlantic, two symmetrical chains of seamounts extend from the continental margins to the oceanic ridge and come together to form an open V. Deep trenches flank volcanic island arcs off the north and south margins of South America. The symmetry of the Atlantic Basin even extends to the continental margins: the outlines of Africa and Europe fit those of South America and North America.

THE ECOSPHERE—A MODEL OF PLANET EARTH

One way to simplify this vast array of details is to consider a model of Earth in its simplest form, in which the fundamental components—energy, rock, air, water, and life—are the only elements.

Having surveyed the important components of Planet Earth, you should now look back and consider what these facts imply for life in general and humans in particular. To help you understand, let us contemplate a simple model of Earth—the ecosphere.

An **ecosphere** is a small glass globe, about the size of a large cantaloupe, containing five essential elements: energy, air, water, sand, and living things (algae, seaweed, shrimp, snails, and a variety of microorganisms). The globe is sealed, forming a closed system in which plants and animals are self-sustaining (Figure 1.12). Just like a planet, nothing enters or leaves the system except sunlight and heat. You cannot add oxygen. You can never clean the water or replace the seaweed or remove dead organisms. You can never add food or remove waste. The plants and animals are on their own small planet: an isolated world in miniature.

Experiments have shown that if even one of the five parts is missing, the shrimp will not survive and the entire system will fail. The biological cycle is shown in the diagram in Figure 1.12. The key to the system is energy in the form of light. Light energy powers photosynthesis, the chemical mechanism through which algae make their own food from carbon dioxide and water and release oxygen into the water. The shrimp breathe the oxygen in the water and feed on the algae and bacteria. The bacteria break down the animal waste into nutrients that the algae use in their growth. The shrimp, snails, and bacteria also give off carbon dioxide, which the algae use to produce oxygen. Thus, the cycle is repeated and constantly renews itself. The shrimp and snails are masters of this little world—as long as they do not

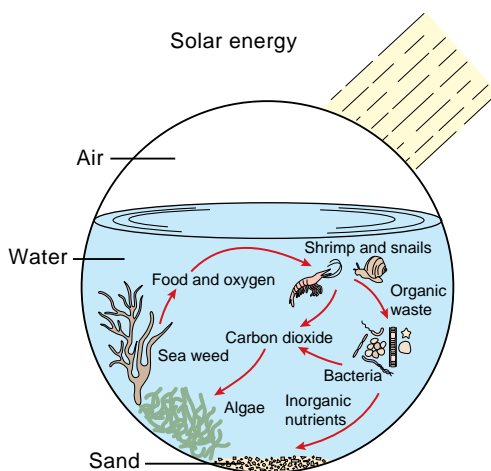
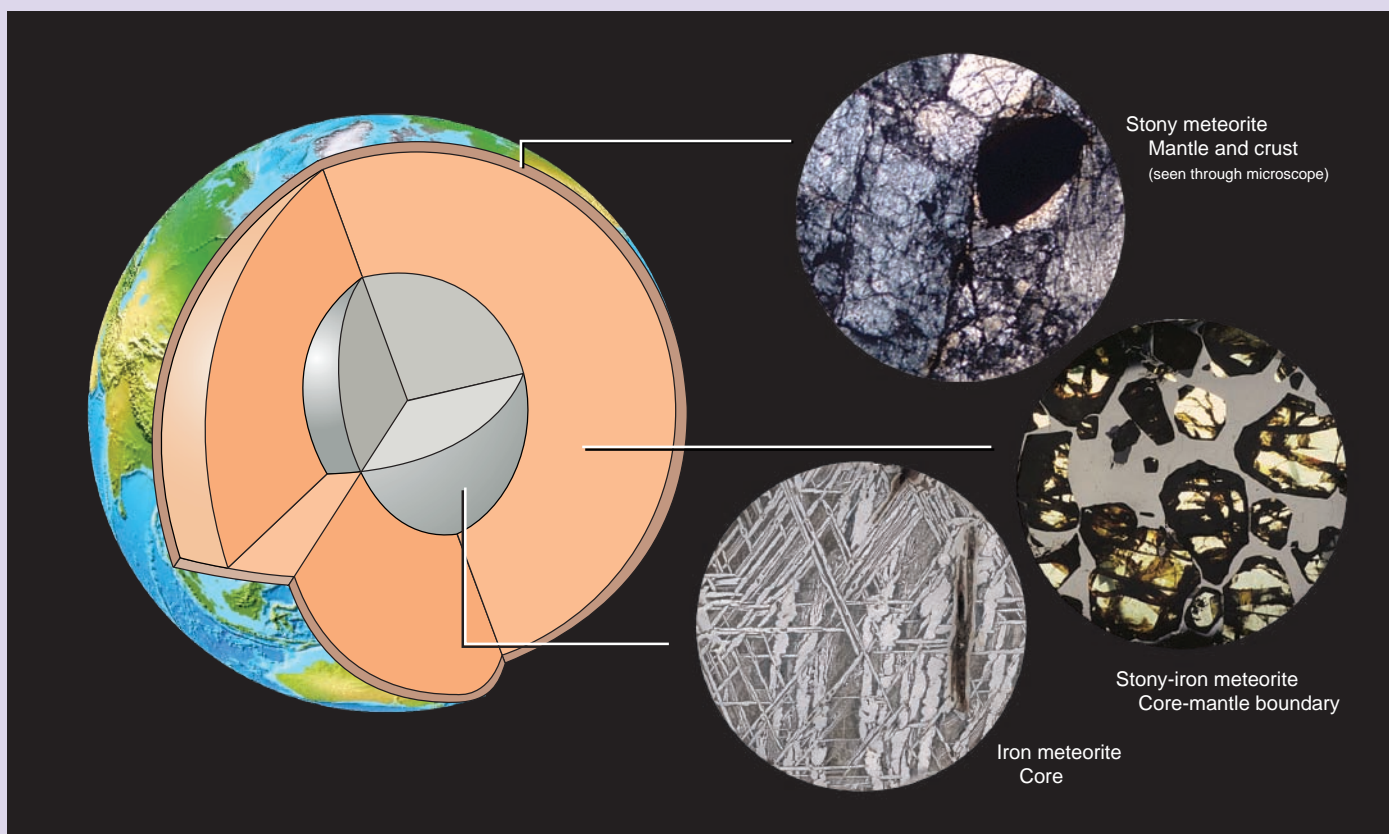


