9.0 Planetary Geology: Earth and the Other Terrestrial Worlds

Think back to a time when you went for a walk or a drive through the open countryside. Did you see a valley? If so, the creek or river that carved it probably still flows at the bottom. Were the valley walls composed of lava, telling of an earlier time when molten rock gushed from volcanoes? Or were they made of neatly layered sedimentary rocks that formed when ancient seas covered the area? Were the rock layers tilted? That's a sign that movements of the Earth's crust have pushed the rocks around.

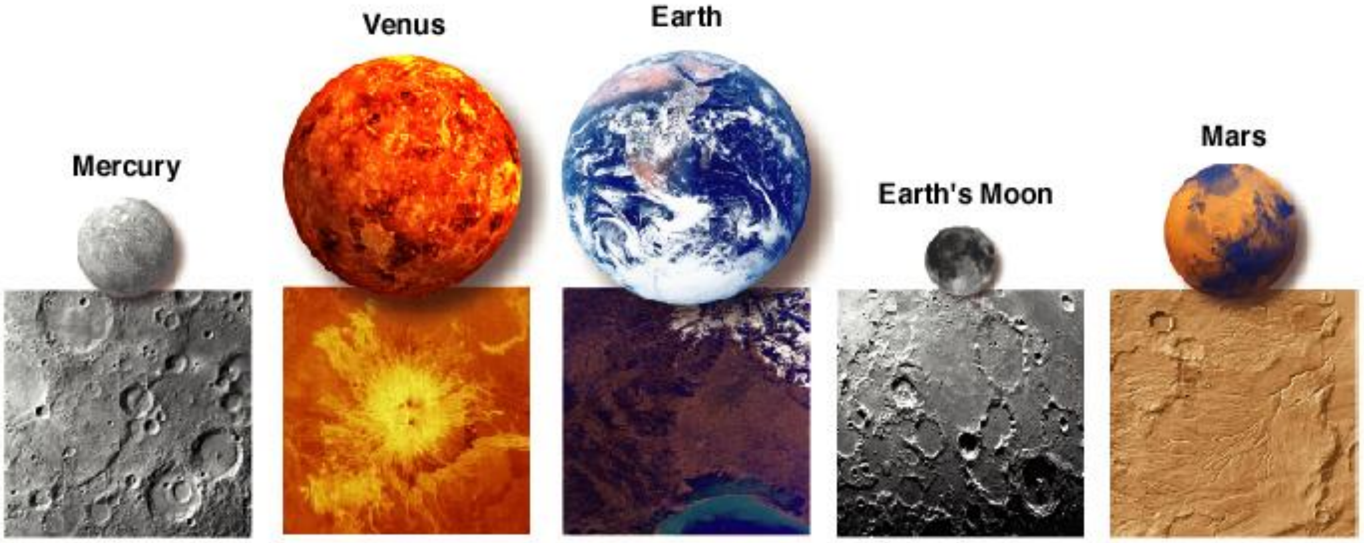
Since the beginning of the space age, we've been able to make similar observations and ask similar questions about geological features on other worlds. As a result, we can now make detailed geological comparisons among the different planets. We've learned that, even though all the terrestrial worlds are similar in composition and formed at about the same time, their geological histories have differed because of a few basic properties of each world. Thus, by comparing the geologies of the terrestrial worlds, we can learn much more about the Earth.

9.1 Comparative Planetary Geology

The five terrestrial worlds—Mercury, Venus, Earth, the Moon, and Mars—share a common ancestry in their birth from the solar nebula, but their present-day surfaces show vast differences. Mercury and the Moon are battered worlds densely covered by craters except in areas that appear to be volcanic plains. Venus has volcanic plains that appear to have been twisted and torn by internal stresses, leaving bizarre bulges and odd volcanoes that dot the surface. Mars, despite its middling size, has the solar system's largest volcanoes and is the only planet other than Earth where running water played a major role in shaping the surface. Earth has surface features similar to all those on other terrestrial worlds and more—including a unique layer of living organisms that covers almost the entire surface of the planet. Our purpose in this chapter is to understand how the profound differences among the terrestrial surfaces came to be.

The study of surface features and the processes that create them is called geology. The root geo means "Earth," and geology originally referred only to the study of the Earth. Today, however, we speak of planetary geology, the extension of geology to include all the solid bodies in the solar system, whether rocky or icy.

Geology is relatively easy to study on Earth, where we can examine the surface in great detail. People have scrambled over much of the Earth's surface, identifying rock types and mapping geological features. We've pierced the Earth's surface with 10-kilometer-deep drill shafts and learned about the deeper interior by studying seismic waves generated by earthquakes. Thanks to these efforts, today we have a fairly good



Global views of the terrestrial planets to scale and representative surface close-ups, each a few hundred kilometers across. The global view of Venus shows its surface without its atmosphere, based on radar data from the Magellan spacecraft; all other images are photos (or composite photos) taken from spacecraft.

understanding of the history of our planet's surface and the processes that shaped it.

Studying the geology of other planets is much more challenging. The Moon is the only alien world from which we've collected rocks, some gathered by the Apollo astronauts and others by Russian robotic landers in the 1970s. We can also study the dozen or so meteorites from Mars that have landed on Earth. Aside from these few rocks, we have little more than images taken from spacecraft from which to decode the history of the other planets over the past 4.6 billion years. It's like studying people's facial expressions to understand what they're feeling inside—and what their childhood was like! Fortunately, this decoding is considerably easier for planets than for people.

Spacecraft have visited and photographed all the terrestrial worlds. Patterns of sunlight and shadow on photographs taken from orbit reveal features such as cliffs, craters, and mountains. Besides ordinary, visible-light photographs, we also have spacecraft images taken with infrared and ultraviolet cameras, spectroscopic data, and in some cases three-dimensional data compiled with the aid of radar. Finally, we have close-up photographs of selected locations on all the terrestrial worlds but Mercury, taken by spacecraft that have landed on their surfaces. The result is that we now understand the geology of the terrestrial worlds well enough to make detailed and meaningful comparisons among them.

Solid as a Rock?

We often think of rocks as the very definition of strength, but rocks are not always as solid as they may seem. Most rocks are a hodgepodge of different minerals, each characterized by its chemical composition. For example, granite is a common rock composed of crystals of quartz (SiO_2), feldspar ($NaAlSi_3O_8$ is one of several varieties), and other minerals. Rocks are solid because of electrical bonds between the mineral molecules. But when these bonds are subjected to sustained stress over millions or billions of years, they can break and re-form, gradually allowing rocky material to deform and flow. In fact, the long-term behavior of rock is much like that of Silly Putty™, which stretches when you pull it slowly but breaks if you pull it sharply.

The strength of a rock depends on its composition, its temperature, and the surrounding pressure. Rocks of different composition are held together by molecular bonds of different strength. Even two very similar rocks may differ in strength if one contains traces of water: The water can act as a lubricant to reduce the rock's strength. Higher temperatures also make rocks weaker: Just as Silly Putty becomes more pliable if you heat it, warm rocks are weaker and more deformable than cooler rocks of the same type. Pressure can increase rock strength: The very high pressures found deep in planetary interiors can compress rocks so much that they stay solid even at temperatures high enough to melt them under ordinary conditions. (Most substances are denser as solids than as liquids, so the compression caused by high pressure tends to make things solid. Water is a rare exception, becoming less dense when it freezes—which is why ice floats in water.)

At high enough temperatures (usually over 1,000 K), some or all of the minerals in a rock may melt, making it molten (or partially molten, if only some minerals have melted). Just as different types of solid rock are more deformable than others, different types of rock behave differently when molten. Some molten rocks are runny like water, while others flow slowly like honey or molasses. We describe the "thickness" of a liquid with the technical term viscosity: Water has a low viscosity because it flows easily, while honey and molasses have much higher viscosities because they flow slowly. As we'll soon see, molten rock viscosities are very important to understanding volcanoes.

9.4 Shaping Planetary Surfaces

When we look around the Earth, we find an apparently endless variety of geological surface features. The diversity increases when we survey the other planets. But on closer examination, geologists have found that almost all the features observed result from just four major geological processes that affect planetary surfaces:

- Impact cratering: the excavation of bowl-shaped depressions (impact craters) by asteroids or comets striking a planet's surface.
- Volcanism: the eruption of molten rock, or lava, from a planet's interior onto its surface.
- Tectonics: the disruption of a planet's surface by internal stresses.
- Erosion: the wearing down or building up of geological features by wind, water, ice, and other phenomena of planetary weather.

