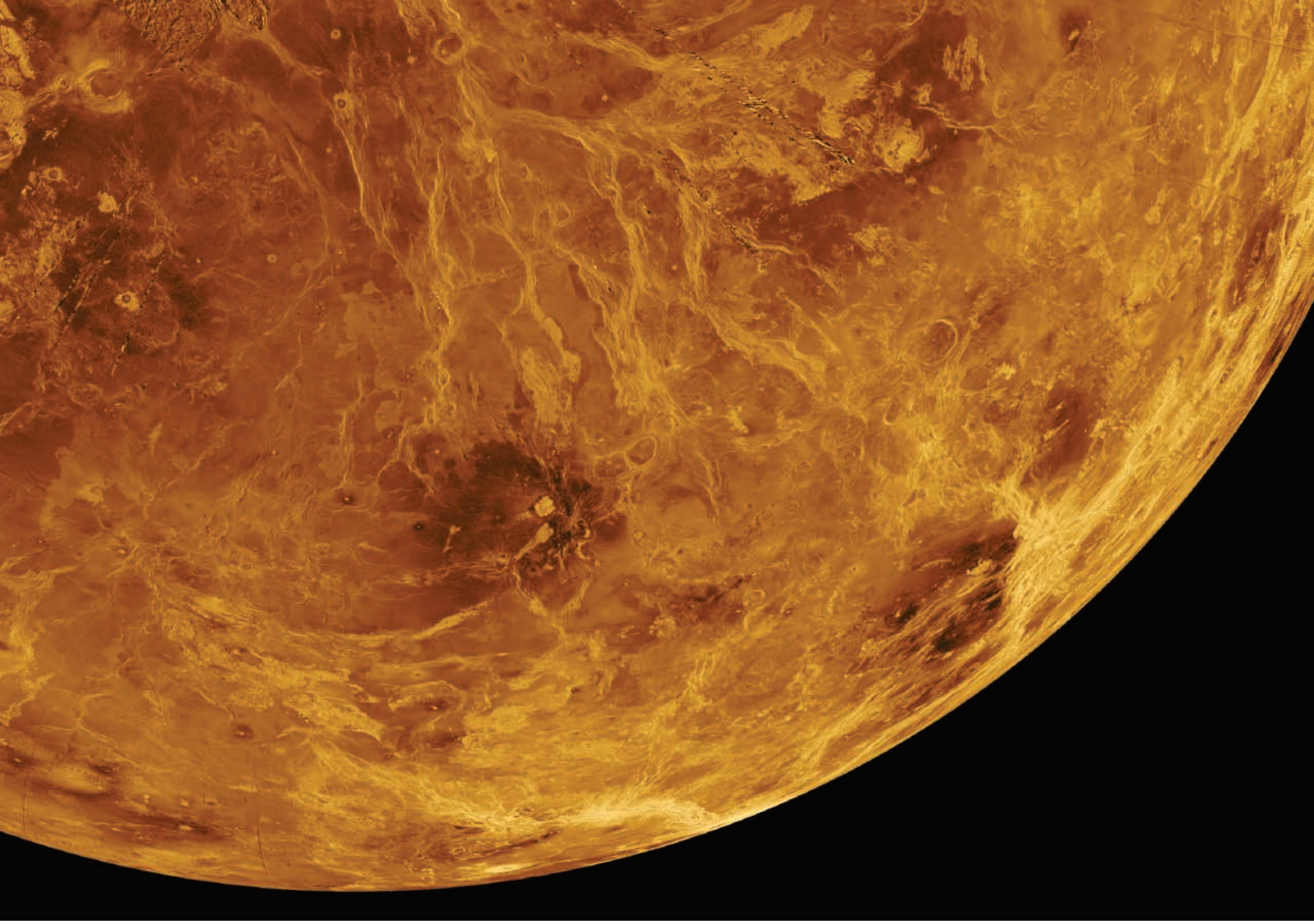
25 Other Planets

The exploration of the solar system is one of the most exciting adventures ever experienced by humankind; for the first time, we are exploring whole new worlds and can compare them with Earth. The study of planetary geology, however, does much more than merely satisfy scientific curiosity. By comparing in detail the geologic nature and evolution of different planets, we can better recognize those principles and processes that are fundamental to the geology of Earth and those that are of secondary importance.

Take for example, the two planetary bodies shown above. On the left is the Moon. It is an airless body only one-fourth the diameter of Earth. Its surface is not dissected by river valleys, but is instead a forest of impact craters. Each crater is the record of the collision of an asteroid or comet. Some of the craters are over 1000 km across. The bright areas are heavily cratered and ancient—dating back nearly to the origin of the Moon. The smooth dark areas are covered by floods of lava, but the youngest are 2 or 3 billion years old.

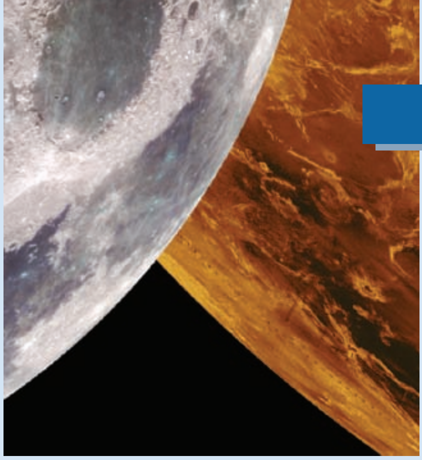
On the right is Venus, a planet almost the same size and density as Earth. Look carefully at this false color, radar map of its surface. Like the Moon, Venus also lacks any sign of liquid water; it has no ocean basins or river channels. On the other hand, how many impact craters



can you count? Indeed, there are only a few. What is the meaning of this difference between Venus and the Moon? It seems that Venus does not have an ancient surface that kept a record of impacts long ago. Instead, its surface is quite young. Our best estimates are that its surface is less than 0.5 billion years old. Much of the surface is highly deformed by tectonic processes and the rest consists of a great variety of volcanic features, including smooth plains covered by flood lavas, channels thousands of kilometers long, lava domes, calderas, and shield volcanoes, to name the most common. The tectonic and volcanic activity have destroyed what was once a cratered surface like the Moon's.

While you study this chapter, try to find out why these two planets are so different. This chapter contains some of the most spectacular images ever made: A photo album of our cosmic family—the solar system. Keep in mind that each planet, moon, or asteroid was shaped by geologic systems that were created by the unique conditions found on each body. Understanding the conditions, such as surface temperature, composition of the rocks and atmosphere, extent of internal differentiation, impact history, size, and especially the amount of internal heat, is critical for developing a true appreciation of the geologic systems of other planets. You will find that this comprehension will reinforce the fundamental concepts you have already learned about Earth's dynamic geologic systems. To gain an insight into the systematic reasons for these differences, we will venture into a brief but exciting study of the planets.

Courtesy of NASA/JPL/Caltech.



MAJOR CONCEPTS

1. Impact cratering was the dominant geologic process in the early history of all planetary bodies in the solar system.
2. Earth, the Moon, Mercury, Venus, and Mars form a family of related planets, known as the inner planets, that probably experienced similar sequences of events in their early histories.
3. Both the Moon and Mercury are primitive bodies, and their surfaces have not been modified by hydrologic and tectonic systems. Much of their surfaces are ancient and heavily cratered.
4. Mars has had an eventful geologic history involving crustal uplift, volcanism, stream erosion, and eolian activity. Huge tracts of cratered terrain remain, but they are intensely eroded. Liquid water may have existed on its surface, and there is controversial new evidence that life may have evolved there.
5. The surface of Venus is dominated by relatively young volcanic landscapes and such tectonic features as faults and folded mountain belts. The crust of Venus does not appear to be broken into tectonic plates, however, and much of its evolution is related to the development of mantle plumes.
6. Cratering on the icy moons of Jupiter, Saturn, Uranus, and Neptune suggests that a period of intense bombardment affected the entire solar system more than 4 billion years ago.
7. Most of the icy moons of Uranus and Neptune show evidence of geologic activities, such as volcanic extrusions of slushy ice and rifting.
8. Asteroids and comets are the smallest members of the solar system. They appear to be remnants of the bodies that accreted to form the larger planets.
9. The planets formed in a thermal gradient around the Sun. The inner planets are thus rich in silicates and iron, which are stable at high temperature, and the outer planetary bodies have large amounts of ice, which is stable at low temperature.
10. The geologic evolution of a planet depends on its source of heat energy, its size, and its composition.

THE SOLAR SYSTEM

Three types of planets formed in our solar system. The inner planets are small and made mostly of silicates and iron metal. The outer planets are large and made largely of gaseous hydrogen and helium. The icy planets also lie in the outer solar system but are small and have surfaces dominated by water ice.

Review in your mind the intellectual journey we have taken in space and in time as we studied Earth. Now we will contrast our home planet with the other worlds of the solar system. Turn back to Figure 1.1, which shows our solar system. The planets, moons, and other objects that orbit the Sun have an almost infinite variety if we dwell on the details of their surfaces, interiors, sizes, and densities. However, if we step back, we recognize only three fundamentally different types of planets. The differences between these groups can be appreciated by looking at the simplified model planets in Figure 25.1 and Table 25.1.

What are the major differences between the inner and outer planets?

The **inner planets** are small rocky bodies composed mostly of silicates and iron metal—materials that solidify at high temperatures. Their interiors are probably differentiated by density into metallic cores, mantles, and crusts. Several of these planets also have atmospheres composed of volatile gases; the most common are carbon dioxide, nitrogen, and oxygen. Io, a satellite of Jupiter, is the only sizable object in the outer solar system that falls into this group.

The large **outer planets** are **gas giants**—large balls of hydrogen and helium—and lack solid surfaces entirely. Obviously, they are extremely rich in volatile materials—

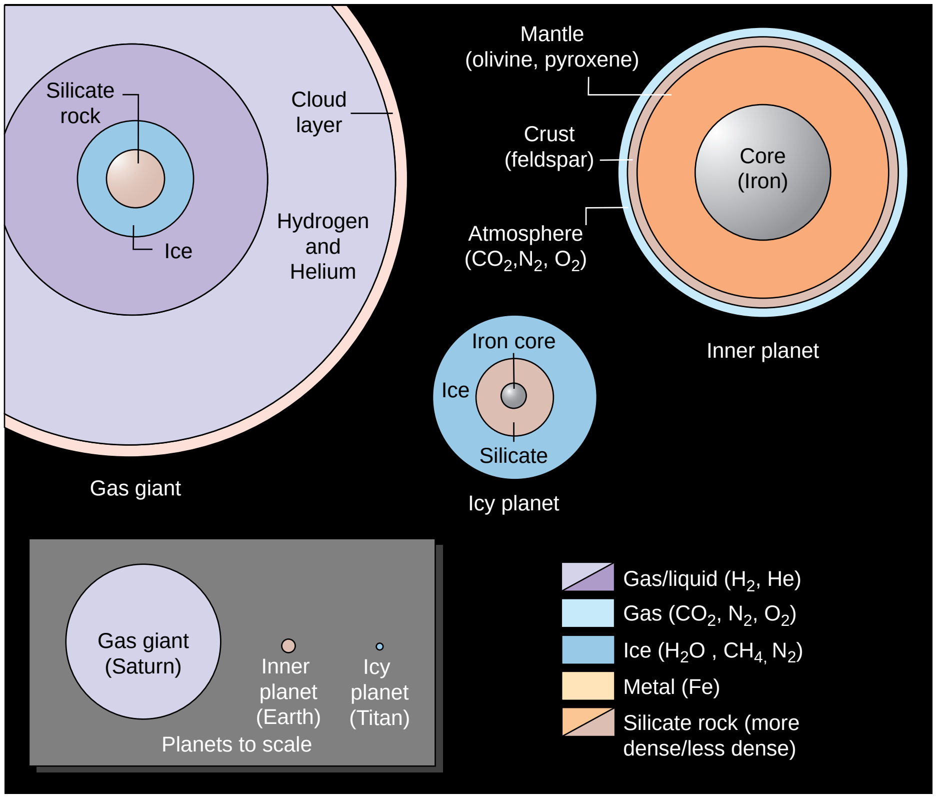


FIGURE 25.1 Three different types of planets are found in the solar system as shown in these cross sections. The inner planets are small and made mostly of silicates and iron metal. The outer planets are large and made largely of gaseous hydrogen and helium. The icy planets also lie in the outer solar system but are small and have surfaces dominated by water ice. An example of each is drawn to scale in the inset.

compounds that refuse to solidify except at very low temperatures. These planets are also layered on the basis of density. Buried deep inside their interiors, smaller Earth-sized masses of silicate, metal, or even water ice constitute their cores.

Transitional between these two extremes, at least in terms of density and abundance of volatile elements, are the **icy planetary bodies.** Here we include, along with Pluto and comets, almost all of the moons of the outer planets. Water ice blankets these relatively small bodies, but ices of ammonia, methane, and nitrogen may also be present. Denser silicate minerals and perhaps metals are mixed with the ices or form discrete cores, as illustrated in Figure 25.1.

Thus, a simple pattern emerges out of this complexity. Only a few materials are really important: silicate rocks, iron metal, ice, and gas. The proportions of these materials inside a planet are reflected by its density. More important, the types of planets show a systematic relationship with distance from the Sun. Keep these characteristics in mind as we review the nature of the planets. We first discuss the inner planets in order of their sizes (Table 25.1), because size exerts such a strong control on their histories.

THE INNER SOLAR SYSTEM

> The inner planets are composed of rocky material that condensed near the Sun. The Moon and Mercury were too small to generate enough heat to sustain a tectonic system and ceased to be active after their first major thermal event. Mars, being larger, developed a more prolonged period of tectonism. Venus, nearly as large as Earth, has continent-like highlands; a young, dominantly volcanic surface; and folded mountain belts.

The Moon

With the development of the space program, the Moon has become one of the best-understood planetary bodies in the solar system. As curious as it may seem,

TABLE 25.1 Physical Characteristics of the Planets and Selected Moons

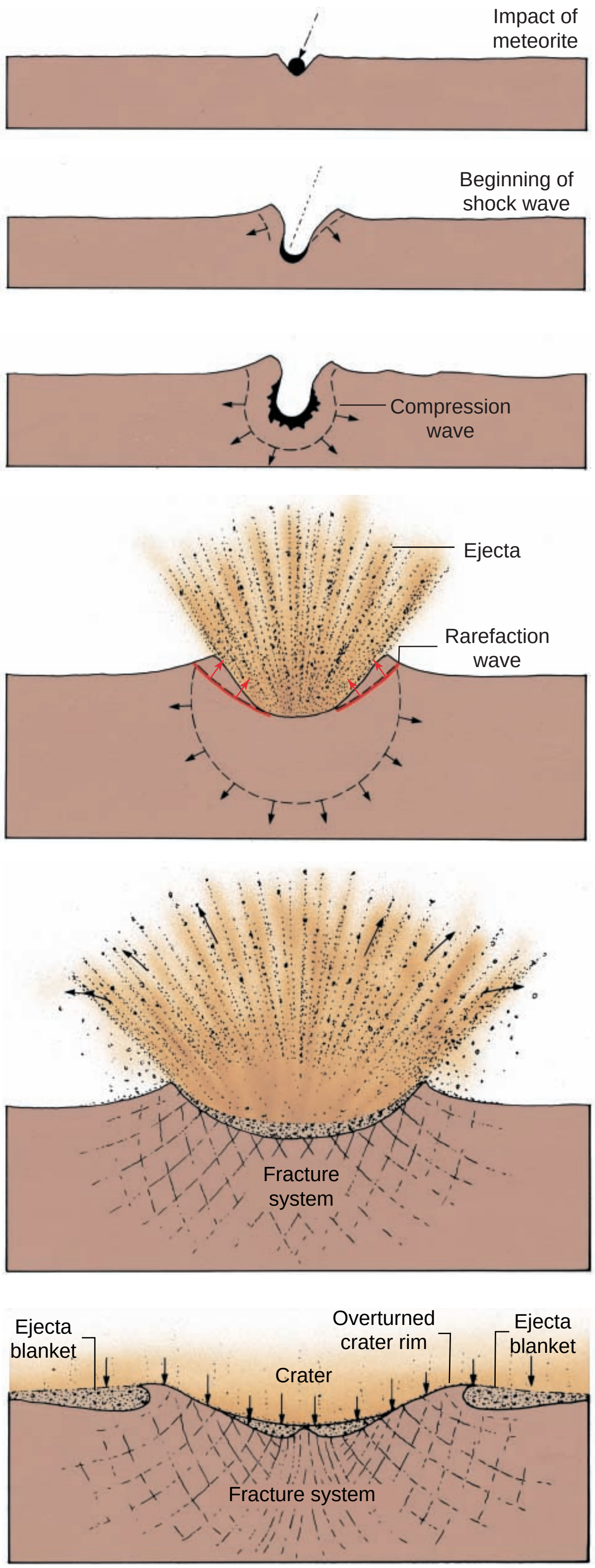
Planetary Body	Density (g/cm^3)	Diameter (km)	Surface Composition	Atmosphere Composition	Known Moons
Mercury	5.43	4880	Silicate		0
Venus	5.24	12,104	Silicate	CO_2	0
Earth	5.52	12,756	Silicate and water	N_2 and O_2	1
Moon	3.34	3476	Silicate		
Mars	3.93	6787	Silicate	CO_2	2
Asteroids					
Eros	2.7	33	Silicate		
Vesta	3.3-3.9	549	Silicate		
Ida	2.2-2.9	56	Silicate and iron		1
Ceres	2.0-2.7	1020	Silicate and carbon		
Jupiter	1.33	143,800		H_2 and He	60
Io	3.53	3640	Silicates and sulfur	SO_2 (thin)	
Europa	2.99	3130	Water ice		
Ganymede	1.94	5280	Water ice		
Callisto	1.85	4840	Water ice		
Saturn	0.69	120,660		H_2 and He	31
Mimas	1.14	392	Water ice		
Enceladus	1.12	500	Water ice		
Tethys	1.0	1060	Water ice		
Dione	1.44	1120	Water ice		
Rhea	1.24	1530	Water ice		
Titan	1.88	5150	Water ice	N_2	
Uranus	1.32	51,120		H_2 and He	21
Miranda	1.20	470	Water ice		
Ariel	1.67	1150	Water ice		
Umbriel	1.40	1170	Water ice		
Titania	1.71	1580	Water ice		
Oberon	1.63	1520	Water ice		
Neptune	1.64	49,560		H_2 and He	11
Triton	2.05	2700	N_2 and CH_4 ice	N_2, CH_4 (thin)	
Pluto	2.06	2284	Nitrogen ice	N_2	1
Charon	2.24	1170	Nitrogen ice		

only a few decades after putting astronauts on the Moon, we probably understand the Moon's earliest history better than Earth's, for Earth lacks a rock record of the first 800 million years of its history. The Moon is a comparatively small planetary body (Table 25.1), with a diameter only about one-fourth of Earth's. Moreover, it is less dense than Earth, with a density (3.3 g/cm^3) that suggests it is made almost entirely of silicate rocks, which have densities of about 3.0 g/cm^3. If there is an iron core, it must be very small.

