U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ATLAS OF THE SOLAR SYSTEM
GEOLOGIC SERIES
GEOLOGY OF THE SOLAR SYSTEM
I–2596

Introduction

Geology has come a long way—less than 100 years after geology first became a profession that one could do for a living, geologists have plied their trade to the edge of our Solar System. Mapping the geology of the Solar System offers many challenges to the planetary geologist: making base maps from images taken by a spacecraft cruising past a planet at 15 km/s is like a land surveyor setting his surveying equipment up on a speeding truck and trying to get good information, and geologic field work, for the most part, has to be done robotically (at least for the near future). Familiar concepts take on new meaning in the context of the exotic landscapes, environments, and chemistries of the other planets: for example, lavas can be freezing cold (those that erupted on Ariel were probably 100 °C below zero); on Io, volcanic activity is so intense that the geology there changes almost as fast as our weather does; sea level, a common reference level on Earth, is not an option on oceanless planets; weathering on many airless bodies comes from solar or interstellar weather, such as solar winds, radiation effects, and meteoroid storms. Applying our geologic knowledge, with its inherent terrestrial (Earthlike) bias, to other bodies with very different conditions is clearly a challenge.

However, many of the traditional principles used by geologists for unraveling Earth's geologic history are general enough to be applicable to other planetary bodies. The methods are still valuable, even if the clues and the stories to be deciphered are much different. Studies of impact craters are of particular value in understanding and comparing the early processes throughout the Solar System. Although impact craters have not even been acknowledged as important on Earth by most geologists until recently, the principles of superposition and accumulation are familiar to geologists, and application of these traditional principles to craters allows them to use craters to help establish a chronology of major geologic events for many of the planets. After the initial phase of planetary formation from the accretion of planetesimals, impacts have occurred nearly randomly, so by determining the rate at which craters accumulate, we can determine approximate ages of surfaces by analysis of the number of craters that have accumulated.

This map is intended as a companion to U.S. Geological Survey map I–2447, "Mapping the Solar System." Some of the bodies shown on that sheet are not represented here because there is insufficient data to derive even a rudimentary geologic map. The geologic maps that are shown here do not represent the true complexity of those bodies for one of two reasons: some bodies are undoubtedly more detailed, but we do not have enough data to map them better; while for other bodies more detailed information is known than could be presented at this scale. Where spacecraft data are not of sufficient resolution to allow global mapping of the geology, low-resolution shaded relief airbrush map data are shown. The large gaseous planets do not seem to have distinct mappable surfaces, therefore they are shown here for reference only. Although an adequate overview of the geology of each planet and satellite shown cannot be given in the space available here, the interested readers can explore more information from the various printed and on-line sources available.

Table 1. *Data relevant to the geologic character of selected Solar System bodies.*[1]

	Study phase[2]	Diameter (km)	Bulk density	Recent geologic activity[3]	Past activity	Approximate mean surface age (m.y.)	Mean surface temperature	Atmosphere[4]
Mercury	1	4,879	5.4	-	v,t	?	440 K	
Venus	2	12,104	5.2	?	v,t	500?	730 K	CO_2
Earth	3	12,742	5.5	v,t,g,e	v,t,g,e	700	290 K	N_2,O
Moon	2/3	3,469	3.3	-	v	4,000	350 K	
Mars	2	6,776	3.9	?	v,t,g,e	3,000	220 K	CO_2
Asteroids	1	varied	-	?	v, g	4,500?	varied	
Jovian system								
Io	1	3,660	3.5	v,g,t	v,g,t	~ 1	130 K	
Europa	1	3,130	3.0	?	g?,v,t	50	110 K	
Ganymede	1	5,268	2.0	-	v?, t	3,500?	150 K	
Callisto	1	[5]4,808	1.9	-	-	4,000?	150 K	
Saturnian system								
Enceladus	1	512	1.0	?	v, t	2,000?	100 K	
Tethys	1	1,046	1.2	-	t	3,000?	100 K	
Dione	1	1,120	1.4	-	t	3,000?	100 K	
Rhea	1	1,528	1.3	-	t	4,000?	100 K	
Titan	1	5,150	1.9	?	e?	?	90 K	N_2, CH_4
Iapetus	1	1,436	1.2	?	v?	3,500?	100 K	
Uranian system								
Miranda	1	472	1.2	-	v?,t	3,500?	70 K	
Ariel	1	1,158	1.6	-	v,t	3,000?	70 K	
Umbriel	1	1,169	1.5	-	t	4,000?	70 K	
Titania	1	1,578	1.7	-	t	3,500?	70 K	
Oberon	1	1,523	1.6	-	t	4,000?	70 K	
Neptunian system								
Triton	1	2,705	2.0	g	v,t	600?	38 K	N_2, CH_4
Pluto	1	2,300	2.0	?	?	?	[6]40 K	N_2, CH_4
Charon	1	1,186	1.4	?	?	?	[6]40 K	

1 For other information such as mass, gravity, and orbit data, see companion sheet "Mapping the Solar System" (USGS map I–2447).
2 Exploration phases: 1, reconnaissance—telescopic study, spacecraft flybys.
2, exploration—orbiters, landers, initial sampling, rovers, global mapping, gravity mapping, and so forth.
3, intensive study—detailed, methodic, global sampling, interior studies, manned exploration.
3 Geologic activity observed: v, volcanism; t, tectonism; g, geothermal; e, erosion; ?, possible activity.
4 Only indicated for bodies with geologically significant atmosphere.
5 Value for radius of Callisto that is printed on map I–2447 is in error. Correct radius is 2404 km.
6 Varies due to eccentric orbit.