Planetary geology once consisted largely of cataloging the number and kinds of geological features found on the planets. The field has advanced remarkably in recent decades, however, and it is now possible to describe how planets work in general and what geological features we expect to find on different planets. This progress has been made possible by a detailed examination of the geological processes and the determination of what factors affect and control them.

Understanding Geological Relationships

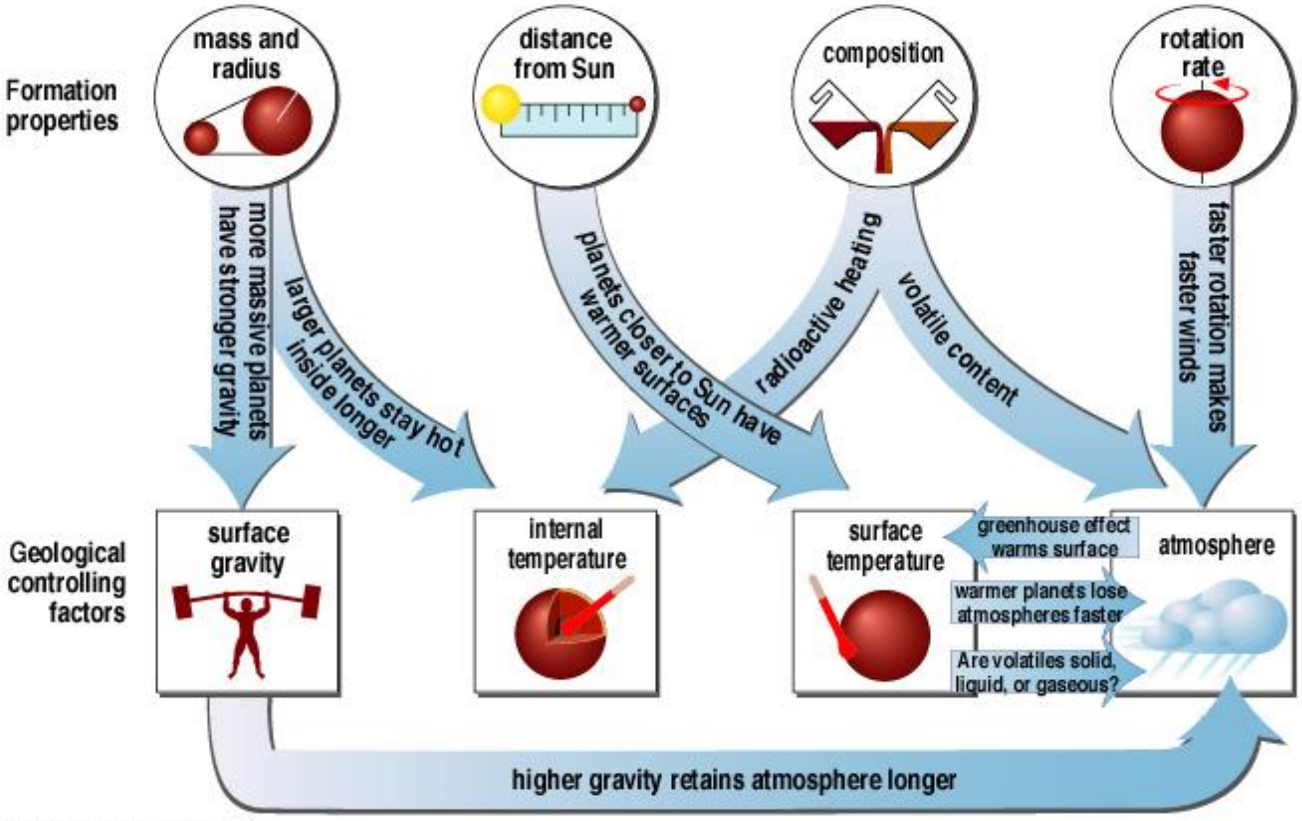
We can understand the fundamental ideas of comparative geology by exploring just a few key cause-and-effect relationships. Some of the important relationships are fairly easy to see. For example, a planet can have active volcanoes only if it has a sufficiently hot interior; and water, a major agent of erosion, remains liquid only if the planet has a temperature in the proper range and an atmosphere with sufficient pressure. Other relationships are subtler, such as that between the presence of an atmosphere and the planetary surface temperature. We can use flowcharts (or "concept maps") to help us keep track of the most important geological relationships.

The figure below shows one such planetary flowchart. The first row lists four formation properties with which each planet was endowed at birth: size (mass and radius), distance from the Sun, chemical composition, and rotation rate. These properties generally remain unchanged throughout a planet's history, unless the planet suffers a giant impact. The second row lists four geological controlling factors that drive a planet's geological activity: surface gravity, internal temperature, surface temperature, and the characteristics of the planet's atmosphere. Before we move on, let's briefly discuss how to interpret blocks and arrows on the flowchart:

Each block represents a particular property, controlling factor, or process.

Each arrow represents a cause-and-effect relationship between one block and another. (There may be other connections besides those shown; the figure includes only those that have substantial effects on geology.)

Arrows from the first row to the second row show how a planet's formation properties help determine the geological controlling factors. The single arrow pointing from mass and radius to



surface gravity shows that the strength of gravity at the surface is determined solely by size, in accord with Newton's law of gravity. Two arrows point to internal temperature, indicating that the formation properties of size and composition both affect it: Size is the most important factor in determining how rapidly a planet loses its internal heat, and composition—particularly the amount of radioactive elements—determines how much new heat is released in the interior. Other arrows from the first to the second row show that a planet's surface temperature depends in part on its distance from the Sun and that its atmosphere is affected by both its composition and its rotation rate.

Arrows between the geological controlling factors show how they affect one another. Both surface gravity and surface temperature have arrows pointing to atmosphere, because a planet's ability to hold atmospheric gases depends on both how fast the gas molecules move (which depends on temperature) and the strength of the planet's gravity. A second arrow from surface temperature to atmosphere shows that the temperature also influences what substances exist as gases (versus solid or liquid). The atmosphere, in turn, points back to surface temperature because a thick atmosphere can make a planet's surface warmer than it would be otherwise (through the greenhouse effect).

Time Out to Think

To make sure you understand the planetary flowchart, answer the following questions: (1) What planetary formation properties determine whether a planet's interior is hot, and why? (2) How does surface gravity affect a planet's atmosphere, and why?

The planetary flowcharts in this chapter contain all the information needed for a conceptual model of how planetary geology works—a model that allows us to answer questions about why different planets have different geological features. In the sections that follow, we will add each of the four geological processes (impact cratering, volcanism, tectonics, and erosion) to the set of relationships we have just covered, ending up with a fairly complete model for planetary geology. You do not need to memorize the model in this graphical form; instead, use it to help you understand planetary geology. You should also think about how you could adapt this technique of developing a conceptual model to any other problem that interests you.

Impact Cratering

Impact cratering occurs when a leftover planetesimal (such as a comet or an asteroid) crashes into the surface of a terrestrial world. Impacts can have devastating effects on planetary surfaces, which we can see both from the impact craters left behind and from laboratory experiments that reproduce the impact process. Impactors typically hit planets at speeds between 30,000 and 250,000 km/hr (10–70 km/s) and pack enough energy to vaporize solid rock and excavate a crater (the Greek word for "cup"). Craters are generally circular because the impact blasts out material in all directions, no matter which direction the impactor came from. A typical crater is about 10 times wider than the impactor that created it, with a depth about 10–20% of the crater width. Thus, for example, a 1-kilometer-wide impactor creates a crater about 10 kilometers wide and 1–2 kilometers deep. Debris from the blast, called ejecta, shoots high into the atmosphere and then rains down over a large area. If the impact is large enough, some of the atmosphere may be blasted away into space, and some of the rocky ejecta may completely escape from the planet.

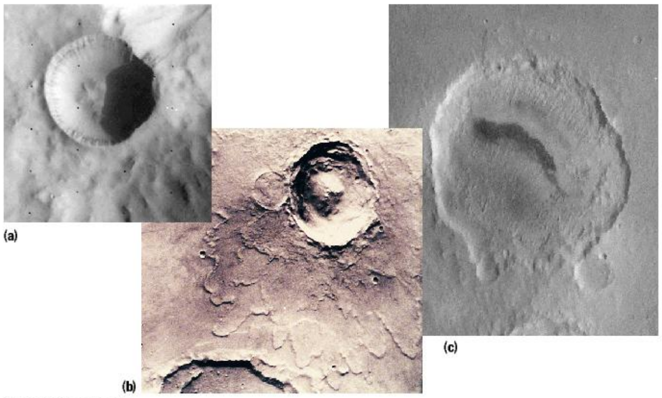
Craters come in all sizes, but small craters far outnumber large ones because there are far more small objects orbiting the Sun than large ones. Very large impacts can form impact basins. The lunar maria, easily visible with binoculars, are impact basins up to 1,100 kilometers across. (Maria is the Latin word for "seas"; they got their name because their smooth appearance reminded early observers of oceans.) These large impacts violently fractured the Moon's lithosphere, making cracks through which molten lava later escaped to flood the impact basins; when the lava cooled and solidified, it left a smooth surface in the region of the lava flood. The impacts that made the largest basins were so violent they sent out ripples that left tremendous multi-ring basins shaped like bull's-eyes.