What role does a shock wave play in the origin of an impact crater?

Impact Processes. One of the most important results of the exploration of the Moon is the discovery that cratering, from the impact of meteorites and comets, is a fundamental and universal process in planetary development. The Moon is pockmarked with billions of **impact craters,** which range in size from microscopic pits on the surface of rock specimens to huge, circular basins hundreds of kilometers in diameter. How are impact craters formed, and what is their geologic significance?

Conceptually, the process is relatively simple, as is illustrated in Figure 25.2. As a **meteorite** strikes the surface, its kinetic energy is almost instantaneously transferred to the ground as a shock wave that moves downward and outward from the point of impact. This initial compression wave is followed by a relaxation wave as rocks decompress back to low pressure, causing material to be ejected from the



(A) The impact of a meteorite causes the rock to be instantly fractured, fused, and partly metamorphosed.

(B) A shock wave is propagated downward and outward from the point of impact.

(C) The shock wave expands.

(D) The shock wave is reflected back toward the surface. The crater begins to form, and material is fragmented. The result is similar to that produced by an explosion.

(E) The fragmented material is thrown upward and outward. Solid bedrock is fractured and forced upward to form a crater rim.

(F) The crater rim may be overturned and a peak may develop in the center of the crater floor. Ejected particles fall back to the surface to form a blanket of debris and a system of rays.

FIGURE 25.2 **Hypothetical stages in the formation of a meteorite impact crater.** The kinetic energy of the meteorite is almost instantly transferred to the ground as a shock wave that moves out, compressing the rock. At the point of impact, the rock is intensely fractured, fused, and partly vaporized by shock metamorphism. The shock wave is reflected back as a rarefaction wave that throws out large amounts of fragmental debris, and the solid bedrock is forced upward to form the crater rim. A large amount of fragmental material falls back into the crater.

surface along ballistic trajectories. This fragmented material accumulates around the crater, forming an **ejecta blanket** and a system of splashlike **rays.** A central peak on the crater floor can result from the rebound, and rocks in the crater rim can be overturned. Its steep walls rapidly slump and move downslope by mass movement. This process results in partial filling of the excavation and forms concentric terraces (slump blocks) inside the crater rim. Many large craters (more than 300 km in diameter) contain a series of concentric ridges and depressions and hence are known as **multiring basins.** Meteorite impacts create new landforms (craters) and new rock bodies (ejecta blankets), so records of the events are preserved.

How is an impact structure modified with time?

After a crater is formed on the Moon, it is subject to modification. Isostatic adjustment can arch up the crater floor to compensate for the removal of material in the crater's formation. The rays and eventually the entire crater may gradually become obliterated by subsequent bombardment. In addition, the crater and ejecta can be buried by lava flows.

The Surface of the Moon. Study the surface of the Moon in Figure 25.3 and you will see two contrasting types of landforms; these reflect two major periods in its history. The bright, densely cratered highland resulted from an intense bombardment of meteorites, most of which impacted more than 4 billion years ago. The dark, smooth areas that mostly occupy low regions, such as the circular interiors of impact basins, are maria (singular **mare**). We know from rock samples brought back from the *Apollo* missions (1969–1974) that the maria resulted from great floods of basaltic lava that filled many large craters and spread out over the surrounding area. Most of this volcanic activity, therefore, occurred after the formation of the densely cratered terrain. Radiometric dates on samples brought back from the Moon indicate that most of the lavas are between 4 and 3 billion years old. Almost no global tectonic activity has occurred on the Moon during the last 3 billion years; in fact, very little has occurred in its entire history. We find no evidence of intense folding or thrust faulting and no indication of major rifts. The main lunar features that can be attributed to structural deformation are narrow grabens, formed by minor extension, and wrinkle ridges, formed by minor compression. Nor has the lunar surface been modified by wind, water, or glaciers. Without an atmosphere, it has no hydrologic system, and its surface is strikingly different from Earth's.

Lunar History. One of the most significant results of geologic exploration of the Moon has been the construction of a lunar geologic time scale. This was done by using the same principles of superposition and crosscutting relations devised in the early nineteenth century by geologists studying Earth. In Figure 25.3 you can read much of the record of lunar history yourself.

What principles did scientists use to develop a geologic time scale for the Moon?

A period of intense bombardment is recorded in the densely cratered terrain. The heavy cratering gives us an important insight into the origin of all planetary bodies. Apparently, they formed by **accretion** when one body after another collided and merged into a growing planet. So much heat was released by this process that much of the outer layers of the Moon melted during a process that led to the internal differentiation of the Moon into layers of different density.

Accretion and differentiation were followed, or accompanied, by the impact of large asteroid-sized bodies that produced the huge multiring basins such as Imbrium Basin. A subsequent event is evident in the floods of lava that filled the lowlands and spread over parts of the densely cratered terrain. A period of light bombardment by meteorites followed that formed craters upon the lava flows of the maria. The light cratering episode reveals that most of the debris that formed the planets had been swept up by this time. Radiometric dates of lunar rock samples provide benchmarks of absolute time, and the major events in lunar history have been outlined as shown in Figure 25.4.

Perhaps the most important aspect of the Moon's geologic evolution is that the most dynamic events occurred during the early history of the solar system,

FIGURE 25.3 **The surface of the Moon** shows two contrasting types of landforms: densely cratered highlands, called terrae, and dark, smooth areas of lava plains, called maria. We know from rock samples brought back by the *Apollo* missions that the maria resulted from great floods of basaltic lava filling many large craters and spreading over the surrounding area. The volcanic activity thus occurred after the formation of the densely cratered terrain. These relationships between surface features imply that the Moon's history involved three major events: (1) a period of intense bombardment by meteorites, (2) a period of volcanic activity, and (3) a subsequent period of relatively light meteorite bombardment (resulting in young, bright-rayed craters). The lunar surface has a very low level of erosion and has not been modified by wind, water, or glaciers. *(Courtesy of Kitt Peak National Observatory)*

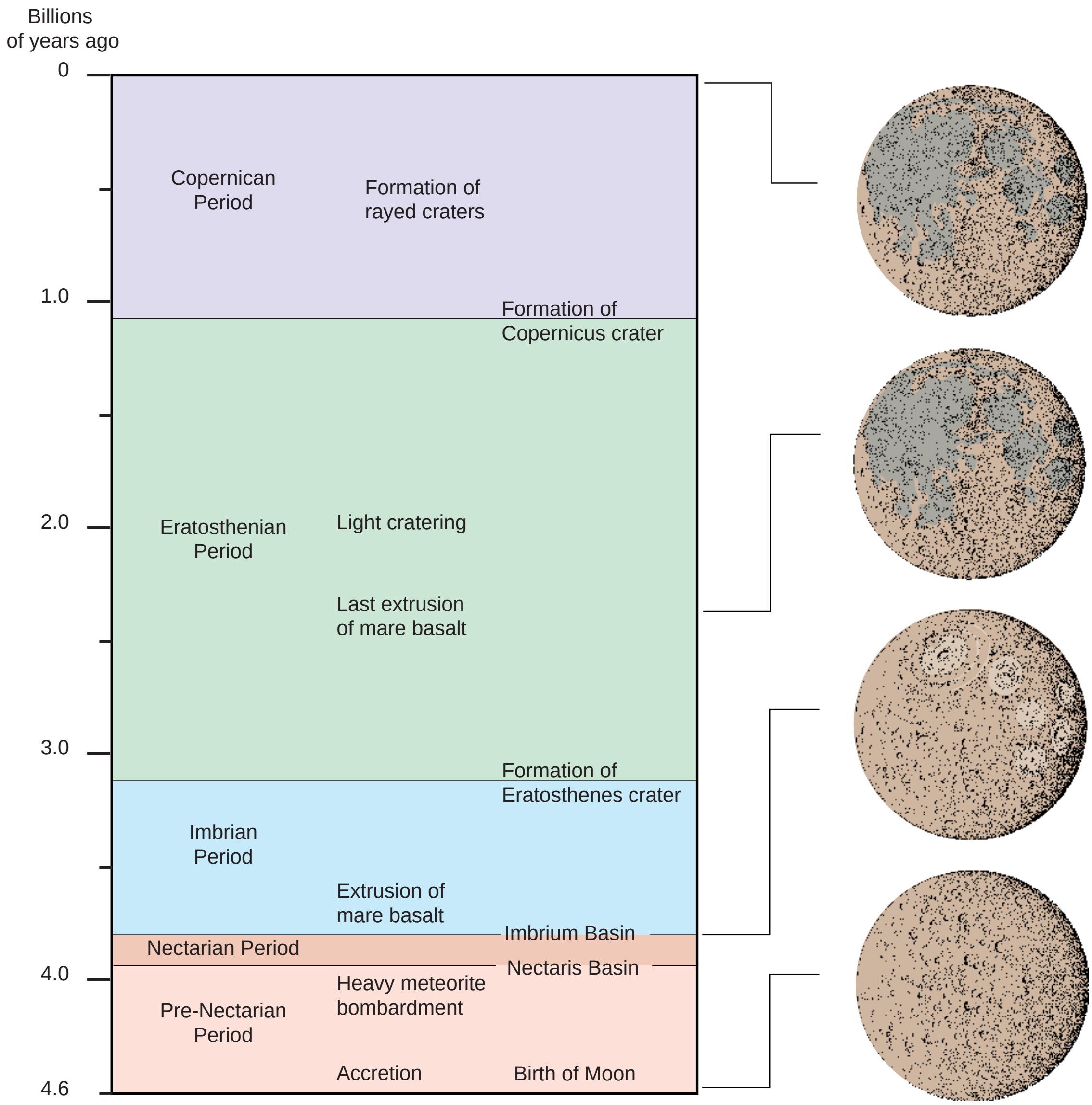


FIGURE 25.4 **The lunar time scale** was constructed on the principle of superposition. Five major periods have been recognized. They are (1) the origin of the Moon and the Pre-Nectarian Period, (2) the Nectarian Period (intense bombardment), (3) the Imbrian Period (extrusion of basalt), (4) the Eratosthenian Period (light bombardment), and (5) the Copernican Period (light bombardment).

even before the oldest rock preserved on Earth was formed. The Moon thus provides important insights into planetary evolution that are unobtainable from studies of Earth.

Mercury

What evidence suggests that the Moon and Mercury had similar histories?

Mercury is nearly 1.5 times larger in diameter than the Moon and has a much greater density (Table 25.1), suggesting that much of its interior is made of dense iron metal. Thus, Mercury's interior is quite different from the Moon's. However, Mercury's surface features are strikingly similar to the Moon's, as is evident from the images in Figure 25.5. Most of Mercury's surface is nearly saturated with craters, whose range of sizes is similar to that of the Moon's craters. Some are obviously old because they are battered by the impact of other meteorites; others are younger and have bright rays extending out from the point of impact.

The largest impact structure seen on Mercury is the Caloris Basin. It is a multiring basin similar in size and form to the Imbrium Basin on the Moon. Smooth plains cover the floor of the Caloris Basin, as well as much of the lowlands beyond. The similarity to the lunar maria suggests that the plains also formed by the

STATE OF THE ART

Geologists on Other Worlds: The Apollo Program

(Courtesy of NASA)

Sometimes it seems hard to believe, but 30 years ago astronauts from Earth stepped from a spindly legged spacecraft out onto a truly alien world, the Moon, and declared that this was, "One small step for man, one giant leap for mankind." Indeed, many people think that this event was the most important in the century or perhaps of the entire millennium. What event could match this, the first time humans left their home planet?

Why did we go to the Moon? Although there were many political justifications for pursuing a lofty goal as part of a Cold War strategy, certainly one goal of the Apollo Project was to better understand the Moon, and thereby come to a better understanding of our home planet.

To accomplish this latter task, all of the tools of the geologist were brought to bear. Aerial photographs, rock hammers, drills, magnetometers, seismographs, and many other instruments were used on the Moon's surface. Astronauts, specially trained in lunar geology, worked in nine different field areas on the near side of the Moon (*Apollo 11, 12, 14, 15, 16,* and *17*). They returned with more than 380 kg of rock and soil. Back in the laboratory these special rocks were carefully analyzed with the most sophisticated instruments to determine their physical characteristics, ages, and precise chemical compositions, all in an attempt to decipher the Moon's history.

Top Ten Discoveries of Lunar Exploration

1. **The Moon Is Old.** Radiometric ages show that the Moon formed 4.6 billion years ago, at the same time that Earth formed.
2. **Accretion.** The Moon formed when a multitude of smaller objects, in orbit around the ancient Earth, collided with one another and by mutual gravitational attraction collected into a large body.
3. **The Moon's Outer Layers Melted.** Geochemical studies show that the Moon probably melted to a depth of several hundred kilometers during its early history.
4. **Crust Formation.** The bright lunar highlands are made of anorthosite that formed when plagioclase feldspar floated to the top of this huge global magma ocean.
5. **Meteorite Impact.** Meteorite impact, not volcanism, is the principal cause of lunar craters. Heavy meteorite bombardment lasted until about 3.8 billion years ago.
6. **Basalt Is Common.** The vast dark lunar maria formed from a series of flood basalt eruptions—most of them 3 to 4 billion years ago.
7. **The Moon Is Dead.** No lava flows younger than about 3 billion years old have been found. The small Moon quickly cooled after its hot start.
8. **The Moon Is Dry.** No water was found in any lunar rocks. Even less volatile elements, such as potassium, are found in low abundances on the Moon. However, the Moon's poles may harbor ice in permanently shadowed areas.
9. **Small Lunar Core.** Seismic and geochemical studies show that if the Moon has an iron core, it is very small.
10. **The Moon Is Earth's Daughter.** The facts revealed by study of the lunar rocks, suggest that the Moon formed when a Mars-sized object crashed into Earth, ejecting part of its mantle (Figure 25.27).

One day astronauts from Earth will return again to the Moon and continue the geologic exploration they began so long ago. One day we will have permanent bases on the Moon that will serve as outposts for furthering our understanding of our neighbor in space.

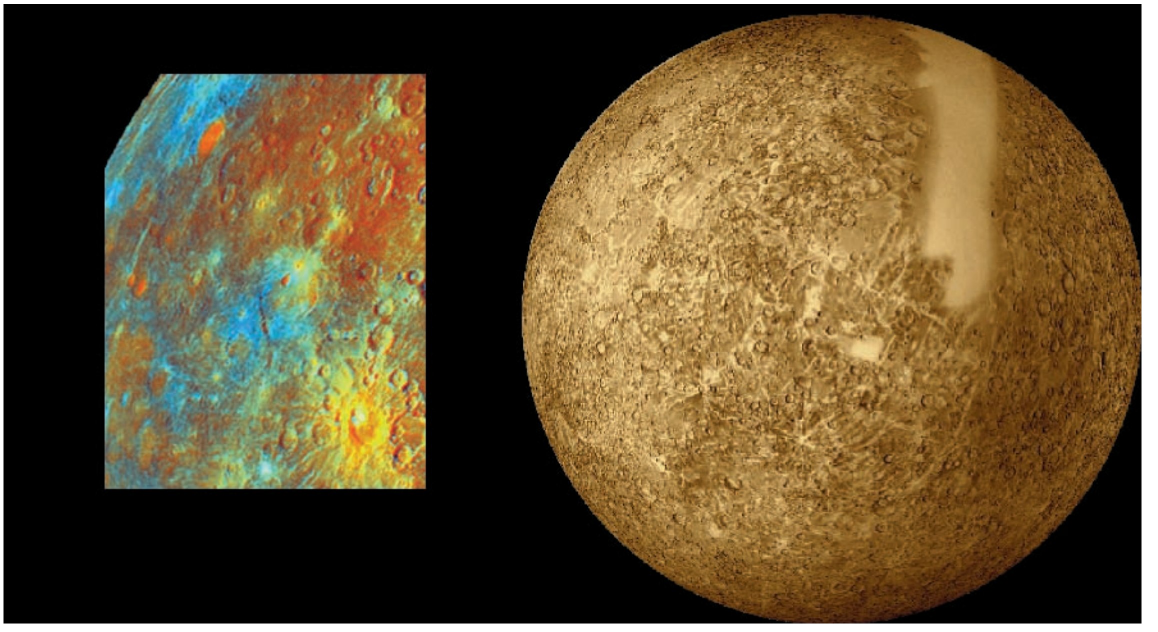


FIGURE 25.5 **Mercury** and the Moon are strikingly similar. Each has a densely cratered terrain, multiring basins, younger plains (maria), and young rayed craters. The false-color image on the left shows the surface is made of materials with different compositions. *(Courtesy of U.S. Geological Survey and M. S. Robinson)*

extrusion of fluid basaltic lava, but we have no samples from Mercury to prove that they did.

Geologists have established a preliminary geologic time scale for Mercury and have developed a hypothesis for its geologic evolution. Mercury's surface features indicate a sequence of four major events, broadly similar to the sequence of events recorded on the Moon: (1) accretion, planetary differentiation, and intense meteorite bombardment; (2) formation of multiring basins; (3) flooding of basins by the extrusion of basaltic lava; and (4) light meteorite bombardment. Because there is no atmosphere or water on Mercury, its surface has not been modified by a hydrologic system.