FIGURE 1.12 An **ecosphere** is a small model of Earth. It is a closed system of air, water, sand, and living organisms. Sunlight enters, providing the energy needed by the algae to make oxygen from carbon dioxide and water. Shrimp and snails breathe the oxygen and consume some algae and bacteria. Bacteria break down the animal waste into nutrients, which are used by the algae. The shrimp, snails, and bacteria also give off carbon dioxide, which the algae use to make more oxygen. This is an interlocking cycle of constant decay and renewal. If any component is missing, or is too far out of proportion, the system collapses and the entire biosphere of this tiny planet becomes extinct. (Photograph by Stan Macbean)

overpopulate or contaminate their environment. In this closed system, plants and animals grow, reproduce, and die, but the self-renewing cycle continues. The ecosphere in Figure 1.12 operated well for more than three years, until it was moved to a spot near a window. There it received more sunlight. The algae grew too fast and upset the critical balance, causing everything to die. Some ecospheres have sustained themselves for more than 10 years.

As you might suspect, an ecosphere is much the same as Planet Earth—a closed, self-contained system with a few basic parts. The only real external input is energy from sunlight. Our ecosphere—the lithosphere, atmosphere, hydrosphere, and biosphere—provides the rest. When astronauts look back at our planet from space, they see an ecosphere made of continents and oceans, forests, and polar bodies of ice, all enclosed in a thin blue dome of gases, bathed in sunlight.

These five “spheres” interact to form a single dynamic system in which components are interconnected in fascinating ways with a strength so amazing that a change in one sphere can affect the others in unsuspected ways. In the next chapter, we will consider in greater detail the concept of natural systems and introduce you to the two fundamental geologic systems of our planetary ecosphere.



(Photograph of stony-iron meteorite by C. Clark, Smithsonian Institution)

Can you imagine any part of Earth more inaccessible than the core? Our best estimates place it at a depth of almost 3000 km. The deepest mines or even caves extend only a few kilometers deep—in spite of what you may have read in Jules Verne's *Journey to the Center of the Earth*. Our deepest drill holes only penetrate to a depth of 15 or 20 km. And yet geologists believe they know a great deal about Earth's interior. For example they believe that Earth's core is made mostly of iron, that it supports a huge magnetic field, and that it has a temperature of 5000 C°. While we cannot justify all of these propositions here, we can present a few of the facts that lead to the logical conclusion that Earth's core is made of molten metal.

Observations

1. There are three fundamentally different types of meteorites (rocks that fall from space). The most common are similar to rocks found at Earth's surface and are called stony meteorites. Other meteorites are mixtures of stony materials and shiny metal, and a third type is made solely of metal.
2. When cut open, polished and etched with acid, metallic meteorites have spectacular crystalline structures that reveal they formed at high temperatures from molten metal and then crystallized slowly in the solid state.