The present-day abundance of craters on a planet's surface tells us a great deal about its geological history. Even though impacts still occur today, the vast majority of craters formed during the "rain of rock and ice" that ended around 3.8 billion years ago. At that time, the terrestrial worlds were saturated (completely covered) with impact craters. A surface region that is still saturated with craters, such as the lunar highlands, must have remained essentially undisturbed for the last 3.8 billion years. In contrast, the original craters must have been somehow "erased" in regions that now have few craters, such as the lunar maria. The flood of lava that formed the lunar maria covered any craters that had formed inside the impact basin, and the few craters that exist today within the maria must have formed from impacts occurring after the lava flows solidified. These craters tell us that the impact rate since the end of heavy bombardment has been quite small: Radioactive dating of moon rocks shows that the maria are 3–3.5 billion years old, but they have only 3% as many craters as the lunar highlands.

Time Out to Think

Earth must also have been saturated with impact craters early in its history, but we see relatively few impact craters on Earth today. What processes erase impact craters on Earth?

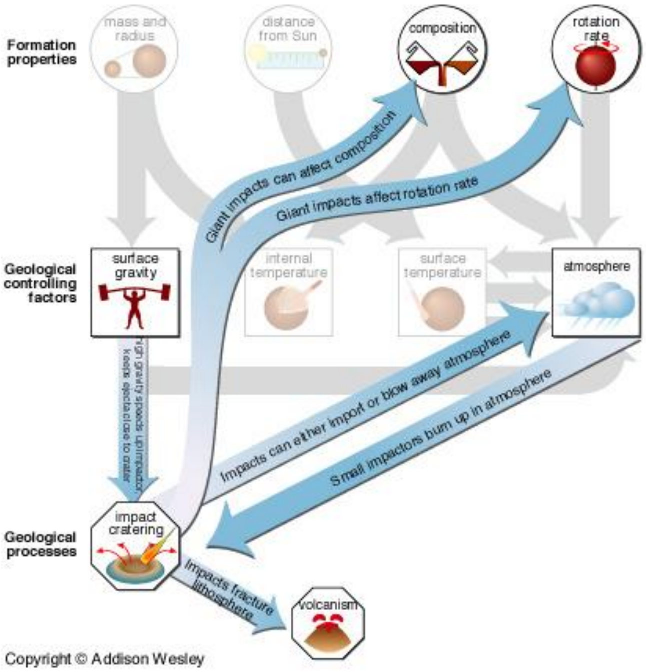
Craters with unusual shapes provide additional clues about surface conditions, as we can see by comparing craters on Mars. Craters in rocky surfaces usually have a simple bowl shape. However, some Martian craters look as if they were formed in mud, suggesting that underground water or ice vaporized upon impact and lubricated the flow of ejecta away from the crater. Other craters lack a sharp rim and bowl-shaped floor, suggesting that geological processes such as erosion have altered their shape over time. Planetary geologists must be cautious in interpreting unusually shaped craters, because impacts are not the only process that can form craters. Fortunately, craters created by other processes, such as volcanism, tend to have distinctly different shapes than impact craters.



Crater shapes on Mars tell us about Martian geology. These photos were taken from orbit by the Viking spacecraft. (a) Many craters are bowl-shaped. (b) Impacts into icy ground may form muddy ejecta. (c) Ancient Martian rains apparently eroded this crater.

The most common impactors are sand-size particles called micrometeorites when they impact a surface. Such tiny particles burn up as meteors in the atmospheres of Venus, Earth, and Mars. But on worlds that lack significant atmospheres, such as Mercury and the Moon, the countless impacts of micrometeorites gradually pulverize the surface rock to create a layer of powdery "soil." On the Moon, the Apollo astronauts and their rovers left marks in this powdery surface. Because of the lack of wind and rain, the footprints and tire tracks will last millions of years, but they will eventually be erased by micrometeorite impacts. In fact, over millions and billions of years, these tiny impacts smooth out rough crater rims much as erosion processes do more rapidly on Earth.

The figure below summarizes the important cause-and-effect relationships linking impact cratering with other geological processes, controlling factors, and formation properties. Note that the planet's formation properties do not greatly affect impact cratering, because the impactors do not come from the planet itself. Craters formed on all the terrestrial worlds, especially early in their histories. But giant impacts can affect formation properties by altering a planet's composition or rotation rate. In addition, impacts affect features



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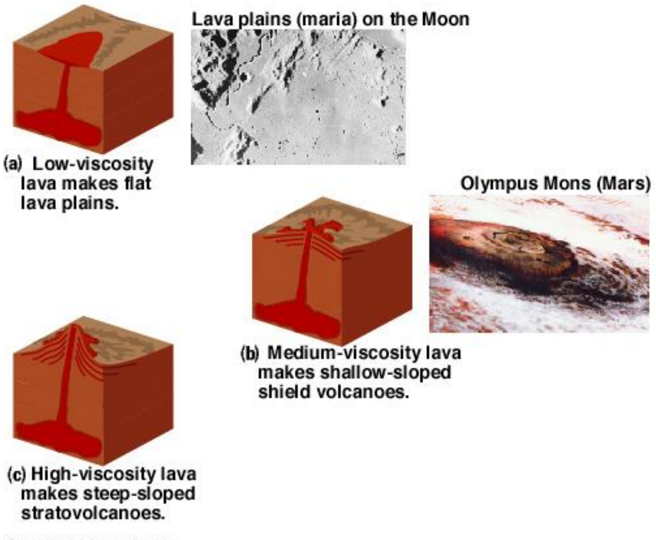
made by other geological processes. Apart from simply obliterating volcanoes, cliffs, or riverbeds, impacts can fracture the lithosphere, creating a path for volcanic lava to reach the surface (as occurred in the lunar maria). The relationships between impacts and the atmosphere are particularly interesting: Not only can an atmosphere burn up small impactors, but the impactors themselves can either bring in atmospheric ingredients or blast away some of the atmosphere. Before you read on, take a bit of time to analyze the remaining arrows and make sure all the connections make sense to you.

Volcanism

We find evidence for volcanoes and lava flows on all the terrestrial planets, as well as on a few of the moons of the outer solar system. (The moons may have "lavas" of water or other normally icy materials.) Volcanic surface features differ from one world to another, but some general principles apply.

Volcanoes erupt when underground molten rock, or magma, finds a path through the lithosphere to the surface. Magma rises for two main reasons: First, molten rock is generally less dense than solid rock, so it has a natural tendency to rise. Second, a magma chamber may be squeezed by tectonic forces, driving the magma upward under pressure. Any trapped gases expand as magma rises, sometimes leading to dramatic eruptions.

The structure of a volcanic flow depends on the viscosity of the lava that erupts onto the surface. The rock type known as basalt makes relatively low-viscosity lava when molten because it is made of relatively short molecular chains that don't tangle with one another. Temperature affects lava viscosity as well: The hotter the lava, the more easily the chains can jiggle and slide along one another and the lower the viscosity. The amount of water or gases trapped in the lava also affects viscosity. Such materials can act as a lubricant, decreasing the viscosity of subsurface magma. But when lavas erupt, materials such as water may form gas bubbles that increase the viscosity. (You can understand why bubbles increase viscosity by thinking about how much higher a "mountain" you can build with bubble-bath foam than you can with soapy water.)



(a) Low-viscosity lava makes flat lava plains.

(b) Medium-viscosity lava makes shallow-sloped shield volcanoes.

(c) High-viscosity lava makes steep-sloped stratovolcanoes.