Mars

A fascinating red planet, Mars orbits the Sun beyond Earth (Figure 25.6). For years it was a planet of mystery and intrigue, and there was much speculation that Mars might host life. Telescopic observations revealed polar ice caps and shifting markings that often darkened during the Martian spring. Before the space program, some observers thought that life on Mars had evolved to a civilized state. Streaks were believed to be canals or vegetated land alongside canals. As it turned out, all this speculation was fanciful.

How does Mars differ from the Moon and Mercury?

Still, the Mars we have just explored by our space probes and landers is a wondrous place, more like Earth than any other planet (Figure 25.7). Many of its Earth-like surface features are not only large, but gigantic (Figure 25.8). There are huge rift valleys, volcanoes, global dust storms, polar ice caps, and dry river beds. Mars has been eroded by enormous floods of water that once flowed across its surface (Figure 25.9), but presently, temperatures and atmospheric pressures are such that water can exist only as vapor or as ice. Thus, nearly all of the water on Mars is frozen as ice caps or is locked up as ground ice. Now, wind alone is the major process altering the landscape of Mars. Some dust storms grow to such proportions that at times they blanket the entire planet.

The huge dry river channels on Mars (Figure 25.9) also create an intriguing mystery. Under what ancient conditions did liquid water once flow in great floods across the surface of Mars? Why did things change on such a global scale? Some

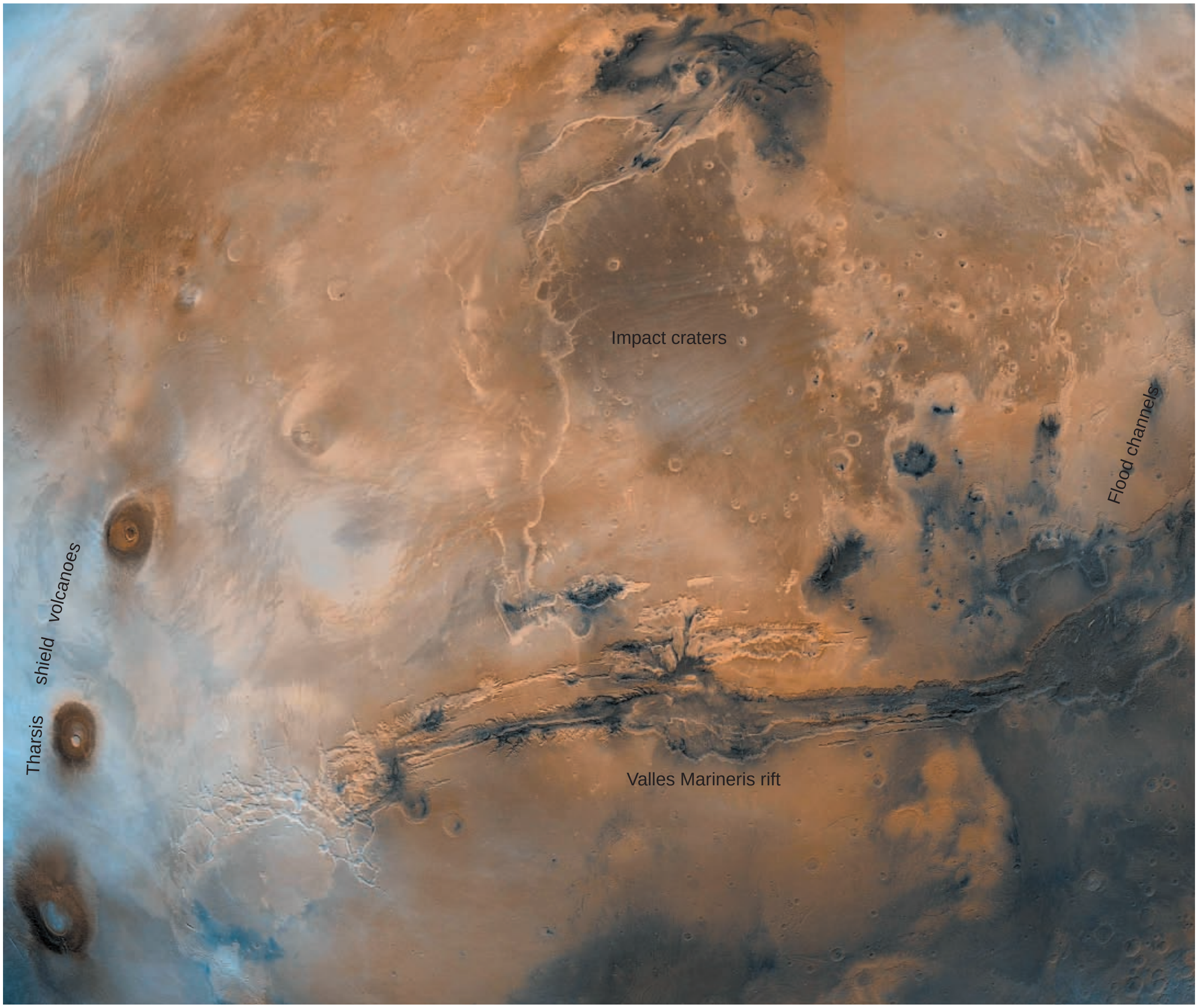


FIGURE 25.6 **The planet Mars,** as photographed from the *Viking* spacecraft, has a surface dramatically different than the Moon's. Although it has some heavily cratered regions, Mars has many features indicating that its surface has been modified by atmospheric processes, recent volcanic activity (circular volcanoes on left), and crustal deformation (the Valles Marineris rift extends across the bottom of the image). *(Courtesy of California Institute of Technology/NASA/JPL/Caltech)*

answers to these questions may be suggested when we consider the size and thermal history of Mars.

Mars has a diameter about half that of Earth or Venus but almost twice that of the Moon (Table 25.1). Thus, Mars generated more internal heat, leading to more geologic activity than experienced by Mercury and the Moon. Like all other planetary bodies in the solar system, Mars experienced an early period of intense bombardment, followed by volcanic activity in which floods of lava were extruded. Two major provinces create a global dichotomy on Mars. A heavily cratered southern hemisphere contrasts with a relatively young, smooth northern hemisphere where the impact craters were buried or destroyed by younger events.

How do river channels on Earth differ from those on Mars?

Apparently, Mars cooled more slowly than the smaller Moon, producing younger giant shield volcanoes and younger deformation of its surface. Huge domes in the lithosphere are also cut by deep rifts, such as Valles Marineris (Figure 25.10).

Mars started much as Earth did, developing a core, mantle, crust, and even a relatively dense atmosphere early in its history. Mars may once have had a moderate climate and abundant liquid water. Small seas may have formed. During this time,

FIGURE 25.7 **The Martian surface** as photographed by *Mars Pathfinder*. The large boulders are approximately 2 m across. Many features shown here illustrate the importance of wind activity in forming details of the Martian landscape. The gravel surface probably formed as a catastrophic flood deposit that was further modified of wind deflation by the surface. *(Courtesy of California Institute of Technology/NASA/JPL/Caltech)*

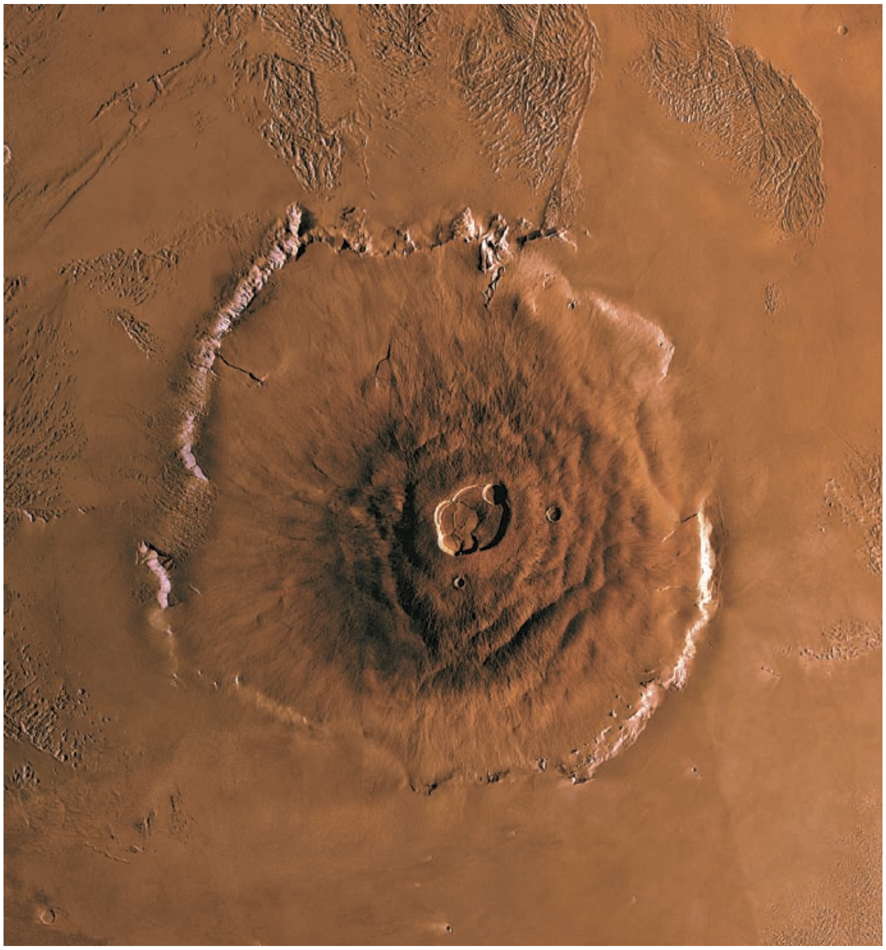


FIGURE 25.8 **Volcanoes in the Tharsis region of Mars** include huge structures, much larger than any found on Earth. Olympus Mons, the largest volcano on Mars, is shown here. It is 700 km across at the base and 23 km high. The complex caldera at the summit is 65 km in diameter. *(Courtesy of U.S. Geological Survey and NASA/JPL/Caltech)*

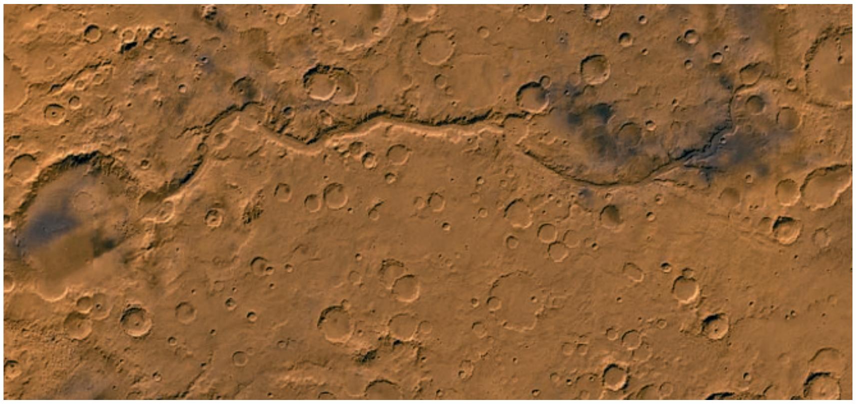


FIGURE 25.9 Dry stream channels on Mars are similar in many respects to dry riverbeds in arid regions on Earth. Some have typical braided patterns; others meander. This photomosaic taken in 1976 by a *Viking* orbiter shows a drainage system more than 500 km long. *(Courtesy of California Institute of Technology/ NASA/JPL/Caltech)*

rainfall and flooding created stream channels and other features somewhat similar to those on Earth. But Mars is much smaller than Earth, has less internal heat, cooled more quickly, and was geologically active over a much shorter period. Its internal convection appears to have been stirred by mantle plumes rather than plate tectonics. Moreover, Mars is farther from the Sun than Earth. Billions of years ago, Mars grew cold and dry. All of its water became locked into ice caps or frozen in the pore spaces of rocks and soil, and stream erosion ceased. As it cooled inside, its volcanoes ceased erupting several hundred million years ago. Although its present carbon dioxide atmosphere is very thin (exerting only 6/1000 of Earth's pressure), great dust storms now rage on Mars as the major process altering its surface.

Life on Mars? In 1996, dramatic headlines and television stories flashed the news around our planet that Earth might not be the only planet inhabited by living things. The putative Martians were not ominous invaders from space, but tiny microscopic blebs seen with a powerful electron microscope (Figure 25.11).

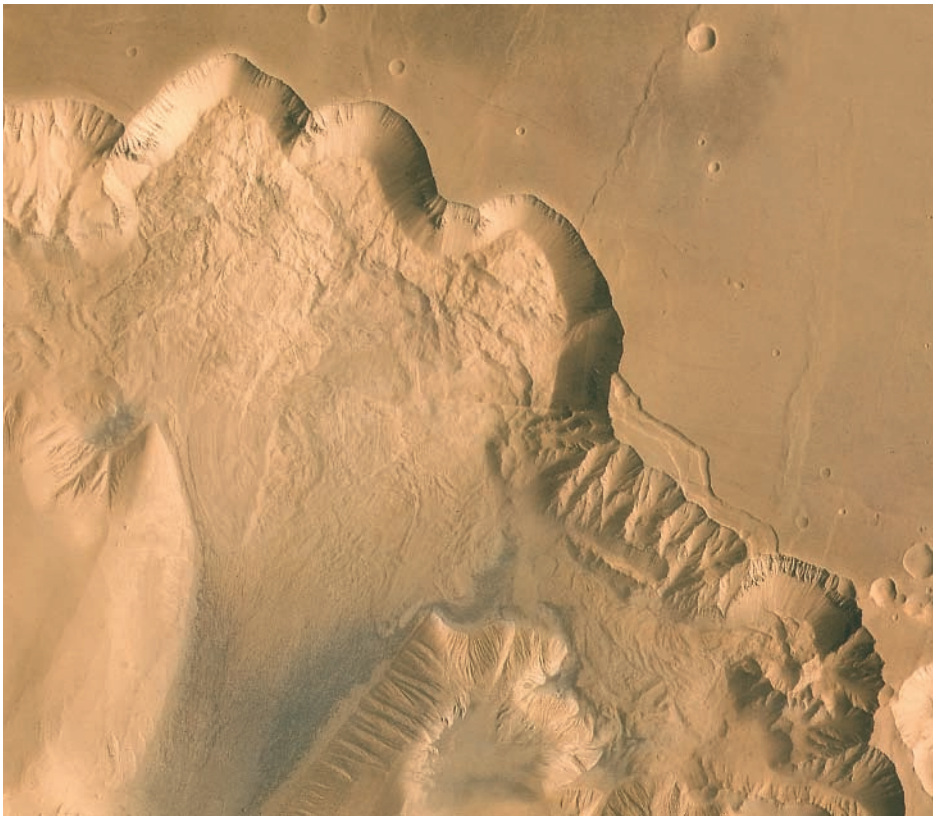
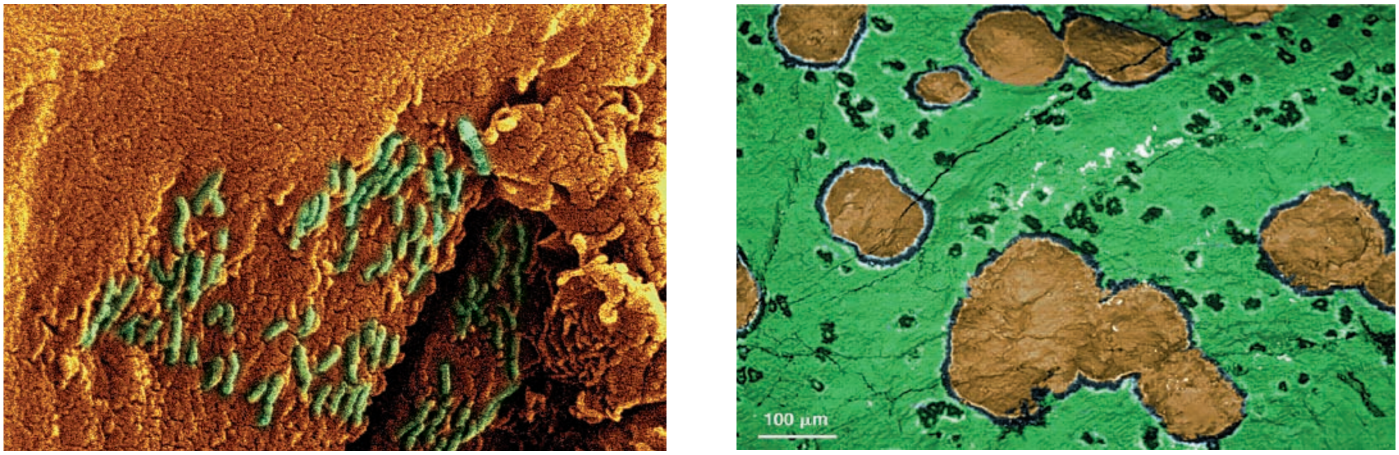


FIGURE 25.10 Landslides in Valles Marineris. The landslide on the far wall has two components: an upper blocky portion, which is probably disrupted cap rock, and a finely striated lobate extension, which is probably debris derived from the old cratered terrain exposed in the lower canyon walls. Similar lineations are found on terrestrial landslides and show direction of movement. This part of Valles Marineris is about 5 km deep. This image is approximately 200 km wide. *(Courtesy of U.S. Geological Survey)*



(A) Scanning electron microscope view of shapes like bacteria (colored) found on the fractured surface of the meteorite.

(B) This false-color microscope image shows carbonate globules (brown) that have rims of iron oxides and sulfides (black) like those formed by some terrestrial bacteria. The carbonate blebs are enclosed in a crystal of pyroxene (green).

FIGURE 25.11 **Evidence for life has been found in a meteorite** thought to have come from Mars. *(Courtesy of NASA)*

Evidence for life on Mars comes from the intensive study of a few of the 14 meteorites that are believed to have come from Mars. The Martian origin of these meteorites is based on very young radiometric ages (less than 1 billion years old), mineral compositions, and especially on the composition of the inert gases trapped inside the meteorites. The ratios of the gases extracted from them match ratios measured by spacecraft for the atmosphere of Mars, but not Earth, Venus, or any other meteorite types.

Is there any evidence for ancient life on Mars?