Mercury

Being so near the Sun and having been visited by only one spacecraft (Mariner 10), Mercury is the least understood of the terrestrial planets. Even so, much has been learned from that one mission and from Earth-based telescopic studies. Although closeup pictures of Mercury are often mistaken for those of the Moon, being similarly highly cratered and mostly colorless, the two bodies have distinct and interesting differences.

Mercury has three major terrain types: (1) heavily cratered, (2) intercrater plains, and (3) smooth plains. A minor but interesting type, the hilly/lineated terrain, was caused by the planet's interior focusing impact-generated seismic waves to a point at the opposite side of the planet from the event that formed the 1,300-km-diameter Caloris basin. Similar antipodal terrains have been found on the Moon opposite the Imbrium and Orientale basins. Computer simulations indicate the focused waves generated vertical ground movements of more than 1 kilometer, creating the hilly terrain. The heavily cratered uplands record the late heavy bombardment period that ended about 3.8 billion years (b.y.) ago. The Caloris basin-forming impact may have been one of the last large impacts from this period. The intercrater plains are probably volcanic, and very old, about 4 b.y. The smooth plains are similar in mode of occurrence and morphology to the dark lunar maria, yet are much less obvious. These plains are found in old basins that formed during the late heavy bombardment and so must have formed around 3.8 b.y. ago. Volcanism mostly died out within the first 800 million years (m.y.) of its history.

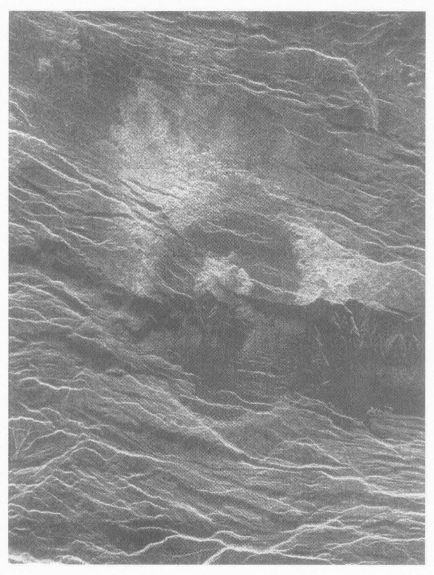
Activity since then may have been limited to global compressive stress, probably caused by the planet shrinking an estimated 4 kilometers in diameter as it cooled (modeling of Mercury's thermal history suggests as much as 10 km shrinkage could have occurred). This compression is indicated by ridges (see figure) that cut the intercrater plains.

Some hints about the interior are given by Mercury's high uncompressed density (5.3 g/cm^3 compared to Earth's 4.4 g/cm^3), which indicates it has not only a higher iron content but also a core that makes up a much larger percentage of Mercury's volume than does Earth's core. Mercury's large core is a mystery. A proposed explanation is that a large impact during the final accretion period stripped off the lighter outer part of the planet. This large core may also account for Mercury being the only terrestrial planet other than Earth with a significant magnetic field. However, the field is so weak (1,000 times weaker than Earth's) that solar wind can reach the surface during high solar activity.

Venus

Venus is usually noted for its proximity to and near identical size with Earth. This was noted shortly after the invention of the telescope hundreds of years ago, yet that is about all we knew of Venus until a few decades ago. Even its unusual retrograde and very slow rotation (243 days) were unknown until radio telescope technology had advanced sufficiently in the mid-1960's.

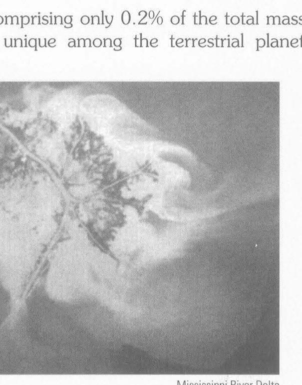
Venus has been the most visited planet, with 9 orbiters, 7 atmospheric probes or hard landers, 2 atmospheric balloons, 10 soft landers, and 6 flybys since 1962. Despite this, geologic studies of Venus were hampered by our inability to see through the dense clouds. Until about 10 years ago, there was only a crude sense of what the overall surface looked like: the Pioneer-Venus mission provided us with a coarse topographic map, and Earth-based radio telescopes gave us images with detail of about 1 kilometer (roughly that which we get when viewing the moon from a small visual telescope). Even these images were limited by a near-orbital resonance with Earth, which brings nearly the same face of Venus into view when it is closest to Earth. It was not until the early 1980's, when the Soviet Venera 15 and Venera 16 spacecraft sent back images of the northern quarter of Venus, that the spectacular nature of the venusian surface was clearly revealed. The Magellan mission mapped nearly the entire planet, and in more detail than the earlier missions; scientists are still interpreting the data and mapping the geology.



These spacecraft revealed a global network of plains on Venus, interrupted by islands and continents of tesserae terrains: high, complex surfaces that are heavily fractured and sometimes bordered by mountainous fold or thrust belts. These tesserae-bounding mountain belts (and also the ridge belts that are found in the low-lying plains) show that crustal convergence has occurred on Venus. The Veneras also revealed the interesting coronae—very broad, low domes that appear to be the surface expressions of rising plumes of hot mantle material. Fracture belts, where the crust appears to be pulling apart, encircle Venus (see figure). Large shield volcanoes and extensive lava flows are often astride these fracture zones. The observed convergent landforms indicate metamorphism of rocks probably occurs, but in the absence of significant erosion these rocks are much less likely to be eventually exposed at the surface (as is common in highly folded mountainous regions on Earth). In the areas of high terrain on Venus, the gravity field is high. This correlation between terrain height and the gravity field is only sometimes true for Earth landforms. Explanations of this phenomenon argue for geologic activity in the past, and some even require that there be some current activity. Having relatively few impact craters further tells us that Venus' surface is no more than about 500 million years old, about the average age of Earth's surface. Though still old, in the absence of any near-surface liquid, erosion on Venus is most likely to be chemical in nature, and therefore less effective than erosion landforms experience on Earth. For this reason, Venus' landforms will still look pristine even though they may be comparable in age to similar features on Earth.