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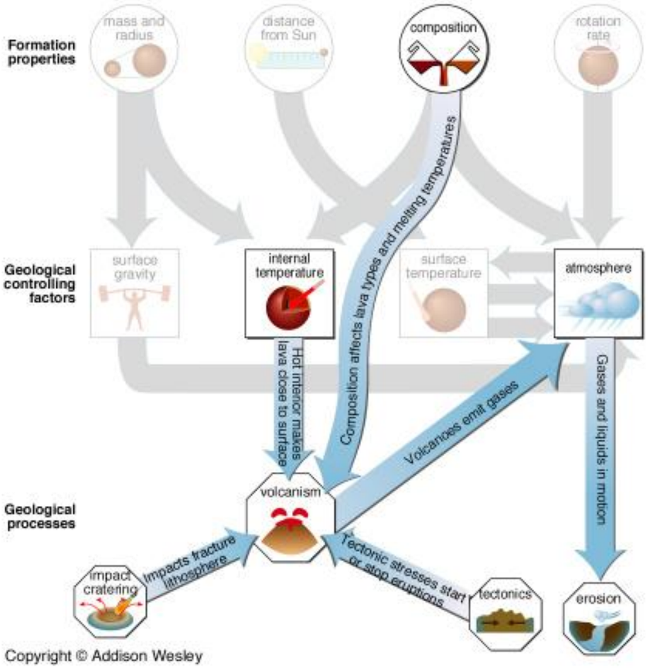

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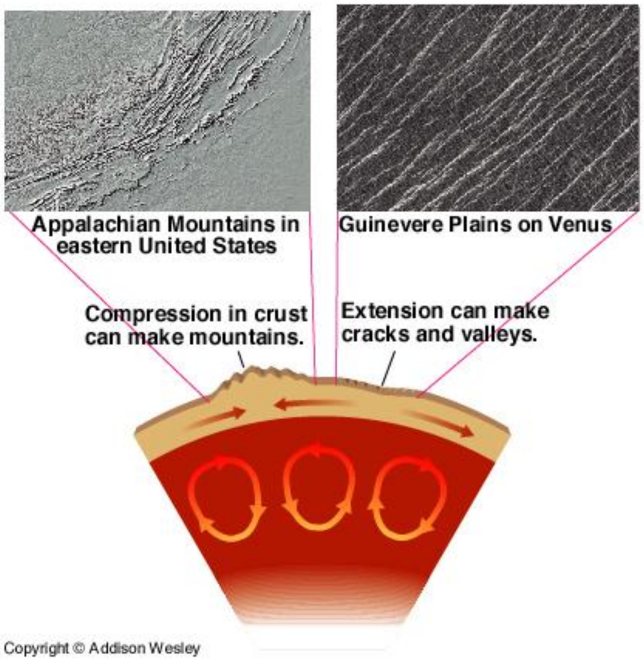
The runniest basalt lavas flow far and flatten out before solidifying, creating vast volcanic plains such as the lunar maria. Somewhat more viscous basalt lavas solidify before they can completely spread out, resulting in shield volcanoes (so-named because they are shield-shaped). Shield volcanoes can be very tall, but they are not very steep; most have slopes of only 5°–10°. The mountains of the Hawaiian Islands are shield volcanoes; measured from the ocean floor to their summits, the Hawaiian mountains are the tallest (and widest) on Earth. Tall, steep stratovolcanoes such as Mount St. Helens are made from much more viscous lavas that can't flow very far befor solidifying.

The figure above summarizes the geological relationships that involve volcanism. The main point to keep in mind is that internal temperature exerts the greatest control over volcanism: A hotter interior means that lava lies closer to the surface and can erupt more easily. The formation property of composition is also very important, because it determines the melting temperatures and viscosities of lavas that erupt and therefore what types of volcanoes form. Volcanism is connected to other geological processes in several ways beyond the simple fact that lava flows can cover up or fill in previous geological features. Tectonics and volcanism often go together: Tectonic stresses can force lava to the surface or cut off eruptions. Another connection reveals far-reaching effects: Volcanism affects erosion indirectly, because volcanoes are the primary source of gases in the current terrestrial planet atmospheres. Before continuing, be sure you understand all the relationships shown in the figure.

Tectonics

We are now ready to discuss tectonics, the third major geological process in our model. The root of the word tectonics comes from Greek legend, in which Tecton was a carpenter. In geology, tectonics refers to the processes that do "carpentry" on planetary surfaces—that is, to the internal forces and stresses that act on the lithosphere to create surface features.

Several types of internal stress can drive tectonic activity. On planets with internal convection, the strongest type of stress often comes from the circulation of the convection cells themselves. The tops of convection cells can drag against the lithosphere, sometimes forcing sections of the lithosphere together or apart. On Earth, these forces have broken the lithosphere into plates that move over, under, and around each other in what we call plate tectonics. Even if the crust does not break into plates, stresses from underlying convection cells may create vast mountain ranges, cliffs, and valleys. A second type of stress associated with convection comes from individual rising plumes of hot mantle material that push up on the lithosphere. (The Hawaiian Islands result from such a plume.) Internal stress can also arise from temperature changes in the planetary interior. For example, the crust may be forced to expand and stretch if the planetary interior heats up from radioactive decay. Conversely, the mantle and lithosphere must respond when a planetary core cools and contracts, leading to planet-wide compression forces. Tectonic stresses can even occur on more local scales; for example, the weight of a newly formed volcano can bend or crack the lithosphere beneath it.



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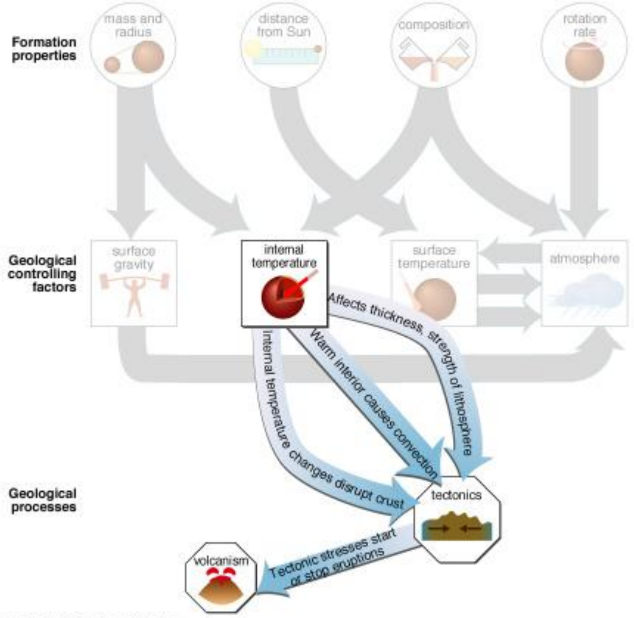
Tectonic features take an incredible variety of forms. Mountains may rise where the crust is compressed. Such crustal compression helped create the Appalachian Mountains of the eastern United States. Huge valleys and cliffs may result where the crust is pulled apart; examples include the Guinevere Plains on Venus and New Mexico's Rio Grande Valley. (The river named Rio Grande came after the valley formed from tectonic processes.) Tectonic forces may bend or break rocks, and tectonic activity on Earth is always accompanied by earthquakes. Other worlds undoubtedly experience "planet-quakes," and planetary geologists are eager to plant seismometers on them to probe their interiors.



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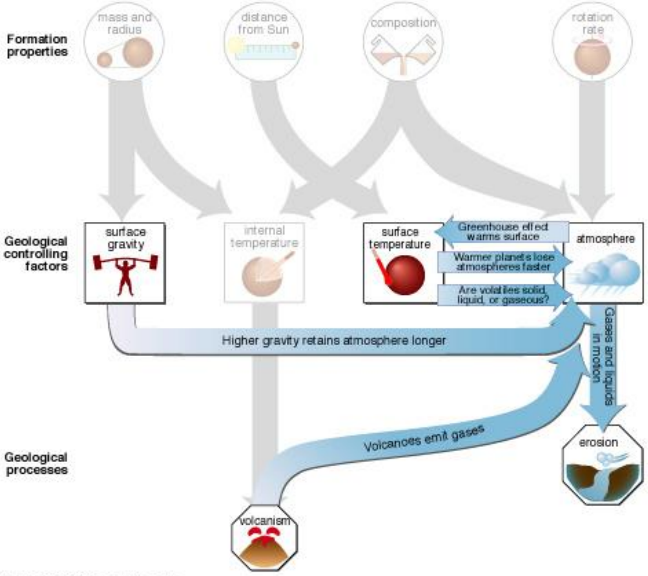
The figure above summarizes the connections between tectonics and other geological processes and properties. Like volcanism, tectonics is most likely on larger worlds that remain hot inside. Tectonics may also have been important in the past on smaller worlds that underwent major shrinking or expansion.