At least one of these meteorites has several bits of evidence of past life on Mars. First, complex organic molecules (long chains of hydrocarbons) are found in these meteorites. Second, tiny globules found on broken surfaces of the meteorite and made of carbonate minerals have wormlike shapes similar to fossils of terrestrial bacteria (Figure 25.11). Moreover, the carbonate blebs have rims that are a mixture of magnetite and iron sulfide minerals; these minerals are also formed by some terrestrial bacteria. Third, the isotopic composition of carbon in the meteorites is like that which is created by living things on Earth.

The hypothesis that these tiny features are actually fossilized bacteria is naturally being intensely scrutinized. Evidence against past life in this meteorite includes the very small size of the "bacteria." No fossil bacteria found on Earth are this small. The objects in Figure 25.11 are 10 to 100 times smaller than terrestrial bacteria and are about the same size as viruses. Moreover, carbonate globules with iron minerals can form by inorganic processes in hot springs on Earth. Finally, hydrocarbons of the sort identified in these Martian meteorites are not particularly rare. Many different kinds of meteorites contain the same kinds of molecule but clearly did not host living organisms.

All of the evidence collected by studying the surface of Mars and by carefully probing these meteorites makes it clear that Mars is rich in water compared with the Moon, Mercury, or Venus. We think that liquid water is critical for the evolution of life on any planet, and the presence of water has led to much speculation about life on Mars. Moreover, there is abundant evidence that Mars once had a more temperate climate and perhaps even higher atmospheric pressures. Nonetheless, only ambitious new missions to Mars in the coming decades will help us resolve the supremely important questions about life there. Ultimately, we need samples actually collected on Mars to understand the details of its early evolution.

Venus

Of all the planets, Venus is most like Earth in both size and density (Table 25.1). Thus understanding the similarities and differences between these two "twins" yields important clues about what controls the major characteristics of a planet. Unfortunately, the surface of Venus is totally obscured by clouds of sulfuric acid in a thick atmosphere made mostly of carbon dioxide. Nonetheless, Soviet and U.S. spacecraft used radar to reveal features as small as a football field. From these data an outline of the planet's history is emerging, though many important facets of its history are still mysterious.

Volcanic plains, mountain belts, volcanoes, and high "continents" that rise several kilometers above vast rolling lowlands show that Venus has a surface similar, in some ways, to the surface of Earth with its continents and ocean basins (Figure 25.12). However, Venus has almost no water, and because of an enhanced greenhouse effect in its carbon dioxide-rich atmosphere, surface temperatures (almost 500°C) are higher than on Mercury. Its atmosphere exerts a pressure almost 90 times that of Earth's.

Venus does not have a heavily cratered terrain dominated by ancient impact structures like those of the Moon, Mercury, and Mars. This is the single most important fact we know about the surface of Venus. It clearly shows that the surface of Venus is young, perhaps only 500 million years old, and has been repeatedly modified by tectonism and extensive volcanism. However, Venus has about 1000 relatively young impact craters.

Although erosional and depositional features dominate the surface of Earth and are common on Mars, they appear to be relatively insignificant on Venus.

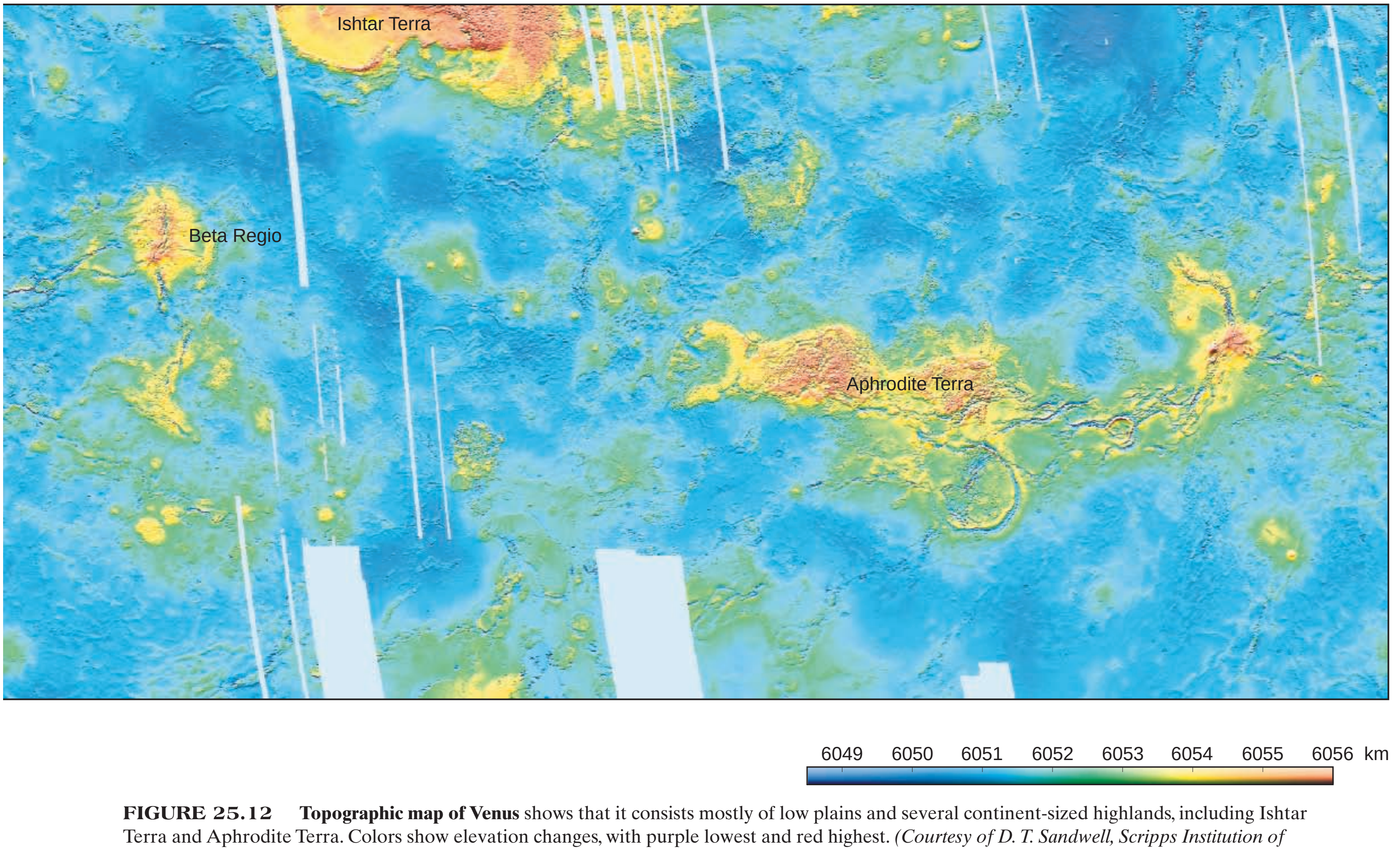


FIGURE 25.12 **Topographic map of Venus** shows that it consists mostly of low plains and several continent-sized highlands, including Ishtar Terra and Aphrodite Terra. Colors show elevation changes, with purple lowest and red highest. *(Courtesy of D. T. Sandwell, Scripps Institution of Oceanography, University of California at San Diego)*

Eolian and mass movement processes are the only effective sedimentary processes. Wind streaks and dune fields have been identified, but they are not widely distributed.

How do the craters on Venus differ from those on the Moon and Mars?

Volcanic features dominate the landscape of Venus. Smooth volcanic plains make up more than 80% of the planet. The plains are built by thin, fluid lava flows. In addition, thousands of small shield volcanoes, generally 2 to 8 km in diameter, with summit craters, are scattered across the plains and concentrated in local clusters. These features are similar to seamounts on Earth. In some areas, eruptions built large volcanoes, as much as 225 km in diameter, that have radial lava flow. Some steep-sided volcanic domes suggest the presence of lavas with higher viscosities and possibly more silicic compositions (Figure 25.13B). Another distinctive volcanic landform is called a corona (Figure 25.13D). It consists of a large (500 km across) raised wreath of faults and fractures surrounding a central volcanic plain that may be dotted by smaller volcanoes and scarred by a large collapse caldera. Many of these and other volcanoes lie on broad structural domes that are cut by long rift valleys. These structures may indicate the presence of broad mantle upwellings or plumes like those on Earth.

What are the major products of volcanic activity on Venus?

Most of the volcanism on Venus appears to be quite young. None of the plains are as heavily cratered as the lunar maria. Lacking confirming radiometric dates from samples collected on the surface, planetary scientists think that the average age of the surface may be only about 500 million years. Compare this with the Moon, where nearly all of the surface is more than 3 billion years old.

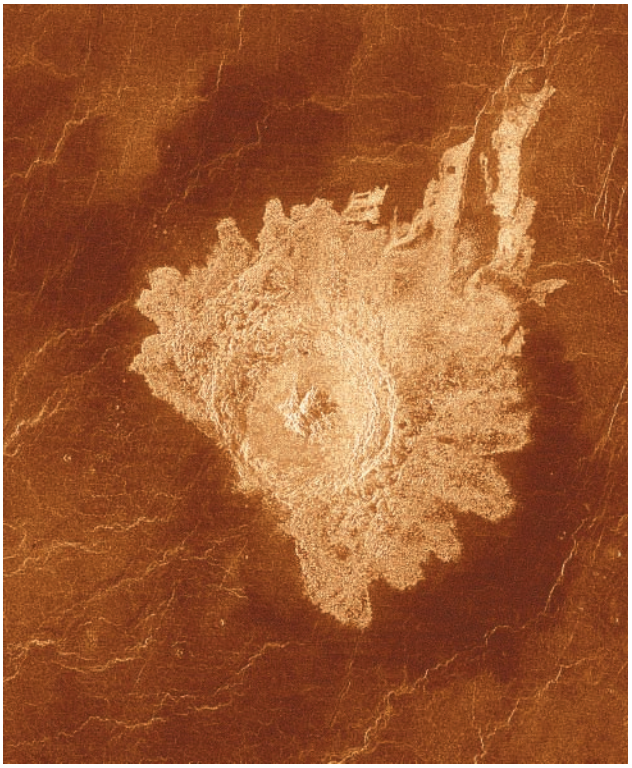
The surface of Venus has tectonic features that are spectacularly displayed because they are essentially unmodified by erosion. Some uplifted domes are completely laced with polygonal patterns of faults and fractures (Figure 25.13). In other areas, deformation of the plains occurs in linear belts of narrow ridges, similar to the wrinkle ridges on the Moon, but wider and longer. Folds and thrust sheets form parallel ridges and troughs that clearly represent compressional deformation.

It appears that Venus has had a long and especially eventful geologic history. Like its sister planet Earth, Venus lacks heavily cratered terrain formed early in the history of the solar system. But billions of years of volcanism and tectonism have erased any vestige of its battered crust. Nonetheless, Venus has not developed a system of plate tectonics to recycle its lithosphere and rid its interior of heat. Instead, Venus, like Mars, seems to be losing heat via hot spot development.

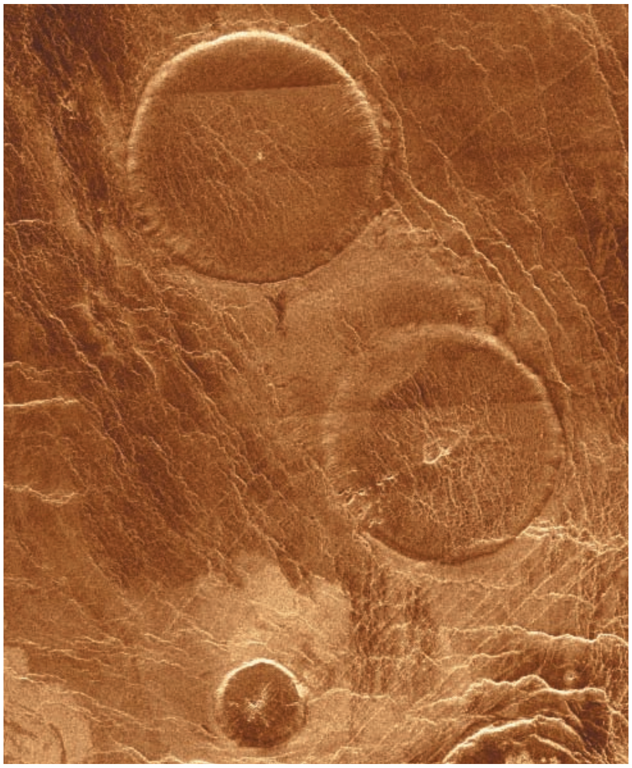
Thermal Histories of the Inner Planets

How does the thermal history of a planet influence its tectonic system?

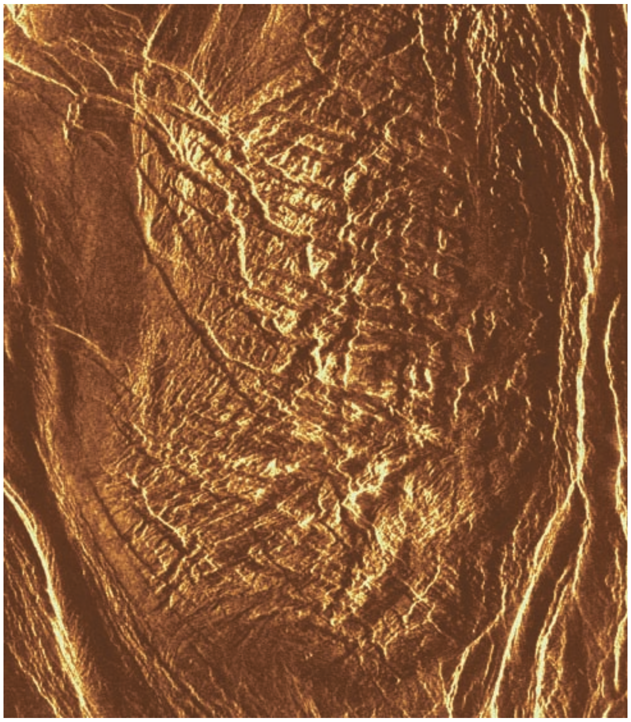
A major, yet simple, lesson has been learned in the few decades of space exploration—the thermal history and resulting geologic activity of a planet are largely dependent on the planet's size. Small bodies cool rapidly because they have large surface areas compared with their masses. Larger bodies retain heat longer and, as a result, have prolonged periods of internal geologic activity, such as volcanism and crustal deformation. Thus, we see a natural sequence arising by examining the ages of the rocks and surfaces of the inner planets. Meteorites are derived from the smallest bodies in the solar system—asteroids—and have crystallization ages clustering between 4.5 and 4.6 billion years old. The Moon preserves many areas of ancient heavily cratered terrains that are more than 3.9 billion years old, but some parts are flooded with younger basaltic lavas, perhaps as young as 3 billion years old. Mercury, Mars, Venus, and finally Earth have progressively younger surfaces, with very young (less than 0.5 billion years old) volcanic rocks forming much of the surfaces of both Venus and Earth. Most of this difference is simply related to the size and slower cooling rates, and hence prolonged tectonic and volcanic activity, on the larger planets.



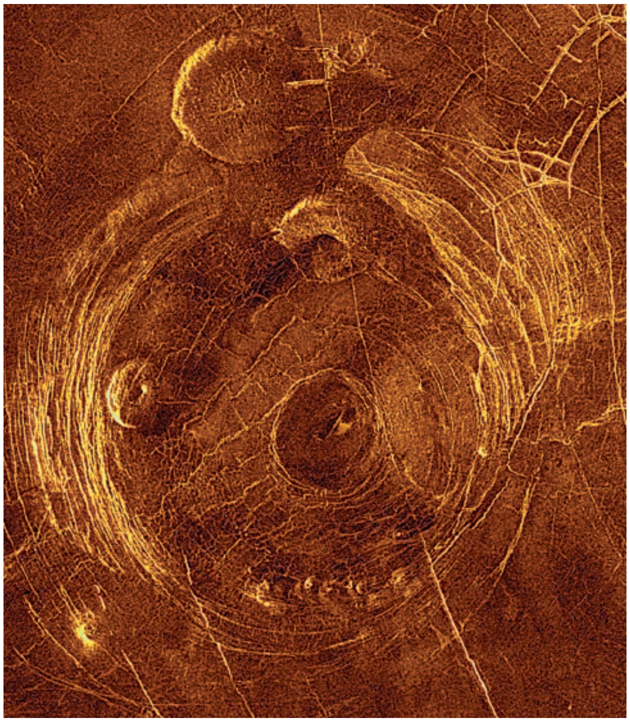
(A) Impact craters on Venus are unique because of the high surface temperature and high atmospheric pressure. This crater is about 30 km in diameter. The asymmetrical, radial-lobate ejecta pattern suggests that the ejected material was fluid, like a mudflow. Note the bright flows extending to the upper right as part of the continuous ejecta deposit.



(B) Steep-sided, flat-topped volcanic domes are similar to silicic domes on Earth. Their structure and morphology suggest that they were formed by viscous magma.



(C) A large structural dome cut by a complex fault system and flanked by a series of folds. The width of the image is about 125 km.



(D) Coronas are important volcano-tectonic features found on Venus. They may be underlain by mantle plumes.

FIGURE 25.13 **The surface of Venus** as revealed by *Magellan* radar images. *(Courtesy of NASA/JPL/Caltech)*

THE OUTER SOLAR SYSTEM

Planetary bodies in the outer solar system were formed mostly of the lighter elements: hydrogen, helium, and oxygen. Therefore, the satellites of the giant planets are composed mostly of ice, not of rock, as are the inner planets. They are relatively small and did not generate enough internal heat to sustain geologic activity much beyond the period of intense bombardment. Io, Europa, Ganymede, Enceladus, Miranda, and Triton are notable exceptions, in that each has a distinctive tectonic style resulting from unique energy systems.

Jupiter and Its Satellites

Jupiter and its moons form a planetary system of incredible beauty and intrigue. The giant planet has a volume 1300 times greater than Earth's (Table 25.1). The surface we see with telescopes is a layer of colorful clouds swirling in complex patterns (Figure 25.14). The exploration of Jupiter proved to be one of the most significant results of the *Voyager* missions (1979–89) to the outer solar system. In addition, Jupiter is now the focus of the *Galileo* mission. Jupiter has no solid surface and hence no record of a geologic history. The density of Jupiter is only 1.3 g/cm^3, slightly more than that of liquid water, and there is conclusive evidence that silicate rock is not its most important constituent. Rather, Jupiter and the rest of the large outer planets are composed dominantly of hydrogen and helium that cloak Earth-sized masses of silicates and metals (Figure 25.1).