Earth

Though comprising only 0.2% of the total mass of all the planets in the Solar System, Earth nonetheless stands out as unique among the terrestrial planetary bodies in having a substantial atmosphere. Earth's atmosphere is mostly nitrogen and oxygen—its nearest neighbors' atmospheres are predominantly carbon dioxide, with little or no nitrogen or oxygen. Though quite thin (75 percent of our atmosphere's mass is within 11 km of the surface), if not for this very thin film of gas, Earth's average surface temperature would be 35 °C colder than it is, or −20 °C. Therefore, without this atmosphere, the Earth's erosion cycle and its surface would be totally different, and life would have evolved along a very different path.



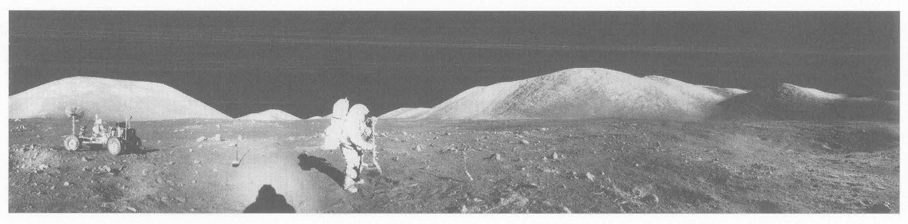
Mississippi River Delta

Though our oceans cover 70 percent of the surface, they are also very thin, and if spread evenly over the entire planet, they would be only 1.5 km thick. Yet the extremely thin (by Solar System standards) atmosphere and hydrosphere have made Earth unique. Our oceans also hide the most significant geologic features on the planet—the globe-circling mountain ranges that are the center of constantly forming new crust. It is this ongoing formation of new crust, and the destruction of old crust elsewhere—in concert with the hydrologic cycle—that constantly change the face of the Earth and redistribute and concentrate minerals and rocky materials into minable accumulations that we use as resources. Where tectonic plates converge, geologic forces have, over the eons, built up continents that provided an exotic new environment for ocean life to exploit. Continued alteration of the continents by plate motions affect climates that in turn challenge life to constantly adapt. To put in perspective how important the geologic forces of Earth are, consider that if not for geologic activity and the oceans, Earth might look like the impact-battered surface of the Moon. Instead, it has high-standing continents, low ocean basins, millions of life forms, and is brilliantly colored.

Moon

The Moon has been studied more closely than any planetary body beyond Earth, having been examined for several centuries by telescope from Earth. Despite this, one of the most obvious features of the Moon was unknown before the era of spaceflight. In 1959 the Soviet spacecraft Luna 3 took pictures as it flew past the far side, making us aware, for the first time, that the near side has an unusual characteristic: the large dark maria, or "seas," that we can see with the naked eye from Earth, occur almost exclusively on the Earth-facing hemisphere. The far side is composed almost totally of the high, bright regions called terrae. These highland terrae are much more heavily cratered than the maria, and so are older. The nearside maria are thin lava flows filling large impact basins that were blasted out of the terrae. The lava flows that filled the maria were very fluid basalts (some are over 1000 km long, yet only about 10 meters thick). In contrast, the highland rocks that compose the terrae represent mostly plagioclase-rich crust formed early in the Moon's history.

The Moon is the only satellite on which we have done hands-on geologic field work: 842 pounds of rocks, drill cores, and loose surface material samples were brought back, and a network of geophysical instruments were deployed by astronauts over a brief 3 year period from 1969 to 1971. The seismometers they set up there picked up waves generated from moonquakes, meteorite impacts, and man-caused seismic waves. Moonquakes are relatively mild in comparison to earthquakes, and occurrences are usually related to tidal effects



caused by changes in the Earth-Moon distance (unlike those of Earth which are the result of shifting plates moving past one another). From analysis of these seismic waves, some information about the interior was obtained. The Moon's crust was determined to vary in thickness, being quite thin—a few tens of kilometers under some basins—to more than 100 km under some highland regions. Sampling rocks thrown out by impacts has allowed the mineralogy of the materials from beneath the crust to be analyzed in the laboratory. Knowledge of the deeper core is more limited, though, due to its depth of more than 1,000 km below the surface. Currently, our knowledge of the core is based on theory, grounded in what is known about the magnetic field and comparison with what we know of our own core. The magnetic field is less than 1/1000 of Earth's, hence we believe that, unlike Earth's core, the Moon's core is relatively free of liquid metal. Rocks returned from the Moon, however, indicate an ancient magnetic field, suggesting a different past.