Erosion

The last of the four major geological processes to be added to our model is erosion, which encompasses a variety of processes connected by a single theme: the breakdown and transport of rocks by volatiles. The term volatile means "evaporates easily" and refers to substances—such as water, carbon dioxide, and methane—that are usually found as gases, liquids, or surface ices on the terrestrial worlds. Wind, rain, rivers, flash floods, and glaciers are just a few examples of processes that contribute to erosion on Earth. Erosion not only breaks down existing geological features (wearing down mountains and forming gullies, riverbeds, and deep valleys), but also builds new ones (such as sand dunes, river deltas, and lakebed deposits). If enough material is deposited over time, the layers can compact to form sedimentary rocks.

Virtually no erosion takes place on worlds without a significant atmosphere, such as Mercury and the Moon. But planets with atmospheres can have significant erosional activity. Larger planets are better able to generate atmospheres by releasing gases trapped in their interiors; their stronger gravity also tends to prevent their atmospheres from escaping to space. In general, a thick atmosphere is more capable of driving erosion than a thin atmosphere, but a planet's rotation rate is also important. Slowly rotating planets like Venus have correspondingly slow winds and therefore weak or nonexistent wind erosion. Surface temperature also matters: Erosion isn't very effective if most of the volatiles stay frozen on the surface, but it can be very powerful when volatiles are able to evaporate and then recondense as rain or snow. The figure above summarizes the connections between erosion and other geological processes and properties.



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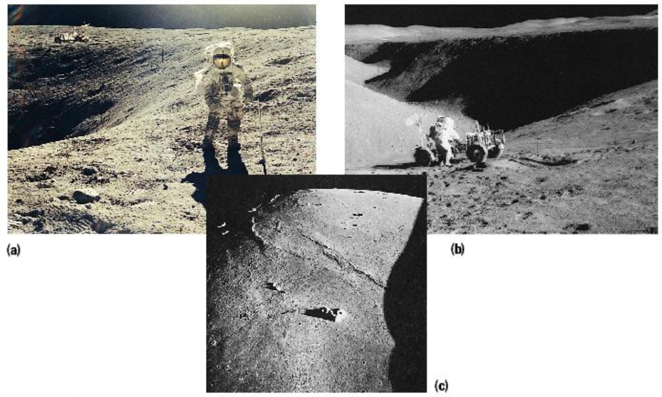
9.5 A Geological Tour of the Terrestrial Worlds

Now that we've examined the processes and properties that shape the geology of the terrestrial worlds, we're ready to return to the issue of why the terrestrial worlds ended up so geologically different from one another. We'll take a brief "tour" of the terrestrial worlds. We could organize the tour by distance from the Sun, by density, or even by alphabetical order. But we'll choose the planetary property that has the strongest effect on geology: size, which controls a planet's internal heat. We'll start with our Moon, the smallest terrestrial world.

The Moon (1,731-km radius, 1.0 AU from Sun)

On a clear night, you can see much of the Moon's global geological history with your naked eye. The Moon is unique in this respect; other planets are too far away for us to see any surface details, and Earth is so close that we see only the local geological history. Twelve Apollo astronauts visited the lunar surface between 1969 and 1972, taking photographs, making measurements, and collecting rocks. Thanks to these visits and more recent observations of the Moon from other spacecraft, we know more about the Moon's geology than that of any other object, with the possible exception of the Earth.



Impact cratering and volcanism are the most important geological processes on the Moon. (a) Astronaut explores a small crater. (b) Site of an ancient lava river. (c) Lava flows filled impact basins to create maria like this one (Mare Imbrium). Wrinkles on the maria are evidence of minor tectonic forces.

As the Moon accreted, the heat of accretion melted its outer layers. The lowest-density molten rock rose upward through the process of differentiation, forming what is sometimes called a magma ocean. This magma ocean cooled and solidified during the heavy bombardment that took place early in the history of the solar system, leaving the Moon's surface crowded with craters. We still see this ancient, heavily cratered landscape in the lunar highlands. Lunar samples confirm that the highlands are composed of low-density rocks. As the bombardment tailed off, around 3.8 billion years ago, a few larger impactors struck the surface and formed impact basins.

Even as the heat of accretion leaked away, radioactive decay kept the Moon's interior molten long enough for volcanism to reshape parts of its surface. Between about 3 and 4 billion years ago, molten rock welled up through cracks in the deepest impact basins, forming the lunar maria. Because the lava that filled the maria rose up from the Moon's mantle, the maria contain dense, iron-rich rock that is darker in color than the rock of the lunar highlands. The contrasts between the light-colored rock of the highlands and the dark rock of the maria make the "man-in-the-Moon" pattern that some people imagine when they look at the full moon.

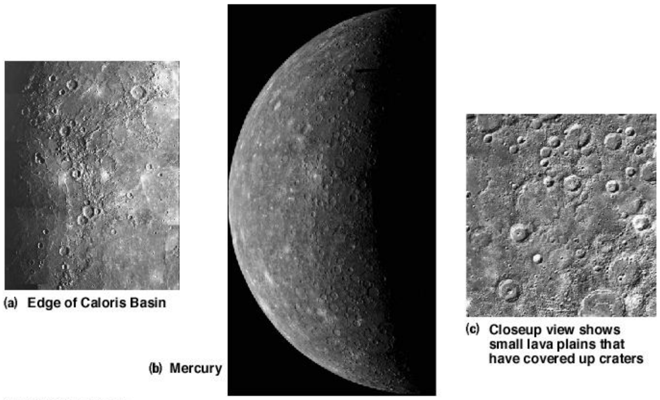
The lunar lavas must have been among the least viscous (runniest) in the solar system, perhaps because the lack of volatiles meant a lack of bubbles (which increase viscosity) in the erupting lava. The lava plains of the maria cover a large fraction of the lunar surface. Only a few small shield volcanoes exist on the Moon, and no steeper-sided stratovolcanoes have been found. Low-viscosity lavas also carved out long, winding channels. These channels must once have been rivers of molten rock that helped fill the lunar maria.

Almost all the geological features of the Moon were formed by impacts and volcanism, although a few small-scale tectonic stresses wrinkled the surface as the lava of the maria cooled and contracted). The Moon has virtually no erosion because of the lack of atmosphere, but the continual rain of micrometeorites has rounded crater rims. The heyday of lunar volcanism is long gone—3 billion years gone. Over time, the Moon's small size allowed its interior to cool, thickening the lithosphere. Today, the Moon's lithosphere probably extends to a depth of 1,000 km, making it far too thick to allow further volcanic or tectonic activity. The Moon has probably been in this geologically "dead" state for 3 billion years.

Despite its geological inactivity, the Moon is of prime interest to those hoping to build colonies in space. The Lunar Prospector arrived at the Moon in early 1998 and began mapping the surface in search of promising locations for a permanent human base. Although no concrete plans are yet in place, several nations are exploring the possibility of building a human outpost on the Moon within the next couple of decades.

Mercury (2,439-km radius, 0.39 AU from Sun)

Mercury is the least studied of the terrestrial worlds. Its proximity to the Sun makes it difficult to study through telescopes, and it has been visited by only one spacecraft: Mariner 10, which collected


(a) Edge of Caloris Basin

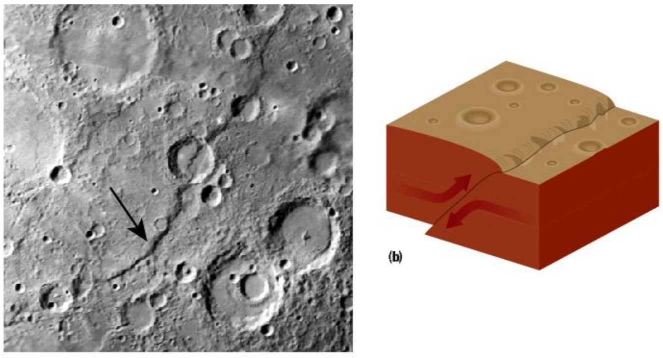
(b) Mercury

(c) Closeup view shows small lava plains that have covered up craters

data during three rapid flybys of Mercury in 1974–1975. Mariner 10 obtained images of only one hemisphere of Mercury, but the influence of Mercury's gravity on Mariner 10's orbit allowed planetary scientists to determine Mercury's mass and average density. Based on its relatively high density, Mercury must be about 61% iron by mass, with a core that extends to perhaps 75% of its radius. Mercury's high metal content is due to its formation close to the Sun, possibly enhanced by a giant impact that blasted away its outer, rocky layers.

Mercury has craters almost everywhere, indicating an ancient surface. A huge impact basin, called the Caloris Basin, covers a large portion of one hemisphere. Like the large lunar basins, the Caloris Basin has few craters within it, indicating that it must have been formed toward the end of the solar system's early period of heavy bombardment.