Jupiter's moons, however, are solid planetary bodies containing geologic wonders that reveal fundamental ideas about the origin of planets. Jupiter's four large moons (Io, Europa, Ganymede, and Callisto) are called the Galilean satellites because they were discovered by Galileo in 1610. Each of Jupiter's moons shows a diverse landscape resulting from impact, volcanism, and fracturing (Figure 25.15). Three of these moons have surfaces composed mostly of water ice, and one is probably made mostly of silicates and iron.

Io. Io is Jupiter's innermost major satellite. In contrast to every other large satellite in the outer solar system, it lacks an icy outer layer and is composed mostly of silicates like the inner planets. It is only slightly larger and denser than Earth's Moon (Table 25.1). However, unlike the Moon, Io is volcanically active (Figure 25.15A). More than a dozen erupting volcanoes were spotted by the *Voyager* cameras as they plummeted past Jupiter (Figure 25.16). More have been discovered by *Galileo,* including an erupting fissure vent. The volcanoes are so active that no impact craters have yet been discovered. There is no ancient cratered terrain; all of it was engulfed long ago by volcanic materials.

Io is the most volcanically active body in the solar system and probably has been throughout much of geologic time. The question is why? The Moon, which is about the same size as Io, cooled quickly because of its small size and has been volcanically dead for almost 3 billion years. Theoretically, Io should be dead, too. However, energy from tidal forces may give it a continual energy boost. Europa and Ganymede, as well as Jupiter, exert a strong gravitational pull on Io, forcing it into an eccentric orbit. Io is therefore constantly massaged by tidal forces as it moves closer to and then farther from Jupiter. These conditions cause the satellite to be heated by internal friction. Indeed, **tidal heating** may make Io molten at a depth of only 20 km, so that volcanic activity would naturally be a dominant surface process.

Why does Io have so many active volcanoes?

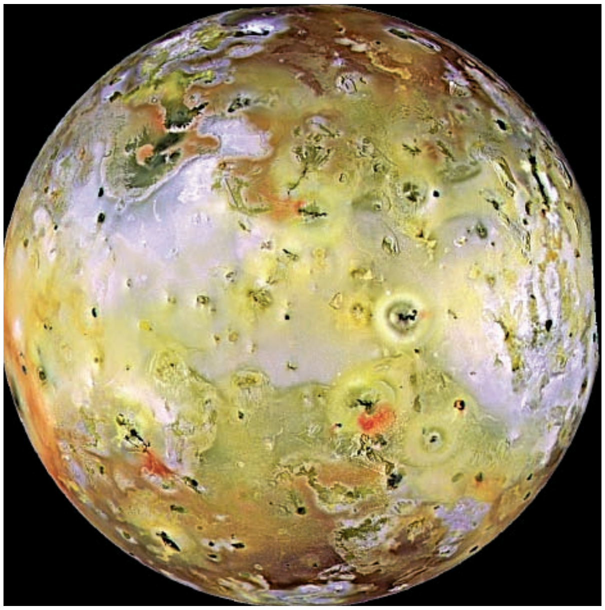
Europa. Europa has a density of about 3 g/cm^3 and must therefore be composed mostly of dense silicate rock (Table 25.1). However, spectroscopic measurements show that Europa is surrounded by a frozen ocean of ice. Europa represents the class of icy planets (Figure 25.1). Its surface is distinctive in that it is essentially

FIGURE 25.14 **Jupiter** as photographed by *Voyager 1.* Not visible are Jupiter's faint rings, seen for the first time on this mission. *(Courtesy of NASA/JPL/Caltech)*

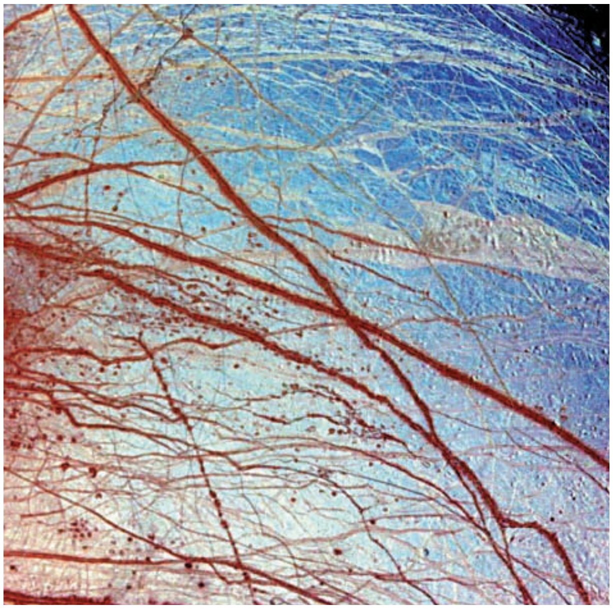
free from large impact craters. Watery lava erupted through cracks and fissures in the crust and repeatedly coated the surface with fresh ice. The most obvious features on Europa are sets of tan streaks or bands that are probably fractures formed by its constant gravitational tug-of-war with Jupiter (Figure 25.15B).

The near-absence of impact craters on Europa shows that the surface is very young, formed after the early periods of heavy meteorite bombardment. Resurfacing by the eruption of lavas must have continued until very recently. This scenario is very similar to what we just described for Io. Yet, Io and Europa have distinctly different surfaces and would not be confused by anyone. What makes the difference? Europa has a surface of solid water ice that probably overlies a deep ocean (Figure 25.17). At the markedly higher resolution provided by the cameras of *Galileo,* parts of Europa's surface can be seen to be similar to the fractured ice packs in Earth's polar regions (see Figure 9.12). An ocean of liquid water must lie at a shallow depth to explain the shapes and sizes of the ice floes. Could Europa, then, host life that evolved in such an ocean? Could internal heat, released from

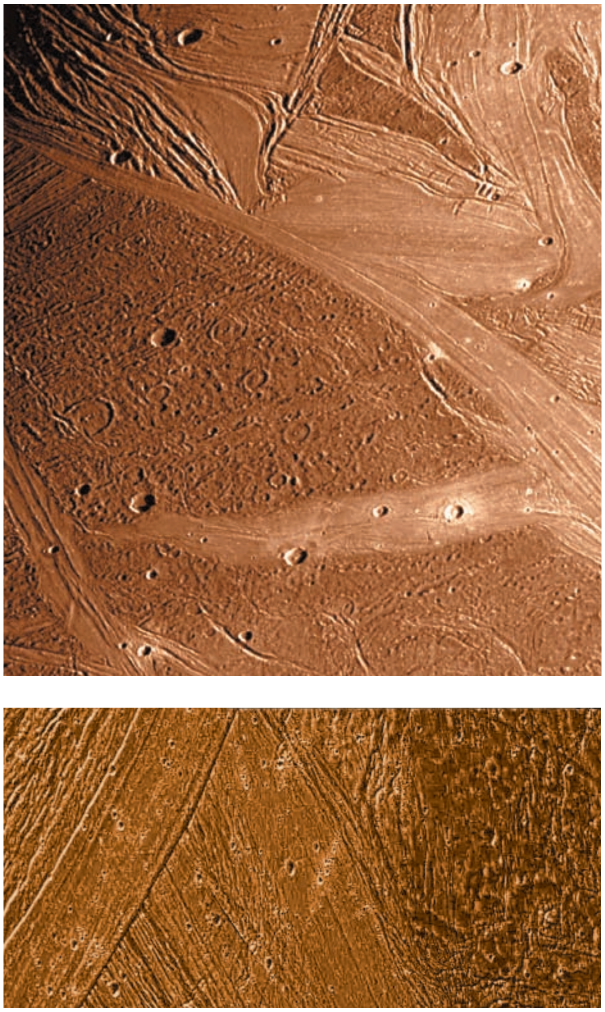
How is the composition of Europa different from the composition of the inner planets?



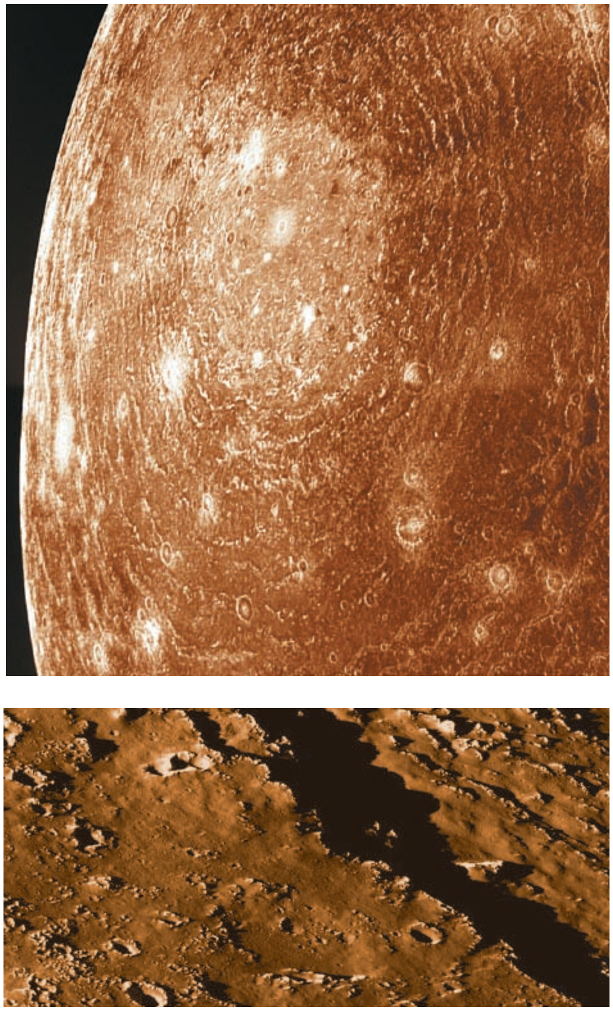
(A) Io: A young surface formed by volcanism.



(B) Europa: A young surface of fractured ice (in false color).

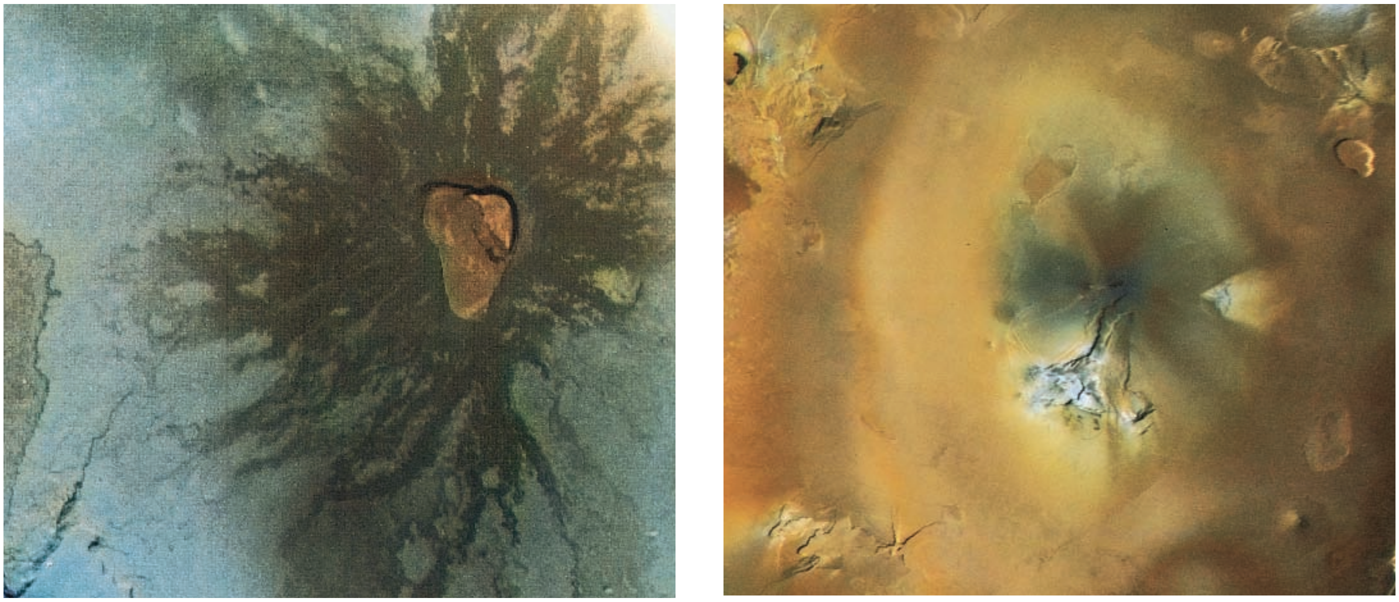


(C) Ganymede: An older icy surface with a complex history of crustal fragmentation. The lower photo shows the details of one area of grooved terrain.



(D) Callisto: An ancient surface dominated by impact structures. The detailed photo shows the rim of the impact structure Valhalla.

FIGURE 25.15 **The Galilean moons of Jupiter.** *(Courtesy of NASA/JPL/Caltech)*



(A) Maasaw Patera is a large central volcano capped by a triangular caldera. Lava flows erupted from near the summit flowed down the flanks of the volcano.

(B) The volcano Pelee is shown in eruption by the *Voyager* cameras. The eruption produces a spray similar to that of a lawn sprinkler. From this vertical view, the margins of this ash cloud form a dark elliptical pattern.

FIGURE 25.16 **Volcanoes are Io's most spectacular landforms.** Many are active today. *(Courtesy A. McEwen, University of Arizona)*

tidal heating, drive communities of organisms like those found clustered around hydrothermal vents in Earth's deep seas?

Ganymede. Jupiter's largest satellite is Ganymede, whose diameter is approximately 1.5 times that of Earth's Moon (Table 25.1). It is even larger than Mercury. It has a bulk density of only 1.9 g/cm^3 and may consist of about 50% water ice surrounding a rocky core. Ganymede has a cratered surface with two contrasting terrain types (Figure 25.15C). The older terrain is nearly saturated with impact craters. It is dark and is believed to be composed of "dirty" ice, containing

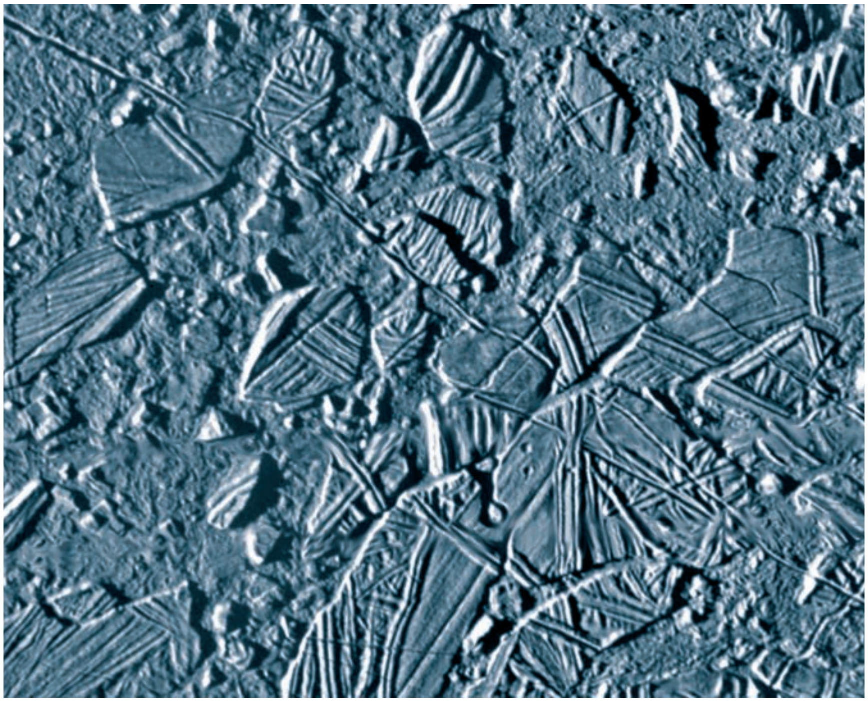


FIGURE 25.17 **Europa's surface is made of ice.** These blocks of fractured ice floated on a liquid ocean, which must lie at a shallow depth, before they refroze. Note the absence of abundant craters on this young surface. *(Courtesy of NASA/JPL/Caltech)*

fragments of dust and particles from outer space. This older crust appears to have fractured and split apart, and many of the fragments have shifted. The younger terrain is brighter and is crossed by closely spaced, nearly parallel grooves. There are fewer craters on the bright grooved terrain than on the darker surface, so the grooved terrain is believed to be much younger. Apparently, the old, cratered terrain fractured at some time late in the period of intense bombardment, and cleaner ice from below was extruded into the fractures to form the grooved terrain. The breaking and movement of the crustal fragments is a type of plate tectonics on a frozen world with a lithosphere of ice.

Callisto. Callisto is the outermost Galilean satellite. It is only slightly smaller than Ganymede (Table 25.1) and is also believed to consist of a rocky core surrounded by a thick mantle of ice. Callisto, in contrast to the other Galilean satellites, is saturated with craters (Figure 25.15D). The surface of Callisto is very old, recording events during the early history of the solar system. Callisto is covered with ancient dark, dirty ice, similar to the old terrain on Ganymede. Many craters have bright interiors and ejecta blankets. The bright material is probably clean, melted ice from below the dirty crust, ejected onto the surface during impact. Aside from the densely cratered terrain, the most striking feature on Callisto is a large multiring basin. This feature is reminiscent of the multiring basins on the planets of the inner solar system. Important differences exist, however, in the numbers of rings, their spacing, and their elevation. Apparently, ice responds quite differently to the shock of impact than rock.

What geologic features are unique on each of the Galilean satellites of Jupiter?