Rocks returned from the Apollo missions have allowed specific ages to be determined for some units. The highlands formed about 4 b.y. ago, and the maria about 2.5 to 3.8 b.y. ago. Thus, most of the youngest lavas we see today on the Moon's surface flowed before many of the oldest rocks found on Earth were even formed, indicating that the Moon has been largely geologically inactive for the last 2.5 billion years, except for occasional impact events (large impacts still occur sporadically: the 80-km-diameter crater Tycho was formed about 105 million years ago, not long (geologically) before a larger impact on Earth closed out the Mesozoic era and presumably killed off the dinosaurs). Because of this geologic stability, and the lack of water, weathering on the Moon is limited to impact "gardening" and darkening by solar radiation. As a result, Tycho looks very fresh. Geological processes on Earth, in contrast, have buried the younger Mesozoic-ending impact beneath thousands of feet of sedimentary deposits, making it visible only by geophysical prospecting methods.

Despite our having visited the Moon, the origins of some of its features still remain controversial, and much is yet to be learned. This is not surprising, considering that less than 80 hours of geologic field work have been conducted on the Moon. Though no manned missions are currently planned to go back to the Moon, recent robotic missions are giving our Moon a second look and are providing interesting discoveries such as the possible discovery of water ice at the south pole. An affordable way to map geologic variations of the lunar surface is with multispectral sensors—the Galileo spacecraft obtained a few images in seven different spectral bands as it flew past Moon in 1990 and again in 1992 on its way to Jupiter. The Clementine spacecraft mapped nearly the entire surface in seven bands as it orbited the Moon in 1994. These data are currently being processed to reveal compositional variations. Global altimetry data were also collected for the first time by Clementine. One of the significant discoveries from these data so far is the verification of a previously suspected impact basin near the south pole that is the largest known impact basin in the Solar System.

Mars

Mars has a more varied history than most other bodies. With twice the diameter of Earth's Moon, and half that of Earth, it is not surprising that it shares geological characteristics of both. First mapped in detail in the 1970's by Mariner 9 and Vikings 1 and 2, Mars exhibits a variety of landscapes, geologic materials, and geologic structures that reveal a long history of activity. Most significant is the global division into two geographic terrains: the old, cratered, southern highlands that stand 1 to 5 km above the average elevation, and the younger, sedimentary and volcanic, northern lowlands, 0 to 3 km below the average.

The ancient cratered highlands formed in the first of three major historical periods (before 3.5 b.y. ago). Many stream valleys are seen that date from this period, indicating that a warmer, thicker atmosphere probably covered Mars at that time, or at least that the crustal rocks were warmer. Volcanoes also erupted sporadically in the highlands. Rock units formed in this early period show the scars of being battered by the still-numerous impacts that followed the formation of the Solar System. The history of the low northern plains is not preserved from this period, perhaps, as some suggest, because they were carved out by an enormous impact.

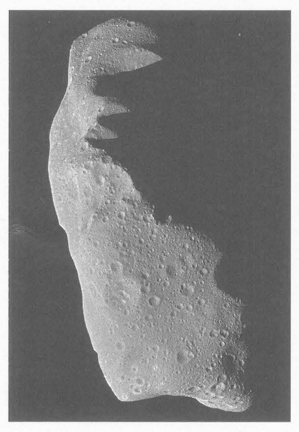
The next major period in Mars' history was dominated by the effects of internal heat loss. This led to extensive volcanism and tectonism at the surface, and also to catastrophic erosional events—the sudden releases of huge stores of millions of cubic kilometers of ground water, causing ice and entrained rock debris to scour enormous channels on their way to the low northern plains basin. At the headwaters of these channels are chaotic, jumbled blocks positioned in steep-walled canyons, where the ground collapsed as the water was released, taking much of the surrounding rock with it. Lesser releases of water occurred on flanks of volcanoes. There, geothermal heating seems to have driven ground water to the surface, where it easily cut through the soft volcanic ash deposits. Still farther upstream the Solar System's largest canyon, Valles Marineris (or "Mariner Valley"—named for the spacecraft that discovered it), formed during this period, probably by rifting of the crust and subsequent sideward erosion of the canyon's walls. Elsewhere, lava flows continued to pour onto the surface, covering over one-third of the planet. The Tharsis rise, for example, a broad 3- to 10-km-high volcanic plateau straddling the boundary between the cratered highland and low plains, formed during this period.

Geologic activity declined during the last period; large volcanoes, some of the Solar System's largest, formed at this time. With the small planet having lost much of its internal heat by now, the crust thickened and shifted less, so that outpourings of lavas continued to reach the surface via only a few access conduits to the surface. Massive landslides also continued to occur in areas of steep terrain. Today, Mars' atmosphere—reduced to only 1/100 the density of Earth's—has lost its ability to cause significant erosion, although solar heating still imparts enough energy to seasonally move dust and small amounts of atmospheric water around. These latter effects nonetheless continue to vary in intensity due to long-term climate fluctuations driven by Mars' erratic orbital behavior.

New knowledge about Mars' surface composition, coupled with advances in chemical analysis, has led to the recent recognition that some meteorites found on Earth are very likely rocks from Mars—knocked free by impact events.

Asteroids

While no asteroids can truly be said to have been geologically mapped to date, their importance nonetheless warrants a discussion. The total mass of all the asteroids is less than that of the Moon, but they continue to play a significant role in the Solar System: as supplier of many satellites and ring material to the outer planets and as a source of crater-causing projectiles. Most of the estimated billions of asteroids reside in the "main-belt" between Mars and Jupiter, but Jupiter's large mass occasionally perturbs the orbit of an asteroid and sends it into a much different orbit. Some of these cross the orbits of other planets. Of particular interest are those that pass near Earth, the Near-Earth Asteroids (NEA's). The importance of NEA's is demonstrated by the recent discovery that the great extinction at the end of Earth's Mesozoic era was caused by an NEA or comet that hit Earth 65 m.y. ago. Asteroids are also important in that they will continue to help improve our knowledge of the early Solar System: the smaller ones may be essentially unaltered since their formation, and hence would provide primordial materials for studying the earliest conditions in the Solar System. In the future, they may serve as a source of raw materials.