Despite the superficial similarity between their cratered surfaces, Mercury and the Moon also exhibit significant differences. Mercury has noticeably fewer craters than the lunar highlands. Smooth patches between many of the craters tell us that volcanic lava once flowed, covering up small craters. Mercury has no vast maria but has smaller lava plains almost everywhere, suggesting that Mercury had at least as much volcanism as the Moon.


(a)

(b)

Tectonic processes played a more significant role on Mercury than on the Moon, as evidenced by tremendous cliffs. The cliff shown in Figure 9.24a is several hundred kilometers long and up to 3 kilometers high in places; the central crater apparently crumpled during the cliff's formation. This cliff, and many others on Mercury, probably formed when tectonic forces compressed the crust (Figure 9.24b). However, nowhere on Mercury do we find evidence of extension (stretching) to match this crustal compression. Can it be that the whole planet simply shrank? Apparently so. Early in its history, Mercury gained much more internal heat from accretion and differentiation than did the Moon, owing to its larger proportion of iron and stronger gravity. Then, as the core cooled, it contracted by perhaps as much as 20 kilometers in radius. This contraction crumpled and compressed the crust, forming the many cliffs. The contraction probably also closed off volcanic vents, ending Mercury's period of volcanism.

Mercury lost its internal heat relatively quickly because of its small size. Its days of volcanism and tectonic shrinking probably ended within its first billion years. Mercury, like the Moon, has been geologically dead for most of its existence.

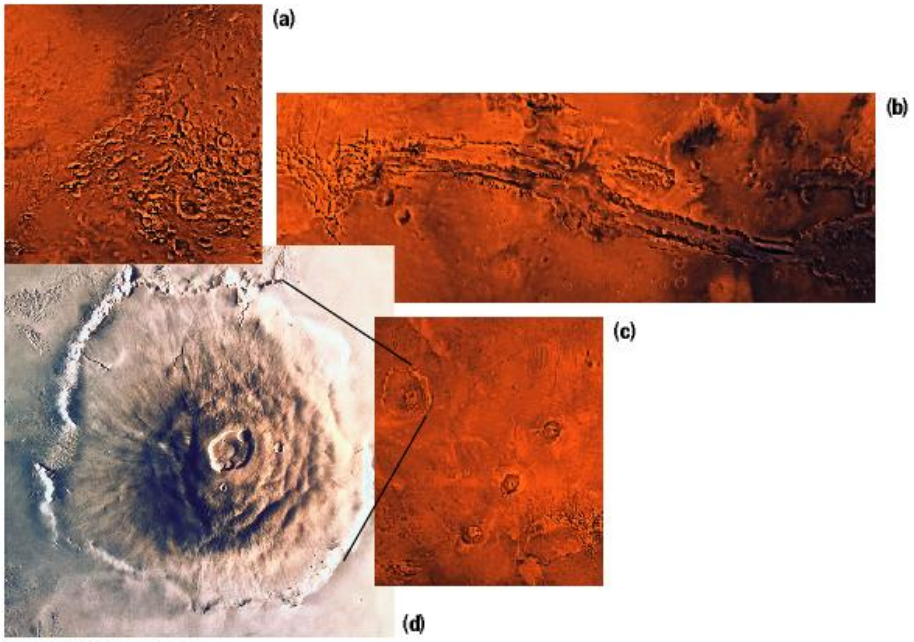
Time Out to Think

Geologists have discovered that the ejecta didn't travel quite as far away from craters on Mercury as it did on the Moon. Why not? (Hint: What planetary formation properties affect impact craters?)

Mars (3,396-km radius, 1.52 AU from Sun)

Several spacecraft studied Mars in the 1960s and 1970s, culminating with the impressive Viking missions in 1976. Each of the two Viking spacecraft deployed an orbiter that mapped the Martian surface from above and landers that returned surface images and regular weather reports for almost 5 years. More than 20 years passed before the next successful missions to Mars, the Mars Pathfinder mission and Mars Global Surveyor mission in 1997. These were followed by the wildly successful twin Mars Rovers that are still chugging along on Mars.

Martian Geology The Viking and Mars Global Surveyor images show a much wider variety of geological features than seen on the Moon or Mercury. Some areas of the southern hemisphere are heavily cratered, while the northern hemisphere is covered by huge volcanoes surrounded by extensive volcanic plains. Volcanism was expected on Mars—40% larger than Mercury, it should have retained a hot interior much longer. But no one knows why volcanism affected the northern hemisphere so much more than the southern hemisphere, or why the northern hemisphere on average is lower in altitude than the southern hemisphere.



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These photos of the Martian surface, taken from orbiting spacecraft, show that impact cratering has been an important process on Mars, but volcanism and tectonics have been even more important in shaping the current Martian surface. a The southern hemisphere of Mars is heavily cratered. The image spans several hundred kilometers. b Valles Marineris is a huge valley created in part by tectonic stresses. c A mantle plume below the Tharsis Bulge region was probably responsible for the volcanoes near the bottom of the image and the network of valleys near the top. d Olympus Mons—the largest shield volcano in the solar system—covers an area the size of Arizona and rises higher than Mt. Everest.

Mars has a long, deep system of valleys called Valles Marineris running along its equator. Named for the Mariner 9 spacecraft that first imaged it, Valles Marineris is as long as the United States is wide and almost four times deeper than the Grand Canyon. No one knows exactly how it formed; parts of the canyon are completely enclosed by high cliffs on all sides, so neither flowing lava nor water could have been responsible. Nevertheless, the linear "stretch marks" around the valley are evidence of tectonic stresses on a very large scale.

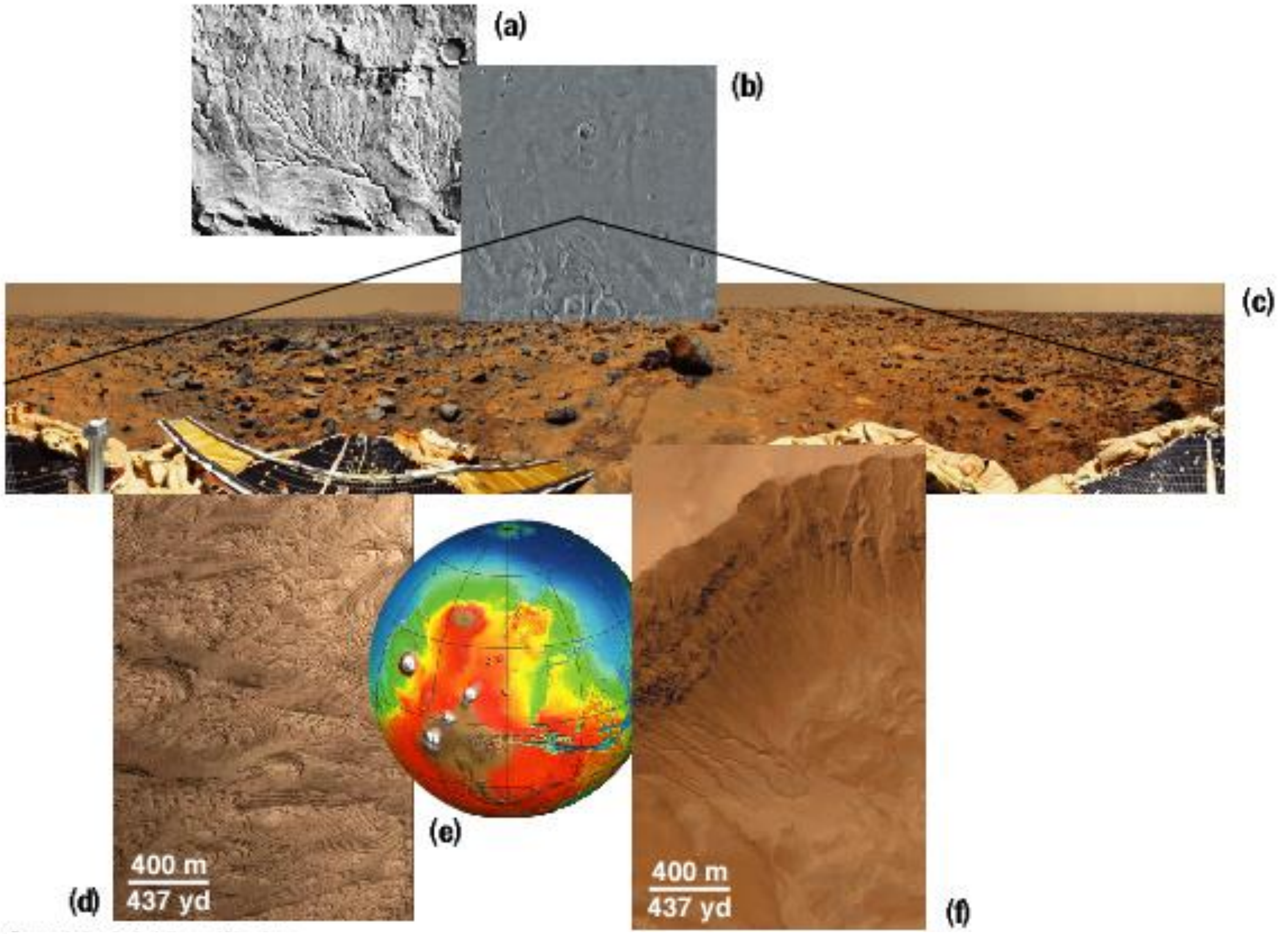
More cracks are visible on the nearby Tharsis Bulge, a continent-size region that rises well above the surrounding Martian surface. Tharsis was probably created by a long-lived plume of rising mantle material that bulged the surface upward while stretching and cracking the crust. The plume was also responsible for releasing vast amounts of basaltic lava that built up several gigantic shield volcanoes, including Olympus Mons, the largest shield volcano in the solar system. Olympus Mons has roughly the same shallow slope as the volcanic island of Hawaii, but it is three times larger in every dimension. Its base is some 600 kilometers across, making it large enough to cover an area the size of Arizona; it stands 26 kilometers high—some three times higher than Mount Everest.