Saturn and Its Satellites

Saturn is similar to Jupiter in many ways (Table 25.1). It is a gigantic ball of gas, mostly hydrogen and helium, and is the center of a miniature planetary system with an elaborate family of at least 18 satellites. Its atmosphere is not as colorful as Jupiter's but is marked by dark bands alternating with lighter zones. Saturn's rings, of course, have long been considered its most dramatic feature; they have intrigued astronomers for more than 300 years (Figure 25.18). They extend over a distance of 40,000 km and yet are only a few kilometers thick. The rings are probably made up of billions of particles of ice and ice-covered rock, ranging from a few micrometers to a meter or more in diameter. Each particle moves in its independent orbit around Saturn, producing an extraordinarily complex ring structure.

Except for Titan, the seven largest moons of Saturn are small, icy bodies. They range from 390 to 1530 km in diameter. In other words, they are only one-half to one-tenth the diameter of the Moon. The surfaces of most of Saturn's icy satellites are saturated with impact craters (Figure 25.18). Many of the moons have large fracture systems and other strange surface markings, probably resulting from an exotic type of icy volcanism.

Are the satellites of Saturn more like those of Jupiter or Earth's Moon?

Two of Saturn's moons warrant separate discussion here. Tiny Enceladus has a rifted terrain and young, smooth plains that may have been produced by "lavas" of slushy water that erupted from fissures (Figure 25.19). The ridged terrain is probably similar in its origin to the grooved areas of Ganymede. Why would such a small body have smooth young plains? The recent heating of Enceladus is probably related to the same type of tidal heating that warms Io. Titan, larger than the planet Mercury, is the only moon in the solar system that has a substantial atmosphere. Surprisingly, the atmosphere of Titan is most like Earth and is composed mainly of nitrogen (N_2). There is no oxygen, however, but there are traces of methane (CH_4). The orange color of Titan comes from a haze or smog of hydrocarbon particles in the atmosphere. Some planetary scientists even speculate that Titan has seas of hydrocarbon liquids washing its surface. However, Hubble Space Telescope images show that Titan is not completely, if at all, covered by seas. There are permanent surface features that rotate with the moon.

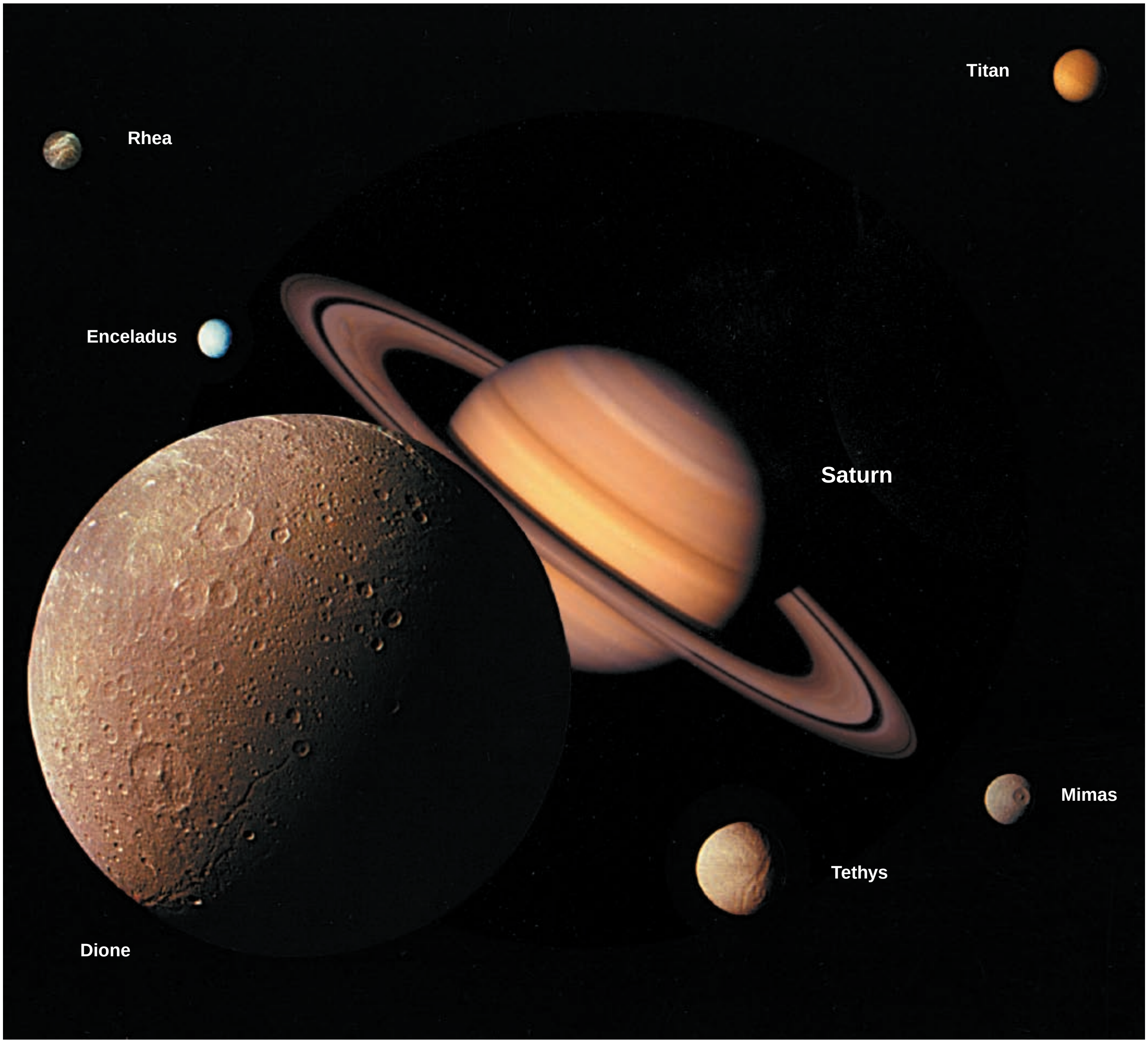


FIGURE 25.18 **Saturn and its major moons** assembled as a composite picture from *Voyager* photographs. This view shows Dione in the forefront, Saturn rising behind, Tethys and Mimas in the distance on the right, Enceladus and Rhea off Saturn's rings to the left, and Titan at the top. Saturn's icy moons are a geologically diverse group of mostly small satellites. They show an amazing variety of young and old surfaces, impact craters, evidence of icy volcanism, and global fracture systems. *(Courtesy of NASA/JPL/Caltech)*

Uranus and Its Satellites

Like the other giant planets, Uranus has no solid surface but is enveloped by a thick atmosphere of hydrogen and helium (Figure 25.20). It is much smaller than Saturn and only about four times as large in diameter as Earth (Table 25.1). Its cloud layer is bland and bluish, because of the presence of methane. It also has a thin dark system of rings that are almost invisible. It is unique among all other planets in the solar system, because its spin axis is tipped on its side; that is, its axis of rotation lies nearly in the plane of its orbit. Thus, it rolls, like a ball, as it moves on its orbital path around the Sun, whereas other planets spin like tops.

Uranus has five major moons (Table 25.1). Each moon occupies a nearly circular orbit, lying in the plane of Uranus's equator. Their orbits share the unusual axial inclination of the planet itself. Oberon, Titania, Ariel, and Umbriel are quite similar in size (1100 to 1600 km in diameter) and are approximately the size of the

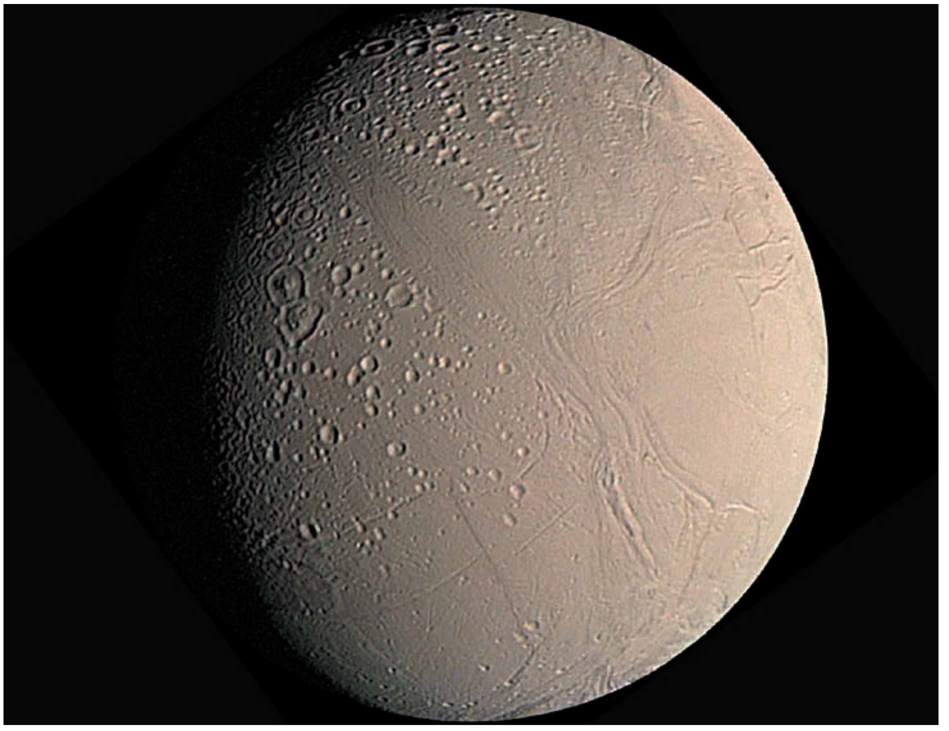


FIGURE 25.19 **Enceladus** is one of the most interesting of the satellites in the solar system. Although it is tiny (less than 500 km across), it shows a remarkable record of geologic activity. Its smooth, uncratered surface is geologically young, which indicates that it has experienced a relatively recent thermal event and an exotic form of volcanic activity in which floods of water and icy slush were extruded. *(Courtesy of NASA/JPL/Caltech)*

intermediate moons of Saturn (Tethys, Dione, and Rhea). Their surfaces are nearly saturated with craters (Figure 25.20) and are composed mostly of water ice.

Neptune and Its Satellites

Neptune is only slightly smaller than Uranus and is similar to its neighbor in composition (Table 25.1). Both planets, called the "twins of the outer solar system," are thought to have large cores of water ice and rock, surrounded by thick atmospheres of hydrogen, helium, and minor methane. However, Neptune's cloud layers are banded in various shades of blue (Figure 25.21). Oval storm systems spin in the atmosphere. Clouds of bright methane ice tower above the storm systems. Like the other gas giants, Neptune has a system of rings made of ice particles in orbit around the planet.

How could volcanism occur on the frigid bodies of outer solar system?

Only two moons were known to orbit Neptune before the *Voyager* spacecraft passed it in 1989. At that time, six additional tiny moons were discovered. Triton is the most interesting and largest moon. It is only slightly smaller than Earth's Moon (Table 25.1). It has an extremely tenuous atmosphere of nitrogen and methane, and its exotic landscape is formed from ices of those gases. Triton has a surprisingly large variety of geologic features, including ice caps, fractured terrain, "lava" lakes, and volcanic or geyser eruptions (Figure 25.22). It is not a simple cratered body. Triton is so cold (only 40° above absolute zero) that nitrogen is frozen solid on its surface. However, there is enough warmth from the Sun to cause the nitrogen to vaporize seasonally. Consequently, nitrogen ice caps shift from pole to pole. Its constantly changing ice caps of nitrogen and methane ice found on its surface mark it as one of the most distinctive planetary bodies in the solar system. Its odd retrograde orbit and young surface features combine to suggest that it formed elsewhere in the outer solar system but was then captured and tidally melted as it went into orbit around Neptune.

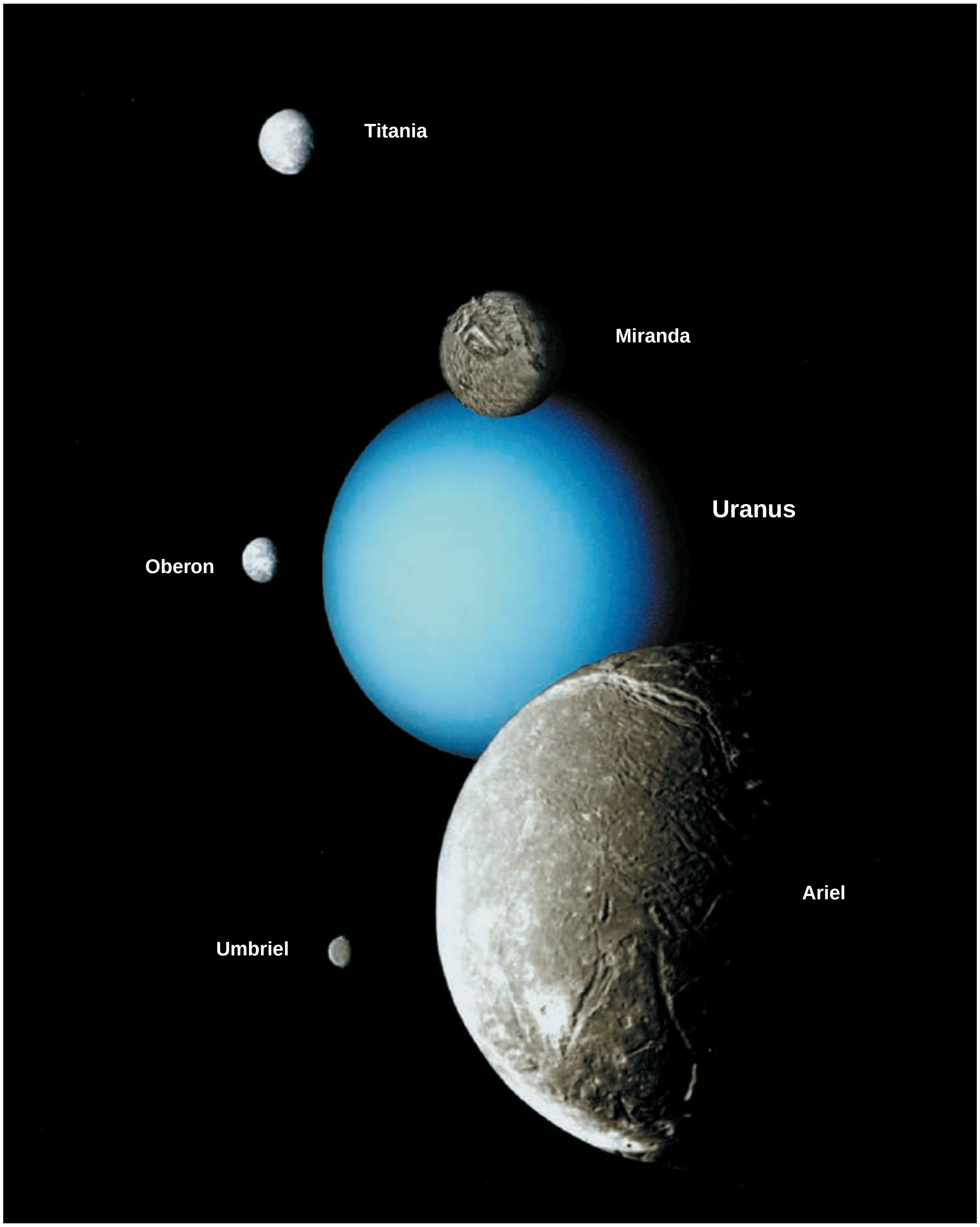


FIGURE 25.20 **Uranus and its five major satellites** assembled in a composite picture from *Voyager.* Uranus is smaller than Saturn, but still has a thick atmosphere of hydrogen and helium. The blue color is caused by methane. The moons are relatively small and all have icy surfaces. *(Courtesy of NASA/JPL/Caltech)*

Pluto

Pluto is a planet of extremes (Table 25.1). It is the farthest, the smallest, the coldest, and the darkest. Discovered in 1930, Pluto was the last of the planets to be found. Because of its great distance from the Sun, it takes nearly 250 years to complete one orbit. Pluto is distinctive among the outer planets in that it lacks a thick, hydrogen-rich atmosphere. Indeed, it is much more similar to the moons of Neptune than to any of the major planets. However, it does have its own moon, Charon.

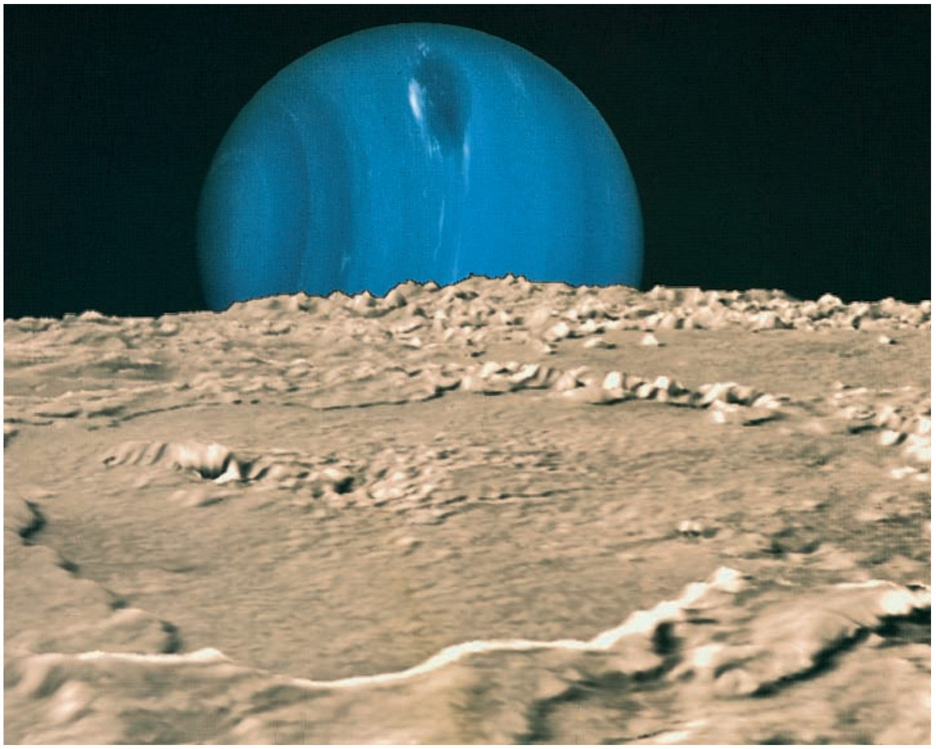


FIGURE 25.21 **Neptune and its largest satellite, Triton,** as photographed by *Voyager 2.* Neptune is about the size of Uranus but has a banded blue atmosphere decorated with brilliant white clouds of methane ice. Triton is so cold that nitrogen ice forms on its surface. *(Courtesy of NASA/JPL/Caltech)*

Our best images come from the Hubble Space Telescope (Figure 25.23). Telescope studies show that Pluto's surface is dominated by nitrogen ice. (At this distance from the Sun, Earth's nitrogen-rich atmosphere would freeze solid to form a thin layer of ice.) Because Pluto is such an oddity—an icy planet among the gas-rich outer planets—there has been much conjecture about its origin. Perhaps, Pluto and Triton both accreted in the same frigid part of the outer solar system as Sun-orbiting planets. Triton was then captured by Neptune. Pluto remained in Sun orbit, but Charon may have formed when Pluto collided with another object and fragmented.