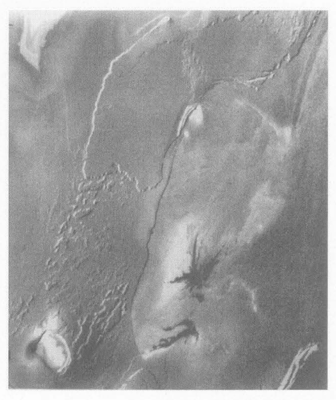
We have more actual samples of asteroids (also known as minor planets) than we do of our much closer neighbor, the Moon: the Apollo expeditions returned 842 pounds (379 kg) of Moon rocks, but roughly 35,000 asteroid samples have been found on Earth. At 66 tons (59,400 kg), the single largest meteorite discovered dwarfs the entire Apollo collection, and over 100 tons more arrive at Earth every day. From the many meteorite samples available for study, much can be deciphered of these bodies. Close study of these reveals evidence of differentiation, volcanism, and aqueous alteration. Subsequent to these internal geologic processes, collision with other asteroids resulted in fragmentation, thus making parts of their interiors available for study: iron meteorites probably originated in the cores of larger asteroids that differentiated; basaltlike stones likely formed in an asteroid crust or mantle, and "stony-irons" are believed to have formed at core-mantle boundaries. Carbonaceous-class meteorites are thought to be from bodies that never grew large enough to have melted enough to have differentiated. Studies of these rocks indicate that the asteroids are material that never accreted to form a planet, perhaps as a result of disruptive influence of Jupiter's gravity. Specific asteroids are now being identified as probable sources for some meteorites by the matching of their spectral reflectance curves. This approach has allowed us to effectively sample specific asteroids without having to wait to go there.

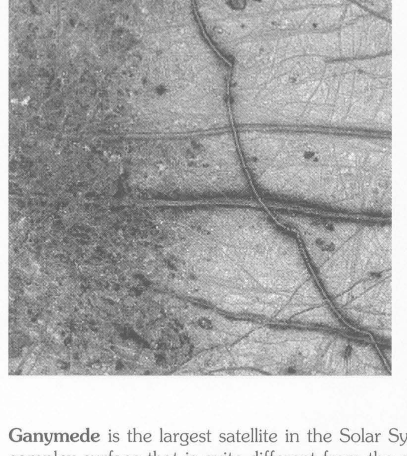
Our first visit to an asteroid was the Galileo spacecraft's flybys of 951 Gaspra in 1991, then 243 Ida (shown above) in 1993, while en route to Jupiter. The first true geologic mapping mission to an asteroid will be the Near Earth Asteroid Rendezvous (NEAR) mission. NEAR is on its way to 433 Eros and is due to arrive in early 1999. During its 12 months in orbit, NEAR will map Eros using seven instruments. The Hubble Space Telescope is also valuable in asteroid studies, having already shown that 4 Vesta has distinct bright and dark areas—suggesting a surface similar to our Moon, with old bright regions flooded by dark, lava-flooded regions.

Jovian System

Of the 16 known satellites orbiting Jupiter, all but four are smaller than 250 km diameter, and many are 80 km diameter or less and very irregular in shape. Most of these smaller bodies are believed to be captured asteroids. The four largest satellites, however, collectively known as the Galilean satellites, are almost a planetary system of their own, with two of them being comparable in size to Mercury. Like the Solar System, this satellite system exhibits a distinct change in composition from one end to the other: ice content increases, and density, reflectivity, and signs of geologic activity decrease with distance from Jupiter.

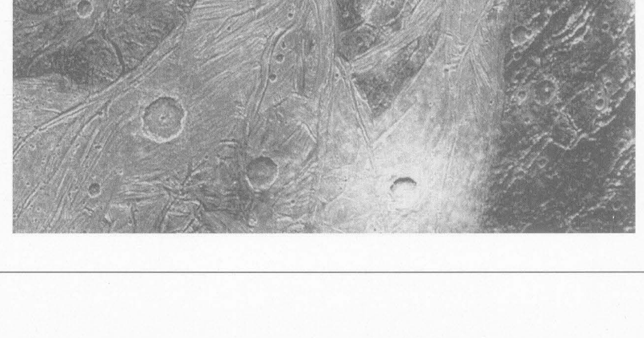
Io is the densest of the Galilean satellites at 3.5 times that of water, and so must consist mostly of rock. As first discovered by the Voyager missions, it is the most active object in the Solar System, with 5 to 10 major eruptions ongoing at any given time. Individual eruptions can last several years, reach 300 km high, and over the years have obliterated all traces of impact craters. The energy driving this over-active volcanic landscape is heat created by constant flexing of Io's interior from tides caused by Jupiter and Europa. The rest of Io's surface is dominated by solidified sulfur flows and sulfur dioxide frosts, and dark liquid sulfur, which give Io its multi-hued surface. Silicate lavas also occur, appearing gray or black, but are denser and so usually remain below the surface. The sulfur dioxide tends to concentrate in topographic basins. Io is thought to have a dense iron-nickel-sulfur core, similar to Earth's. Clearly, various volatiles and liquids are rapidly, and sometimes violently, cycling through Io's crust. Heat from these gigantic eruptions are detectable from sensitive telescopic instruments on Earth, allowing continued monitoring of their activity.