How old are the volcanoes? Are they still active? In the absence of red-hot lava (none has been seen so far), the abundance of impact craters provides the best evidence. The Martian volcanoes are almost devoid of craters, but not quite. Planetary geologists therefore estimate that the volcanoes went dormant about a billion years ago. Geologically speaking, a billion years is not that long, and it remains possible that the Martian volcanoes will someday come back to life. However, the Martian interior is presumably cooling and its lithosphere thickening. At best, it's only a matter of a few billion more years before Mars becomes as geologically dead as the Moon and Mercury.

Martian Water The Martian robotic explorers have also revealed geological features unlike any seen on the Moon or Mercury—features caused by erosion. The upper left no doubt reminds you of a dry riverbed on Earth seen from above. The eroded craters visible on some of the oldest terrain suggest that rain fell on the Martian surface billions of years ago. In some places, erosion has even acted below the surface, where underground water and ice have broken up or dissolved the rocks. When the water and ice disappeared, a wide variety of odd pits and troughs were left behind. This process may have contributed to the formation of parts of Valles Marineris.

Underground ice may be the key to one of the biggest floods in the history of the solar system. The second image shows a landscape hundreds of kilometers across that was apparently scoured by rushing water. Geologists theorize that heat from a volcano melted great quantities of underground ice, unleashing a catastrophic flood that created winding channels and large sandbars along its way.

The Mars Pathfinder spacecraft went to this interesting region to see the flood damage close up. The lander released the Sojourner rover, named after Sojourner Truth, an African-American heroine of the Civil War era who traveled the nation advocating equal rights for women and blacks. The six-wheeled rover, no larger than a microwave



Unlike Mercury and the Moon, Mars shows unmistakable evidence of widespread erosion. The latest results point to the action of liquid water. (a) This Viking photo (from orbit) shows ancient riverbeds that were probably created billions of years ago. (b) This photo shows winding channels and sandbars that were probably created by catastrophic floods. (c) View from the floodplain (see b above) from the Mars Pathfinder; the Pathfinder landing site is now known as Carl Sagan Memorial Station. The Sojourner rover is visible near the large rock. (d) Close-up view of the floor of the eroded crater shown above. Billions of years ago, the crater was apparently a pond, and layer upon layer of sediment was deposited on the bottom. The water is long gone, and winds have since sculpted the layers into the astonishing patterns captured in this photograph from the Mars Global Surveyor. (e) Topographic map of Mars with low-lying regions in blue and higher elevations in red, brown, and white. The white patches are tall volcanoes; Valles Marineris cuts through the terrain to their right. Some planetary geologists believe that an ocean once filled the smooth, low-lying northern regions shown in dark blue. (f) This photograph from Mars Global Surveyor shows gullies on a crater wall; scientists suspect they were formed by water seeping out from the ground during episodic flash floods. The gullies are geologically young, but no one yet knows whether similar gullies may still be forming today.

oven, carried cameras and instruments to measure the chemical composition of nearby rocks. Together the lander and rover confirmed the flood hypothesis: Gentle, dry, winding channels were visible in stereo images; rocks of many different types had been jumbled together in the flood; and the departing waters had left rocks stacked against each other in just the same manner that floods do here on Earth.

In the decades since we first learned of past water on Mars, scientists have debated when water last flowed. Recent images from the Mars Global Surveyor have only deepened the mystery. The sculpted patterns in the crater shown in (d) were probably created as erosion exposed layer upon layer of sedimentary rock, much like the sedimentary layers visible in Earth's Grand Canyon. This suggests that ancient rains once filled the crater like a pond, with the sedimentary layers built up by material that settled to the bottom. Figure e, made from the spacecraft's precise topographic measurements, shows evidence of even more widespread water, suggesting that much of Mars's northern hemisphere was once covered by an ocean. Perhaps the most surprising finding is the presence of small gullies on the walls of many craters and valleys. The gullies probably formed when underground water broke out in episodic flash floods, carrying boulders and soil into a broad fan at the bottom of the slope. Moreover, the gullies must be geologically young, because they have not been covered over by ongoing dust storms, nor have small craters formed on their surfaces. Unfortunately, "young" can be quite ambiguous in a geological sense: No one knows if these gullies formed "just" millions of years ago or if some might still be forming today.

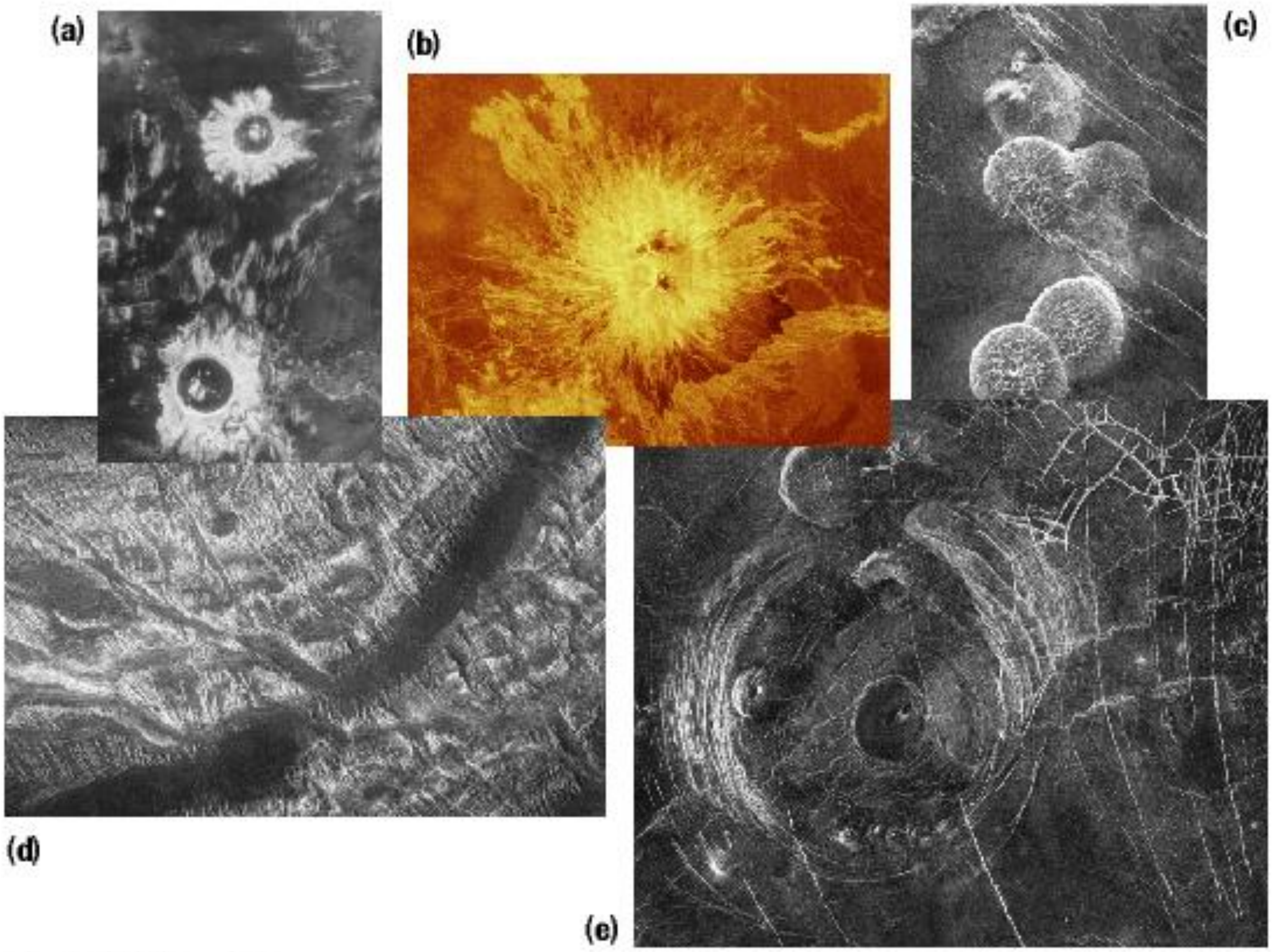
Even if water still flows on occasion, it seems clear that Mars was much wetter in the past than it is today. Ironically, Percival Lowell's supposition that Mars was drying up has turned out to be basically correct, even though he did not have real evidence to support it.