FIGURE 25.22 **Triton** is so far from the Sun and its surface temperature is so low (40°K), that nitrogen is frozen solid to form a large ice cap shown on the bottom of this photo. A fractured terrain with many crisscrossed linear features appears to be the result of rifting. Floods of "lava" (probably mixtures of water, nitrogen, and methane) formed smooth plains and lava lakes. Dark streaks are formed from geyserlike volcanic eruptions from beneath the bright ice cap. *(Courtesy of NASA/JPL/Caltech)*

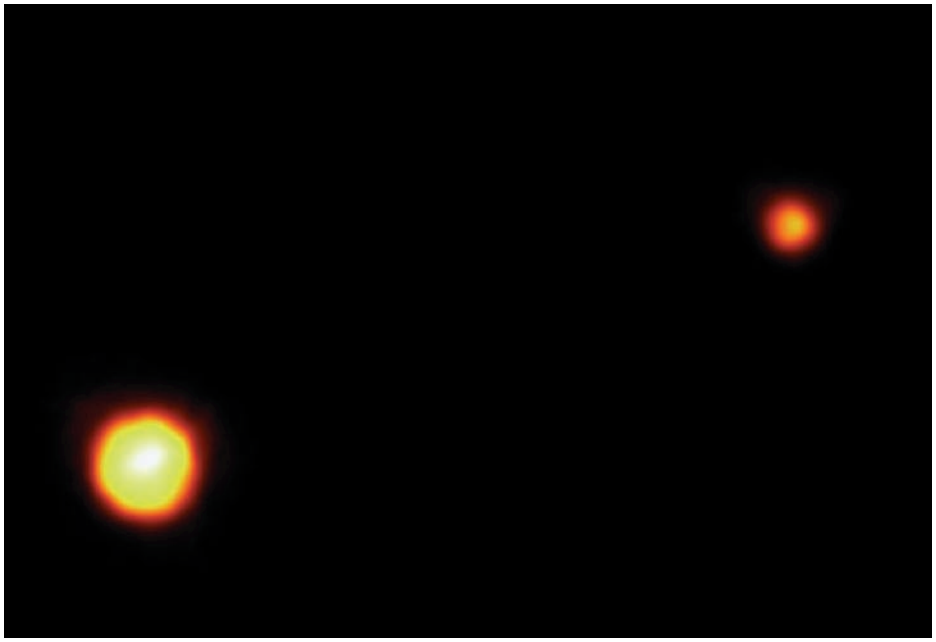


FIGURE 25.23 **Pluto** is the most distant planet in the solar system. Our best views of Pluto and its smaller moon, Charon, are those acquired by the Hubble Space Telescope. *(Courtesy of Hubble Space Telescope Team)*

SMALL BODIES OF THE SOLAR SYSTEM: ASTEROIDS AND COMETS

Although among the smallest members of the solar system, asteroids and comets hold answers to some of the biggest questions regarding the origin of the solar system.

Asteroids

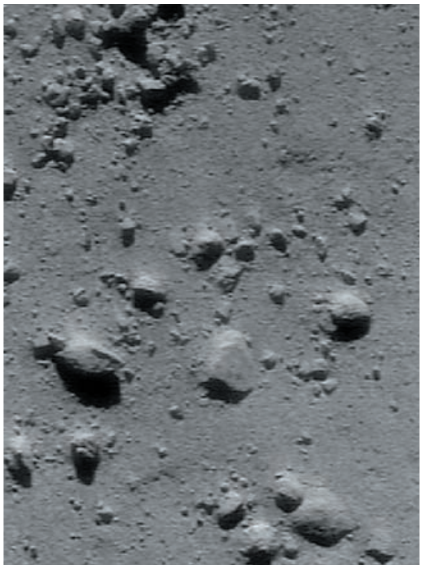
Besides the nine major planets, thousands of smaller planetoids are also part of the solar system. These minor planets are called **asteroids** (Figure 25.24). There are more than 10,000 known asteroids, but many others are far too small to be seen even through the best telescopes. Most are found between the orbits of Jupiter and Mars, where the gravitational force of Jupiter prevented them from accreting to form a single larger planet. The largest asteroid is only about 1000 km across.

Our best information about asteroid surfaces comes from the photographs taken by the *NEAR* spacecraft which orbited and then landed on the small asteroid named Eros. Craters of every size are visible on its surface. Incomplete crater walls define its irregular shape. The abundance of craters suggests that the surface formed billions of years ago, perhaps because of massive fragmentation of a once-larger body. Eros, like most of the other asteroids, is not big enough to sustain active geologic systems driven by internal heat. Perhaps it never was. No lava flows or tectonic features have formed on this small body. Eros lacks the gravitational energy to pull itself into a sphere. *Galileo* also photographed two asteroids. Ida (Figure 25.24) has a long axis that only measures 56 km, but it has its own tiny moon. Ida is also irregularly shaped and heavily cratered. Impact cratering is the main process that shapes asteroids today.

Most meteorites that fall to Earth as shooting stars or meteors are probably fragments of asteroids. By carefully studying the composition of meteorites, we have learned that many came from asteroids that had differentiated anciently, forming iron cores and silicate mantles, and some even had crusts made of basaltic lava flows. These meteorites reveal that the parent asteroids are much like the inner planets in their compositions. Radiometric dates of meteorites have also

(A) Ida was photographed by *Galileo* on its way to Jupiter. It is only 56 km long and 24 km across. Ida, like many other asteroids, is not large enough to be spherical. It was shaped by impact with other asteroids, but it does have its own tiny moon Dactyl.

(B) Eros, photographed by the *NEAR* spacecraft in 2000, is only about 20 km long and heavily cratered.



(C) Closeup photograph of the surface of Eros. The regolith and boulders were created by multiple impacts. This photograph shows an area only 12 meters across and was taken from 250 m above the surface of Eros.

FIGURE 25.24 **Asteroids** are among the smallest members of the inner Solar System. Most are irregularly shaped and orbit between Mars and Jupiter. *(Courtesy of NASA/JPL/Caltech and the Advanced Physics Laboratory, Johns Hopkins University)*

established that the solar system formed during a short interval between 4.6 and 4.5 billion years ago.

It is commonly concluded from this information that asteroids and meteorites are remnants of a swarm of small bodies from which the inner planets formed. Thus, by carefully studying the meteorites, we can understand more about the conditions of formation and differentiation of planetary bodies.

Comets

Comets are the most distant members of the solar system. Some have orbits that take them so far from the Sun that it takes tens of thousands of years to complete a single revolution. Although we have not collected samples of any comet, telescopic and space probe studies of these small bodies show that they are composed basically of ice and dust and have a kinship with the icy bodies of the outer solar system (Figure 25.1). The ices of water, carbon dioxide, carbon monoxide, methane, and ammonia have been identified. These are mixed with various silicate minerals and metal particles. The mixture leads to the common notion that comets are "dirty snowballs."

Because comets have strongly elliptical (elongated) orbits with the Sun at one focus, they occasionally enter the inner solar system, where it is much warmer than in the outer solar system. The icy nucleus of a comet partially vaporizes when it comes close to the Sun, forming a large diffuse coma (the sphere of gas and dust around the nucleus) and spectacularly long tails of gas and dust. During the early months of 1997, Comet Hale-Bopp moved through the inner solar system (Figure 25.25). It treated stargazers to a spectacular view. As it swept through the inner solar system, its head enlarged and its tail became longer and longer as heat from the Sun vaporized ice inside the comet. (Comets do not glow from internal energy. They simply reflect sunlight off the molecules of gas and dust.) Even though the icy nucleus is only a few tens of kilometers across, the bright coma of this comet was as large as Jupiter and its tail extended millions of kilometers behind it. As Hale-Bopp moved back out of the inner solar system, the ice recondensed and the tail disappeared.

FIGURE 25.25 **Comets** are actually small ice bodies that formed in the outer solar system. Some have elliptical orbits that take them near the Sun. When they enter the warmth of the inner solar system, the ice sublimes to vapor and forms a long tail that streams behind it. Hale-Bopp (1997) was probably the most spectacular comet seen in the latter half of the twentieth century. *(Courtesy of D. McClain)*

The origin and history of comets are very enigmatic. Comets may have originally formed near Uranus and Neptune, but subsequent gravitational perturbations from Jupiter must have ejected them to distant orbits that presently envelop the solar system. Periodically, some comets are gravitationally forced, perhaps by a passing star, into shorter elliptical orbits that take them into the inner solar system. Comets must be remnants of the planetesimals that accreted to form the outer planets and their satellites.

Using the Hubble Space Telescope, several of these remnants have been identified in the outer solar system. Ranging in size to as much as 200 km across, these icy bodies orbit beyond Neptune. More than 200 have been discovered since 1992, and some estimates suggest that as many as 200 million may exist. In fact, Pluto and Triton may be large members of this group of outer solar system planetesimals.

ORIGIN OF THE SOLAR SYSTEM

The solar system probably formed by gravitational collapse of a huge cloud of gas and dust. The inner planets formed from dense silicates and metals that crystallized at high temperatures near the forming Sun, while the outer planets additionally included elements that form solids at low temperatures. Dense atmospheres became attached to the large icy cores of the outer planets.

Most scientists believe that the universe began about 15 billion years ago, in what has become known as the Big Bang. This gigantic explosion caused matter to expand outward from one point to form the billions of swirling galaxies and, in time, the stars and their planets. It is generally thought that our solar system was spawned in a cold, diffuse cloud of gas and dust, or a **nebula,** deep within a spiral arm of the Milky Way galaxy. The huge cloud was made up largely of the two lightest elements, hydrogen and helium, along with lesser oxygen and even smaller quantities of heavy elements, such as silicon and iron. The nebula rotated slowly about a central concentration of mass and contained a system of complicated eddies. Under

How did silicates become concentrated in the inner planets and water ice in the planetary bodies of the outer solar system?

(A) A slowly rotating portion of a large nebula becomes a distinct globule as a mostly gaseous cloud collapses by gravitational attraction.

(B) Rotation of the cloud prevents collapse of the equatorial disk while a dense central mass forms.

(C) A protostar "ignites" and warms the inner part of the nebula, possibly vaporizing preexisting dust. As the nebula cools, condensation produces solid grains that settle to the central plane of the nebula.

(D) The dusty nebula clears by dust aggregation into planetesimals or by ejection during a T-Tauri stage of the star's evolution. A star and a system of cold bodies remains. Gravitational accretion of these small bodies leads to the development of a small number of major planets.

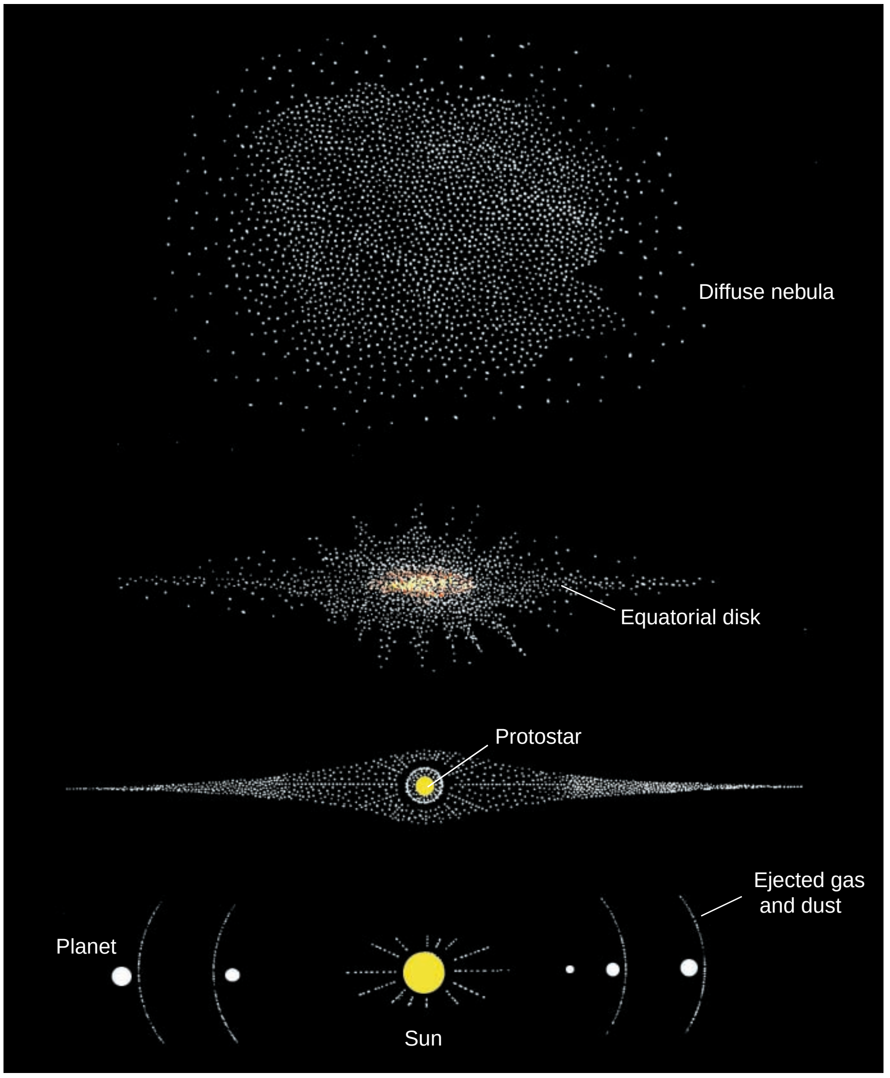


FIGURE 25.26 **The evolution of a dusty nebula** to a star with a surrounding system of orbiting planets.

the force of gravity, the giant cloud began to collapse and assume the shape of a rotating disk, with an increasingly hot and dense mass at the center (Figure 25.26).

During the collapse, much of the cloud's matter swirled toward the dense central core to form the Sun. The outer part of the cloud was naturally the coldest, so substances there—such as water, ammonia, and methane—solidified as low-density ices. Nearer the Sun, those materials remained as vapor, but silicon, iron, aluminum, and similar materials could combine with oxygen and crystallize at high temperatures into solids, to form dense rocky material. However, these elements were not as abundant as the ice-forming materials. Thus, early in the history of the solar system, there was a separation and differentiation of material. Silicate minerals stable at high temperature were concentrated in the central region, whereas icy solids dominated near the fringes of the cloud.

Over a relatively short period (possibly as short as 100,000 years), the small particles in the embryonic solar system accreted into larger and larger particles, until asteroid-sized bodies of rock and ice called **planetesimals** formed. As the planetesimals orbited the infant Sun, the larger bodies grew by accretion as smaller objects repeatedly slammed into them. These planetesimals became the principal planets.

A planet's size and composition were therefore determined to a considerable degree by its distance from the Sun. In the high-temperature regions near the Sun, only materials such as the scarce metals and silicates crystallized into solids and accreted to form planets. Proceeding outward toward cooler and cooler temperatures, materials with lower crystallization temperatures, such as water and then methane and finally nitrogen, also became solid (ices) and accumulated to form planets. Because these volatile elements are much more abundant than the silicates, large icy bodies formed in the outer solar system. Huge amounts of gaseous hydrogen and helium became gravitationally anchored to these giant planets.

Most of the material of the nebula swirled inward toward the very center of the solar system. The intense pressure raised the temperature to a point where it became a vast nuclear furnace—a new star, the Sun. By this time, the principal planets and their satellites already orbited the Sun, and swept up most of the remaining debris in their orbital paths. This final stage of planetary accretion is clearly recorded as densely cratered terrain on the surfaces of the Moon, Mercury, Mars, and most other planetary bodies.

What is the importance of planetary differentiation?

All planetary bodies were heated to some degree because of the impact of the numerous planetesimals that formed them. If heated sufficiently, much of the planet melted and the constituent materials became differentiated—that is, denser materials were separated and concentrated in the core and lighter materials were concentrated near the surface. This process is known as planetary **differentiation** and led to the layered internal structure of the solid inner planets and icy satellites of the outer planets (Figure 25.1).

The Role of Impact Processes in the Origin of the Planets

With all these images of the planets before you, you can probably come to a simple but dramatic conclusion about the fundamental geologic processes in the solar system. Impact cratering may be the most important process in the origin and subsequent evolution of the planets. To understand further and emphasize the role of impact cratering in our solar system, let us consider several examples.

Impact Origin of the Moon. In the last 10 years, an exciting new hypothesis for the origin of the Moon has gained scientific respect (Figure 25.27). A glancing collision of Earth with a Mars-sized object would have vaporized and ejected material from the already differentiated Earth. The refractory silicate portion of this material could have become solid again and accreted while in orbit around Earth to create a small water- and iron-poor natural satellite—the Moon.