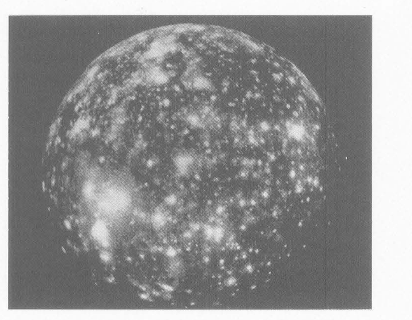


Europa is only slightly less dense than Io at 3.0 g/cm^3, but could hardly be more different. Its surface is composed almost entirely of water ice (so far, no water has been detected at the surface of Io). Extremely flat, with relief usually no more than 100 m (mountains up to about 1,500 meters are very rare), the surface is scarred by a complex crack system that looks similar to that of polar sea ice on Earth, leading to speculation that an ocean lies beneath the ice crust, estimated to be about 20 km thick. Very few impact craters exist on Europa, indicating that some process must be acting to obliterate the craters that inevitably form on planetary surfaces. This further strengthens the theory that an ocean still exists below the crust. A different set of cracks a few kilometers wide and up to 1,000 km long criss-cross the surface. Reddish material flanking these cracks may be deposits from eruptions that sprayed out muddy or salty water (solar radiation or cosmic rays would darken the salts). Like Io, the energy to drive the resurfacing (and perhaps to keep an ocean from totally freezing at the frigid −150 °C temperatures there) is probably from tidal effects of Jupiter and the other satellites.

Ganymede is the largest satellite in the Solar System. One-third water ice, Ganymede exhibits a geologically complex surface that is quite different from the geology of rocky bodies seen in the inner Solar System. Sections of old, dark, heavily cratered crust have survived as islands among younger, bright, grooved crust. Whether the darkness of the older terrain is due to silicate material being more easily entrained in Ganymede's mostly ice crust early in its history before differentiation occurred or whether it has merely darkened with age is unclear. Heating and softening of the crust early in Ganymede's history has caused the large, old craters to flatten out. The younger craters retain relief and have either bright or dark ejecta, indicating variations in subsurface geology. Lacking both an atmosphere and an adequate energy source to continue driving geologic processes at the surface, Ganymede appears to have ceased being active, though its strong magnetic field may indicate some internal activity.

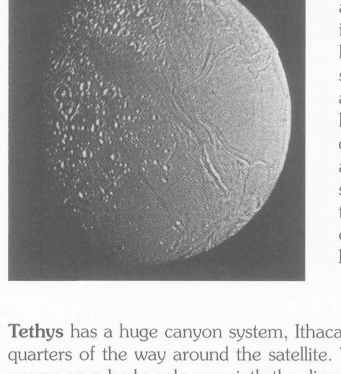


Callisto may be the Solar System's most heavily cratered object, attesting to its billions of years of geologic inactivity. Its most prominent features are impact in origin and are notable only for their size and the concentric ring fractures that formed when the crust around them was fractured by adjustment to the huge impact. The rings extend out to 2,000 km from the centers of the impact sites. The central regions of the impact sites are bright, perhaps from "cleaner" ice that was excavated by the impacts, or flowed out from impact-generated melting of the subsurface. Small craters are extremely numerous, and their only characteristic is that they have thrown out brighter ice, likewise indicating that the surface has been coated with dark material that may have accumulated from billions of years of meteorite bombardment.



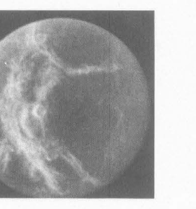
Saturnian System

All of Saturn's larger satellites are made mostly of water ice with some lesser rock component. With the exception of Enceladus, whose surface appears to be virtually pure ice, these moons' surfaces are made of dirty ice, with models suggesting increasing amount of rocky material toward their centers. Enceladus, Tethys, and Dione all exhibit widely varied crater densities and large canyons, indicating that they have all been substantially affected by geologic activity. A likely geologic process on these icy bodies is cryovolcanism, which involves partial melting of an icy satellite's interior and resultant outpourings of icy liquids. Ammonia-water cryovolcanism is widely suspected on all three objects, because the amount of heat available to drive geologic activity there is very meager, and ammonia-water ices (an expected component of Saturnian satellites) have a very low melting point, 176 K (−97 °C).



Enceladus has a density only slightly more than that of pure water and is the least dense Saturnian satellite, therefore the least rocky of all the icy satellites yet known. Evidence of geologic activity abounds; its ridged terrain, for example, is so sparsely cratered (of the icy satellites, only Europa is less cratered) that some geologists believe it may still be active. Enceladus also has some very heavily cratered terrain, and terrain with intermediate crater densities, indicating that it has had a protracted history of geologic activity. Tectonic activity is evidenced by mountains 1 to 2 km high, strike-slip faults, normal faults, and folded strata. All these indicate that large blocks of Enceladus' surface have shifted relative to one another. As with Io and Europa, the driving energy for this activity may be the tidal interactions from orbital resonance—in this case Dione and Saturn causing the tidal heating that led to partial melting and softening of the interior.

Tethys has a huge canyon system, Ithaca Chasma, that is 3 km deep, up to 100 km wide, and extends three-quarters of the way around the satellite. This canyon system is similar in size to Valles Marineris on Mars but occurs on a body only one-sixth the diameter. The formation of the enormous impact crater Odysseus may be related to the origin of the canyon. The moderately to heavily cratered surface indicates all this activity took place early in Tethys' history, and little has happened since. The moderately cratered plains apparently were produced by cryovolcanism similar to that postulated for Enceladus.