Venus (6,051-km radius, 0.72 AU from Sun)

Venus is a big step up in size from Mars—it is almost as big as Earth. Thus, we would expect it to have had an early geological history much like Earth's, with impact cratering, volcanism, and tectonics.

Venus's thick cloud cover prevents us from seeing through to its surface, but we can study its geological features with radar. Radar mapping involves bouncing radio waves off the surface from a spacecraft and using the reflections to create three-dimensional images of the surface. From 1990 to 1993, the Magellan spacecraft used radar to map the surface of Venus, discerning features as small as 100 meters across. During its 4 years of observations, Magellan returned more data than all previous planetary missions combined. Scientists have named almost all the geological features for female goddesses and famous women.

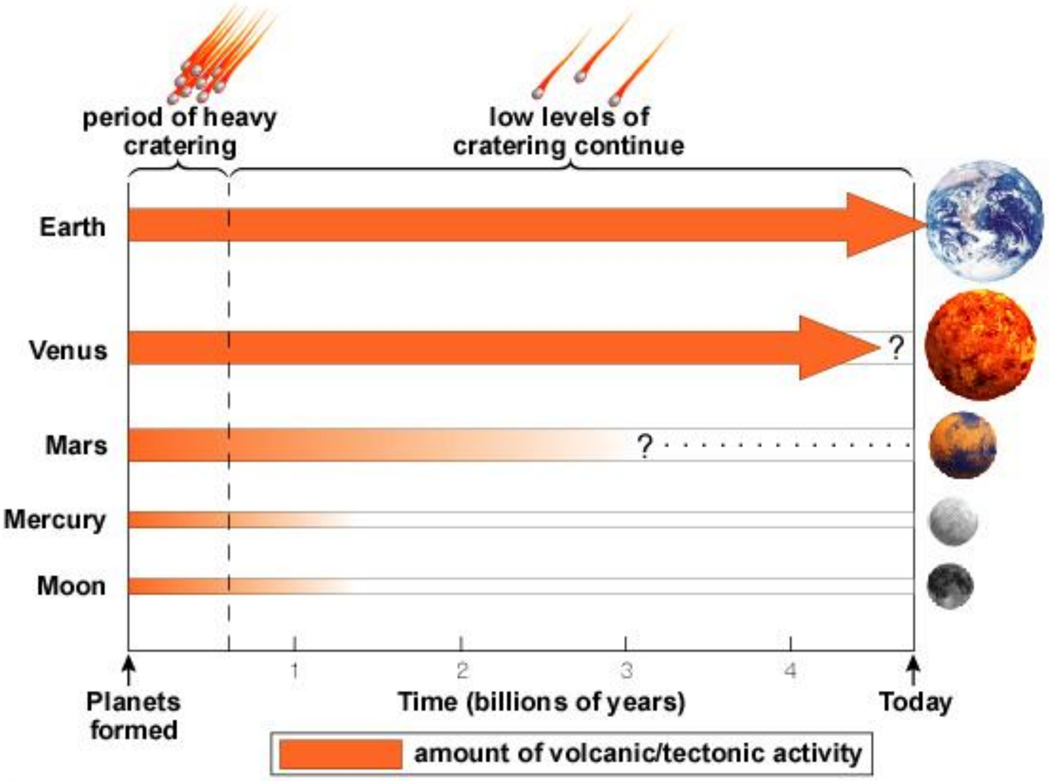
Venusian Impacts and Volcanism Most of Venus is covered by relatively smooth, rolling plains with few mountain ranges. The surface has some impact craters, but very few compared to the Moon or even Mars. Venus lacks very small craters, because small impactors burn up in its dense atmosphere. But large craters are also rare, indicating that they must be erased by other geological processes. Volcanism is clearly at work on Venus, as evidenced by an abundance of volcanoes and lava flows. Some are shield volcanoes, indicating familiar basaltic eruptions. Some volcanoes have steeper sides, probably indicating eruptions of a higher-viscosity lava.



The surface of Venus is covered with abundant lava flows and tectonic features, along with a few large impact craters. Because these images were taken by the Magellan spacecraft radar, dark and light areas correspond to how well radio waves are reflected, not visible light. Nonetheless, geological features stand out well. All images are several hundred kilometers across. a Impact craters like these are rare on Venus. b Shield volcanoes like this one are common on Venus. c These volcanoes were made from viscous lava. d Tectonic forces have fractured and twisted the crust in this region. e A mantle plume probably created the round corona, which is surrounded by tectonic stress marks.

Venusian Tectonics The most remarkable features on Venus are tectonic in origin. Its crust is quite contorted; in some regions, the surface appears to be fractured in a regular pattern. Many of the tectonic features are associated with volcanic features, suggesting a strong linkage between volcanism and tectonics on Venus. One striking example of this linkage is a type of roughly circular feature called a corona (Latin for "crown") that probably resulted from a hot, rising plume in the mantle. The plume pushed up on the crust, forming rings of tectonic stretch marks on the surface. The plume also forced lava to the surface, dotting the area with volcanoes.

Does Venus, like Earth, have plate tectonics that moves pieces of its lithosphere around? Convincing evidence for plate tectonics might include deep trenches and linear mountain ranges like those we see on Earth, but Magellan found no such evidence on Venus. The apparent lack of plate tectonics suggests that Venus's lithosphere is quite different from Earth's. Some geologists theorize that Venus's lithosphere is thicker and stronger, preventing its surface from fracturing into plates. Another possibility is that plate tectonics happens only occasionally on Venus. The uniform but low abundance of craters suggests that most of the surface formed around a billion years ago. Plate



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tectonics is one candidate for the process that wiped out older surface features and created a fresh surface at that time. For the last billion years, only volcanism, a bit of impact cratering, and small-scale tectonics have occurred.

Venusian Erosion? One might expect Venus's thick atmosphere to drive strong erosion, but the view both from orbit and from the surface suggests otherwise. The Soviet Union landed two probes on the surface of Venus in 1975. Before being destroyed by the 700 K heat, they returned images of a bleak, volcanic landscape with little evidence of erosion. Venus apparently lacks the rains and winds that drive erosion, probably because of its high surface temperature and slow rotation rate.

The lack of strong erosion on Venus leaves the tectonic contortions of its surface exposed to view, even though some probably approach a billion years in age. Earth's terrain might look equally stark and rugged from space if not for the softening influences of wind, rain, and life. Like Earth, Venus probably has ongoing tectonic and volcanic activity, although we have no direct proof of it.

Earth (6,378-km radius, 1.0 AU from Sun)

We've toured our neighboring terrestrial worlds and found a clear relationship between size and volcanic and tectonic activity. Thus, it should come as no surprise that Earth, the largest of the terrestrial worlds, has a high level of ongoing volcanism and tectonics.

The figure above summarizes the trends among the terrestrial worlds for volcanism and tectonics. It shows one of the key rules in planetary geology: Larger planets stay volcanically and tectonically active much longer than smaller planets. The situation for erosion is somewhat more complex. Earth has far more erosion than any other terrestrial world, but the most similar erosion is found on Mars, whose surface is sculpted by flowing water despite its small size.

Time Out to Think

Suppose another star system has a rocky terrestrial planet that is much larger than Earth. What kind of geology would you expect it to have: a surface saturated with craters, or widespread volcanic and tectonic activity? Explain.