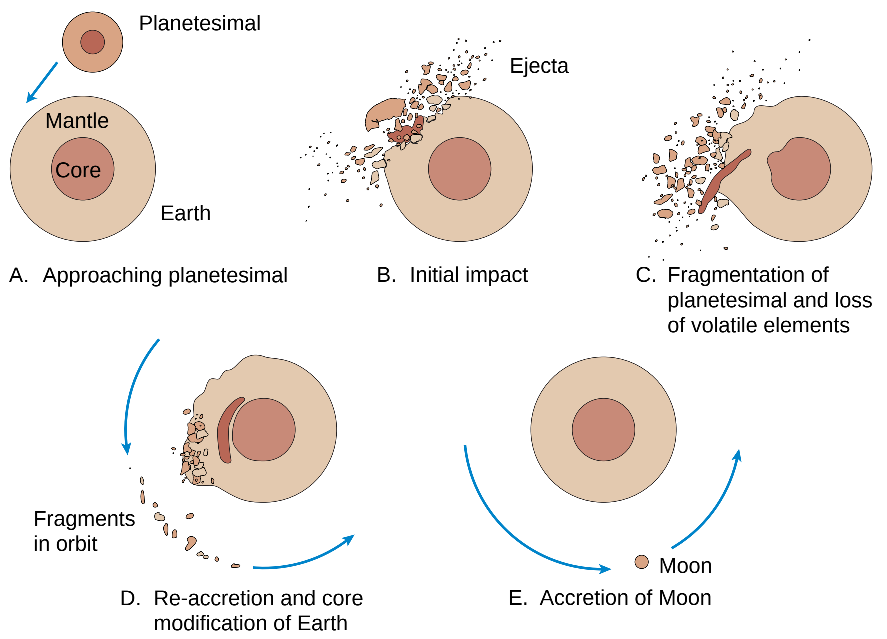


FIGURE 25.27 A giant collision of the early Earth with a body the size of Mars may have ejected material into orbit, where it accreted to form the Moon. The iron core of the impacting body would have plunged through Earth's mantle and merged with the already formed core. Earth may have been stripped of its primordial atmosphere and been left with a globe-encircling ocean of magma.

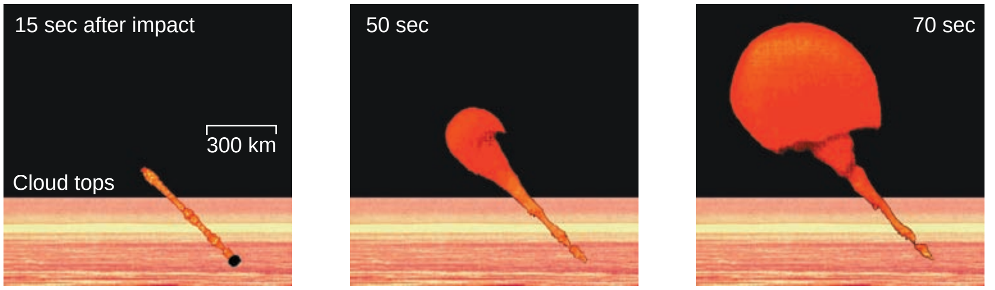


FIGURE 25.28 **The collision of Comet Shoemaker-Levy** was simulated by computer. These illustrations show the sequence of events associated with one of the impacts. First, a fireball forms along the trail of the falling comet. Second, the heated gases rise back along the tunnel. Third, a large fireball modified by an expanding shock wave punches through the cloud tops. *(Modified from the Sandia National Laboratory)*

What role has impact played in the evolution of the planets and moons of the solar system?

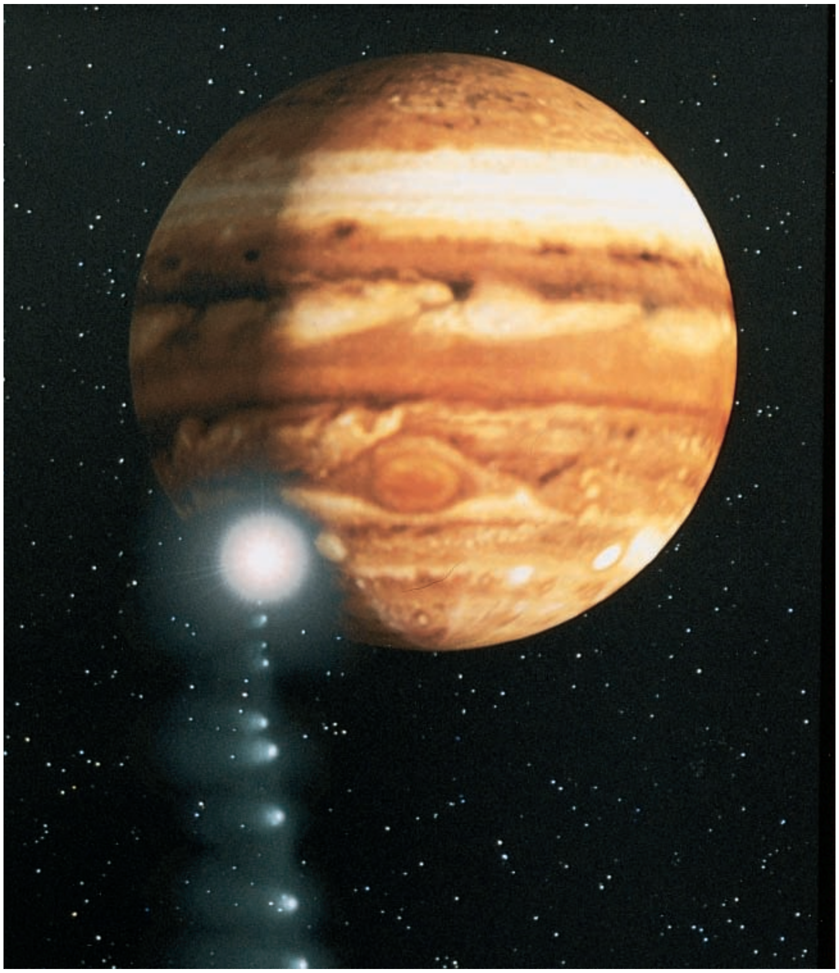
Other Large Impacts. The role of similar large-body impacts in the evolution of other planets is a topic of increasing speculation. For example, Mercury's relatively high density may be explained partly as the result of a giant impact that stripped away the outer silicate layers of the already-differentiated planet, leaving it enriched in the dense metallic iron that formed its core. A late, large impact on Venus may have slowed its spin and reversed its rotational direction, as compared with that of all other planets. The global dichotomy between Mars's heavily cratered northern hemisphere and its relatively young, smooth northern plains may be traced back to a giant impact basin in the northern hemisphere. The small icy satellites of Saturn and Uranus, some scientists conjecture, were fragmented several times, only to reaccrete later. Moreover, the rings that encircle the outer planets may be created again and again by the collisional fragments of small icy moons. At the very least, several icy satellites sustained massive impacts that created global fracture systems, as well as large craters. Finally, a giant collision with a large body may have tipped Uranus on its side, and another may have fragmented Pluto to form a double-planet system.

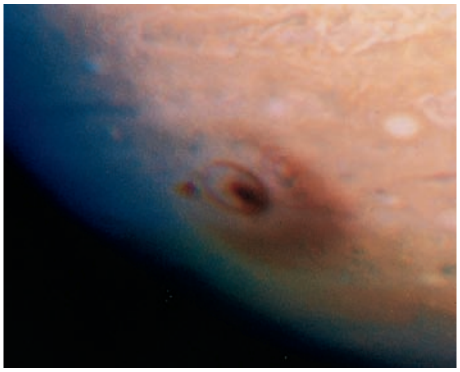
Comet Shoemaker-Levy 9 and Other Comet Impacts. The continuing importance of impact processes in the solar system was dramatically revealed in 1994 when a disrupted comet slammed explosively into Jupiter (Figure 25.28). As the comet approached Jupiter, the massive gravitational force of the giant planet ripped the icy body into a series of at least 21 perfectly aligned fragments, strung out like an orbiting "string of pearls" (Figure 25.29). The fragments became satellites of Jupiter, swinging around the planet in a highly elliptical orbit.

Each newly formed fragment was surrounded by a coma and tail of gas and dust. The best estimates are that the largest comet fragment was little more than 1 kilometer in diameter. From July 16 to 22, 1994, the jewels on this necklace of comets collided one by one with Jupiter.

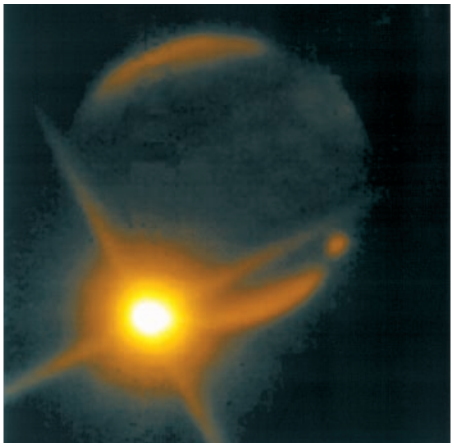
As each fragment entered the atmosphere, it flashed like a shooting star from the friction generated by its rapid flight. Each icy chunk probably tunneled about 75 to 150 km below Jupiter's cloud layer, leaving behind it a trail of hot, pressurized gas and cometary debris. Temperatures reached almost 8000 K. The heat released hurled an upward expanding fireball back through the tunnel created by the falling fragment (Figure 25.29). A powerful shock wave closely followed the fireball, enlarging it into a huge semispherical plume. Some of these huge plumes were larger than Earth. They rose hundreds of kilometers and punched through the cloud tops within minutes of exploding. Momentarily, the light from Jupiter increased 50-fold. The bright plumes disappeared in a matter of hours and were replaced by outward-expanding ripples or waves in the atmosphere and by enigmatic dark scars that eventually disappeared.

Impact is a fundamental process in planetary formation and evolution. It is not the dominant process it was 4.5 billion years ago, but impacts still occur today.





(B) The impacts left a string of dark scars aligned in a ring. The lighter swirls are large storms. *(Courtesy of Hubble Space Telescope Team)*



(A) The string of comets collided one by one with Jupiter, as seen in this artist's conception. *(Courtesy of NASA/JPL/Caltech)*

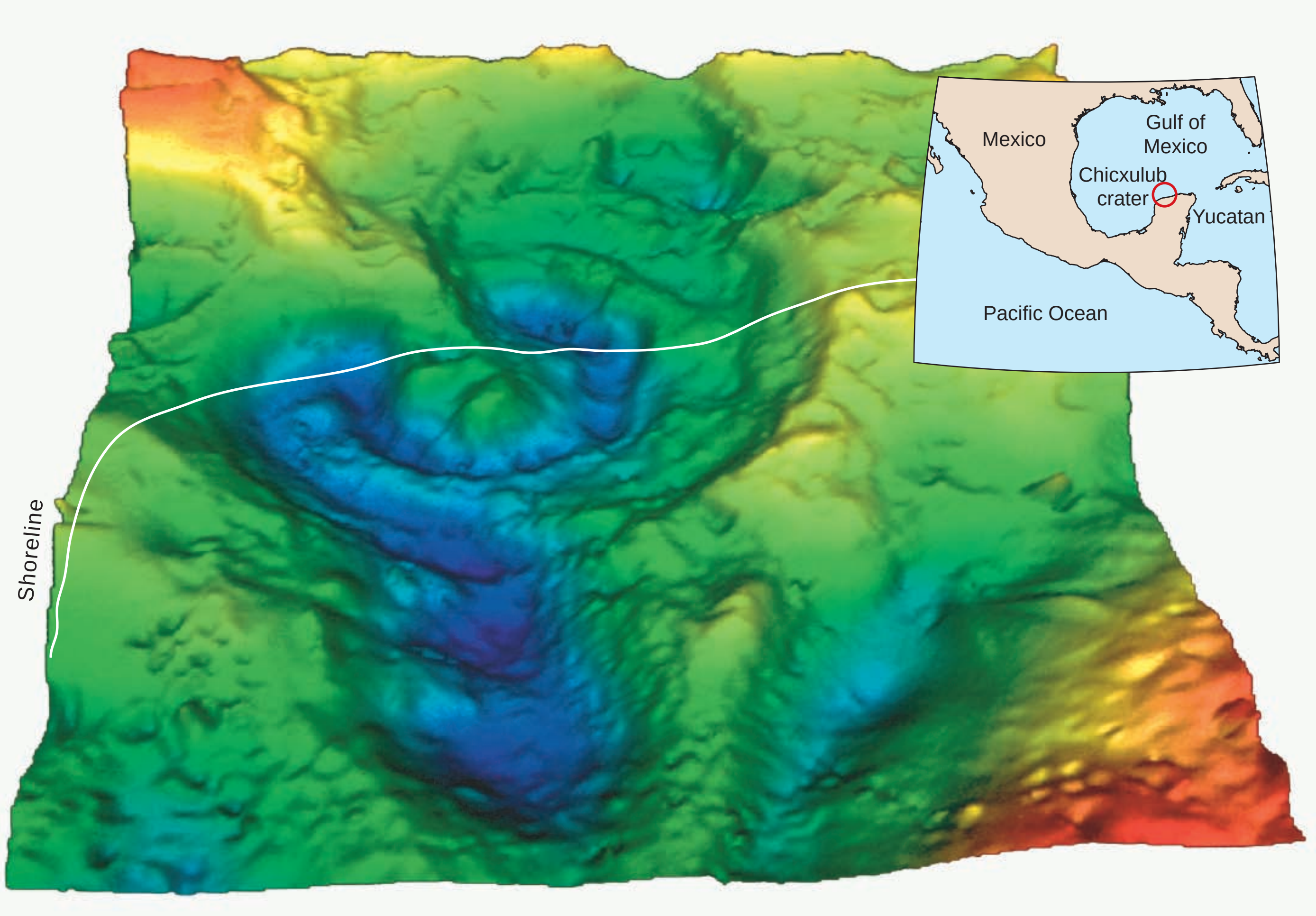
(C) This explosion was captured using an Earth-based telescope. *(Courtesy of P. McGregor)*

FIGURE 25.29 **The collision of comet Shoemaker-Levy 9 with Jupiter** shows that collisions between solar system bodies still occur today. These events occurred in July 1994 and are the first such collisions on another planet ever seen by humans.

Conclusions

We live in an extraordinary period of geologic exploration. We have explored all of the planets except Pluto, with spacecraft flybys or orbital missions. By studying other planetary bodies, we gain a greater understanding of our own Earth. Its size and composition are just right for the development of a tectonic system that recycles the lithosphere, creates continents and ocean basins, and concentrates ores and minerals. Earth's gravitational field is strong enough to hold an atmosphere. Earth is just the right distance from the Sun so that water can exist as solid, liquid, and vapor and can move in a hydrologic cycle. If the planet were a little closer to the Sun, our oceans would evaporate; if farther from it, the oceans would freeze solid. Studying other planets has taught us that Earth is a small place, an oasis in space, a home we are still trying to understand.

GeoLogic   *Chicxulub: Smoking Gun?*



(Courtesy of V. Sharpton/Lunar and Planetary Institute)

A major extinction of many forms of life, on land and sea, and including dinosaurs, marks the boundary between the Cretaceous and Tertiary time periods. What could have caused the extinction?

Observations

1. Iridium concentrations are high in meteoritic material, but low in rocks found at Earth's surface.
2. High concentrations of iridium occur in sedimentary layers formed at the transition between the Cretaceous and Tertiary time periods (65 million years ago) .
3. Fine fragments of minerals in the iridium layer have planar microfeatures that form only at intense but short-lived pressures.
4. The iridium layer is thickest in the areas near the Yucatan peninsula of southern Mexico.
5. Gravity surveys show that a large (nearly 200 km diameter) circular basin is buried below several kilometers of sediment in the Yucatan peninsula.

Interpretations

Though they took decades to accumulate, once in place these facts rapidly led to the earth-shaking interpretation that our planet was struck by a large asteroid 65 million years ago. According to this widely accepted theory, it's impact scattered Ir-rich ejecta across much of the world. The passage of the shock wave though the crust created microscopic shock features in mineral grains. The impact excavated a large depression that rapidly collapsed and a central peak and surrounding moat formed. Many scientists are also convinced that the fine dust blasted into the atmosphere blocked the Sun and helped cause the **mass extinction** that included the dinosaurs.

Are there problems with this interpretation? Of course there are. For example, why was the extinction selective, taking some of the tiniest marine plankton and the biggest animals on the continents, but leaving others unscathed? Nonetheless, the evidence is overwhelming that an impact occurred. The possible relation of the impact to extinction will drive continued research in attempts to strengthen or ultimately reject the impact-extinction connection.

KEY TERMS

accretion (p. 730)
asteroid (p. 751)
comet (p. 752)
differentiation (p. 755)
ejecta blanket (p. 730)
gas giant (p. 726)
icy planetary body (p. 727)
impact crater (p. 728)
inner planet (p. 726)
mare (p. 730)
mass extinction (p. 758)
meteorite (p. 728)
multiring basin (p. 730)
nebula (p. 753)
outer planet (p. 726)
planetesimal (p. 754)
ray (p. 730)
tidal heating (p. 742)

REVIEW QUESTIONS

1. Explain the meaning of the color code in the color bars in Table 25.1.
2. What geologic process has been most significant in modifying the surfaces of the Moon, Mercury, and Mars?
3. Outline the stages in the production of a crater by the impact of a meteorite. What geologic features are produced by impact?
4. How are craters modified with time?
5. Explain how a geologic time scale was developed for events in the Moon's history.
6. Outline the major events in lunar history.
7. Compare and contrast the geology of Mercury with that of the Moon.
8. Why is the Moon so poor in water and iron if it formed close to Earth, where both materials are abundant?
9. Describe the volcanoes on Mars.
10. What tectonic features are found on Mars?
11. Describe the fluvial features on the surface of Mars. How do they compare with fluvial features on Earth?
12. Describe the surface features generated by wind on Mars.
13. Compare and contrast the surface features of Venus with those on Earth and Mars.
14. Compare and contrast the sizes, densities, compositions, and surface features of the four large moons of Jupiter.
15. Why are the surfaces of the Galilean satellites of Jupiter so different in age? In composition and density?
16. Explain why Io is still volcanically active, whereas the Moon, which has a similar size and density, is not.
17. What is the significance of the major surface features on the Saturnian moon Enceladus?
18. How is Earth geologically unique among the planetary bodies of the solar system?
19. Contrast the compositions of asteroids and comets.
20. Why is there such a great composition and size difference between the inner and the outer planets?
21. What do you think is the most common rock type on the surfaces of the inner planets? On the moons of the outer planets?

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- Quantitative Problems
- Critical Thinking Exercises
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- Animations of the formation of the solar system
- Video tour of the planets
- Flyover of Valles Marineris, the Grand Canyon of Mars
- A direct link to the Companion Website