Dione is very similar to Tethys, though it lacks a large impact crater and its canyons are not so immense. Any geologic activity that may have occurred on Rhea occurred long ago and evidence has been obliterated by impact cratering.

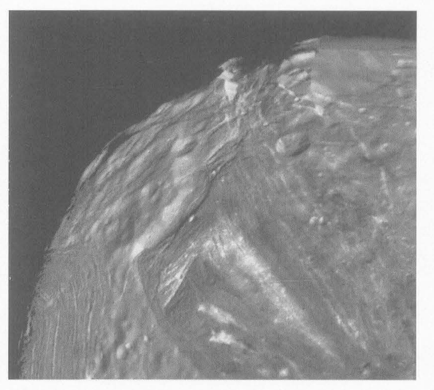
Iapetus, heavily cratered on one hemisphere, is curiously covered by a very dark deposit of hydrocarbon molecules. These may have been erupted onto the surface from Iapetus' interior, or swept up by Iapetus in its orbit around Saturn.

Titan is the second largest satellite in the Solar System and the only satellite with an atmosphere thicker than Earth's; it has long interested planetologists. Like Earth's atmosphere, Titan's is mostly nitrogen but also includes methane, carbon monoxide, and ethane. Rainfall of liquid methane, ethane, and nitrogen is possible at the 93 K (−180 °C) surface temperature, leading to the belief that erosion may be a significant process at work there. Our only opportunity so far to see Titan's surface close up—when Voyager 1 passed by it in 1980—was thwarted by the thick orange smog. We have since discovered that the smog is transparent at certain infrared wavelengths, and so the Hubble Space Telescope was recently used to image Titan's surface, allowing us to see detail as small as 300 km. The overall reflectance of the surface suggests that it could be composed of dirty water ice. Brightness variations suggest that some sort of meteorologic and (or) geologic processes have modified the reflectivity of various parts of the surface.

The origin and geologic histories of the Saturnian satellites should be more fully understood after the future arrival of spacecraft such as the Cassini mission. In 2004, Cassini will enter into orbit around Saturn and drop a probe onto Titan's surface.

Uranian System

The largest Uranian satellites are also icy, but are much darker and also denser than Saturn's satellites, presumably due to having dirtier surfaces and rockier interiors. Nonetheless, they probably have differentiated to the point that they have distinctly icy crusts and mantles and rocky cores. The ices, in addition to that of water, may be more exotic, including ammonia hydrate, methane-water mixtures, and others. These other chemicals, when they occur with water, could allow for thick, ice-lava flows, even at the extremely cold temperatures (−200 °C) in that part of the Solar System. The carbonaceous nature of these ice-mixtures would cause them to darken on exposure to solar radiation and cosmic rays. Darkening also probably occurs from accumulation of meteoritic material. All of the large Uranian satellites now seem to be geologically inactive, but most still show signs of past activity.



Miranda perhaps contradicts the tenet that larger bodies are more active, as this diminutive satellite exhibits a bizarre surface. Ovoid terrains, or coronae, which possess crude concentric color bands and exhibit concentric fault systems as well, may have been formed by an as-yet-to-be-understood process of outflow of material from the interior. Two of Miranda's coronae show indications of cryovolcanic flows associated with them. Another possible origin is that the coronae are simple upwellings due to thermal convection of the interior, possibly driven by tidal forces. A large canyon with a nearly 20-km vertical offset (Verona Rupes) suggests titanic forces at work. Such anomalously large features on such a small satellite also suggest an unusual origin, perhaps being caused by the total disruption of Miranda by an impact, leaving the body in a state of disequilibrium—the coronae and faults being the result of the re-establishment of equilibrium.

Ariel is Miranda's nearest neighbor, but it exhibits nothing like the coronae of Miranda. Deep canyons cut the moderately cratered surface. The canyons are a significant part of the landscape (up to 5 km deep, 100 km wide, and at least 600 km long). Cryovolcanic flows as thick as 1 km erupted into the canyons. Flow edges of these thicknesses suggest the eruptions may have acted more like glaciers than lava flows. Fewer craters are seen within the canyons, suggesting that a long period of time elapsed between the formation of the inter-canyon plateaus and the canyons. Craters on the inter-canyon plateaus have bright ejecta, indicating that fairly clean ice exists below the surface.

Umbriel, Titania, and **Oberon** have such a high density of impact craters that we must conclude that geological activity on these satellites ceased much earlier than on Miranda and Ariel. Umbriel is very heavily cratered and has the darkest, grayest surface of any icy satellite except the dark hemisphere of Iapetus. Geologic activity ceased so long ago that any signs of geologic features have been battered beyond recognition by impacts. Titania's canyons, similar to those on Ariel, are signs of ancient geologic activity. Bright craters again suggest cleaner ice beneath the dark surface. Titania's surface is slightly older than Ariel's, as determined by the greater number of impact craters on Titania. Oberon shows intriguing signs of very ancient geologic processes, including dark crater floors and a mountain peak 20 km high.