3. Detailed chemical studies show that these metallic meteorites are made principally of only two elements, iron and nickel.
4. Iron meteorites are also extremely dense, a cubic centimeter weighs nearly 8 g/cm³, compared to a typical surface rock that weighs less than 3 g/cm³.

Interpretations

Each of these bits of evidence points to a logical interpretation that has implications for the nature of Earth's interior. Apparently, iron meteorites formed by: (1) partial melting of a planet (implied by high temperature of formation); (2) gravitational sinking of the molten metal to near its center (high density and slow cooling rate caused by a thick insulating layer that allowed heat to escape slowly), and finally (3) cooling and crystallization (crystalline structure). Thus, we have concluded that when you hold an iron meteorite in your hand, you are actually holding a piece of the once molten core of another planet. The other types of meteorites appear to have come from the mantles and crusts of small planets that were like Earth in having differentiated interiors.

The average density of the Earth is 5.5 g/cm³. This average density of the surface rocks is about 2.8 g/cm³. How does this support the interpretation above?

KEY TERMS

abyssal floor (p. 21)	continental shelf (p. 22)	hydrosphere (p. 11)	oceanic crust (p. 15)
abyssal hill (p. 21)	continental slope (p. 22)	impact crater (p. 9)	oceanic ridge (p. 21)
abyssal plain (p. 21)	core (p. 13)	inner core (p. 14)	outer core (p. 14)
accretionary heat (p. 9)	craton (p. 16)	inner planets (p. 5)	outer planets (p. 5)
asthenosphere (p. 14)	crust (p. 13)	internal heat (p. 9)	radioactivity (p. 9)
atmosphere (p. 10)	density (p. 5)	island arc (p. 22)	relief (p. 16)
basement complex (p. 16)	differentiated planet (p. 13)	lithosphere (p. 14)	rift valley (p. 21)
biosphere (p. 11)	ecosphere (p. 24)	mantle (p. 13)	seamount (p. 22)
continent (p. 13)	folded mountain belt (p. 16)	mesosphere (p. 14)	shield (p. 16)
continental crust (p. 15)	geology (p. 4)	ocean basin (p. 13)	stable platform (p. 16)
continental margin (p. 22)			trench (p. 21)

REVIEW QUESTIONS

1. Why are some planets geologically active today and others inactive?
2. Why are the atmosphere and the oceans considered as much a part of Earth as is solid rock?
3. Study the view of Earth in Figure 1.3. Sketch a map showing: (a) major patterns of atmospheric circulation, (b) low-latitude deserts, (c) the tropical belt, (d) a folded mountain belt, (e) the stable platform, and (f) the shield of North America.
4. Draw two diagrams of Earth's internal structure. Draw one to show its internal structure based on chemical composition and draw another showing its structure based on mechanical (physical) properties.
5. Draw a cross section showing the lithosphere's major structural features: the continental crust, shields, stable platforms, and folded mountain belts, together with the oceanic ridge, the abyssal floor, and deep-sea trenches.
6. Make a table comparing the differences in the age, thickness, density, composition, and structure of oceanic and continental crust.
7. Briefly describe the distinguishing features of continental shields, stable platforms, and folded mountain belts.
8. Using the map in the back of the book, describe the locations of the shield, stable platforms, and folded mountain belts of Asia, Africa, Australia, and Europe.
9. Briefly describe the distinguishing features of the oceanic ridge, the abyssal floor, trenches, seamounts, and continental margins.
10. Describe the major elements of an ecosphere and how it functions. Relate these elements to their counterparts on the real Earth.

ADDITIONAL READINGS

- Allegre, C. 1992. *From Stone to Star*. Cambridge, Mass.: Harvard University Press.
- Broecker, W. S. 1998. *How to Build a Habitable Planet*. New York, N.Y.: Columbia University Press.
- Lunine, J. I. 1999. *Earth: Evolution of a Habitable World*. Cambridge, U.K.: Cambridge University Press.
- Sagan, C. 1994. *Pale Blue Dot*. New York: Random House.
- Hughes, R. 2002. *Planet Earth*. New York: Alfred A. Knopf.

MULTIMEDIA TOOLS



Earth's Dynamic Systems Website

The companion Website at www.prenhall.com/hamblin provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources



Earth's Dynamic Systems CD

Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Animations of complex global systems
- Video clips of Earth systems in action
- Slide shows with examples of important geologic features
- A direct link to the Companion Web Site