Neptunian System–Triton

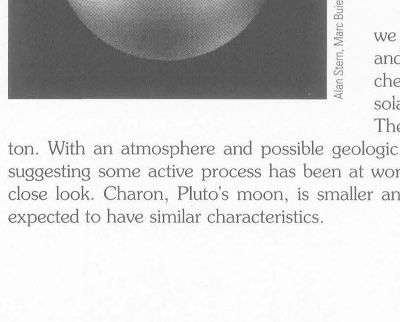
Neptune's largest moon, Triton, is larger than Pluto. Of all satellites in the Solar System, Triton has the second densest atmosphere, though it is still extremely thin. Its mainly nitrogen atmosphere is a characteristic shared with Earth, Titan, and perhaps Pluto. Triton's density is twice that of water; among the major outer satellites only Io and Europa are denser. The density indicates that Triton is about 75 percent rock. The remaining amount is ice, which Voyager data and chemical studies suggest is mostly nitrogen ice near the surface; ordinary water ice probably forms a "bedrock" not far below. This icy crust may extend to a depth of 300 km, below which it is expected that the composition would change to predominantly rock.

With exception of Europa, Triton is the least cratered icy satellite, indicating that the volcanic landscape seen by Voyager is geologically young, being perhaps less than 600 million years in age. Although this seems old, it is less than one-seventh the age of the Solar System and is about the same average age as Earth's surface. Voyager 2 showed an unusual-looking terrain that is unique to Triton—the so-called "Cantaloupe terrain" because of its resemblance to the skin of a cantaloupe. It is believed to result from volcanic and tectonic processes, but the precise mechanism of formation is unknown. Other terrains show rifts, cones with craters on their summits and flanks, domelike extrusions, and steep-walled pits resembling terrestrial calderas, thus appearing like some volcanic landscapes of Earth. Exotic lavas consisting of variations of water-ice-ammonia-methanol mixtures probably erupted to form these features

Though it is still unclear what drives them, it may be that much of Triton's observed volcanic eruptions derive from the energy exchange caused by Triton's capture into orbit around Neptune, triggering melting and intense geological activity (it has been suggested that Triton, which orbits Neptune in a direction opposite that of all other large satellites in the Solar System, was captured by Neptune from a reservoir of similar objects theorized to exist beyond Neptune). The existence of active geysers and the possibility of ammonia in Triton's mantle suggest that the geologic activity may be more recent, even active. Or perhaps Triton may now be geologically dead, except for the occasional venting of gases, changes caused by wind-blown dust, and the migration of nitrogen frost from the south polar ice cap.

Pluto and Charon

With a surface area less than that of Russia, and being 5.9 billion kilometers away, it is not surprising that we know so little about Pluto. Perhaps more amazing is that for being so distant and small, we know a fair amount. The only planet yet to have been paid a call by robotic emissaries from Earth, for the present, we have had to rely on telescopic data. Most recent revelations about Pluto come from the Hubble Space Telescope, whose images reveal intriguing variation in brightness across its surface (see figure). The north and south circum-polar regions are both dominated by bright areas, which are probably nitrogen frost polar caps. Like Earth's ice caps, they wax and wane with the seasons, some 62 Earth-years long there. The equatorial region is darker and redder, suggesting methane ice and tarry hydrocarbons. The brighter of the equatorial regions may be ordinary water ice, which at Pluto temperatures is as hard as rock.



Alan Stern, Marc Buie, NASA, and ESA

At a cool 40° above absolute zero (−233 °C), substances that we on Earth experience only as gases cannot remain gaseous, and condense out as solid ice on the surface. Physically and chemically, Pluto resembles the large icy moons of the outer solar system more than it resembles any other known planet. Therefore, we believe it to be very similar to Neptune's moon Triton. With an atmosphere and possible geologic activity (the brightness contrasts are greater than on Triton, suggesting some active process has been at work), Pluto may show some interesting features when we get a close look. Charon, Pluto's moon, is smaller and so harder to interpret, but having formed near Pluto, it is expected to have similar characteristics.

Kuiper Belt Objects

Proving that spacecraft do not replace telescopes, Earth-bound astronomers have recently discovered an extensive group of unusual large-asteroid-sized objects beyond Saturn. The first of this class (2060 Chiron) was discovered in 1977 but was thought to be an oddity: a comet, or possibly an errant asteroid, trapped beyond Saturn. At 175 km diameter, it is extremely large for a comet, yet unlike an asteroid, it shows much gas venting activity. The recognition of Chiron as only the first in its class came only recently, and the discovery of five more of these objects beyond Saturn indicates that they are likely a subclass of objects from the previously theorized Kuiper belt, a group of large icy objects beyond Neptune.

Over 40 objects, many the size of some saturnian satellites, have also been found beyond Neptune, since the first was discovered in 1992. That so many have been found so quickly indicates that perhaps 35,000 more of these large icy asteroids are yet to be discovered, which would make the Kuiper belt much more massive than the asteroid belt. This huge reservoir of icy bodies may be the source of short-period comets. When comet Shoemaker–Levy-9 impacted into Jupiter in 1994, mankind's attention was focused on the fact that impacts are a very real and active process in the Solar System even today. It is possible that in the distant past, icy objects like these delivered water to Earth early in its history. These active and important objects will undoubtedly exhibit very interesting geology when eventually visited by spacecraft.

Summary

Despite having armies of geologists crawling over Earth for about a century now, it was only 25 years ago that plate tectonics—perhaps its most prominent and important process—was beginning to be understood. Recognition of impacts as a major planetary process has developed only in the past 25 years, and only in the past few years did we first see our sister planet's surface in detail. So it would be very presumptuous of us to think we know very much of these other bodies that, in most cases, we have barely seen. Many exciting discoveries remain—signs that water ice may exist at our Moon's south pole, the possibility that oceans may lie under Europa's surface, and perhaps proof that primitive life existed on Mars. New discoveries continue to be made even on our home planet: it was recently shown that Earth's core is rotating faster than the rest of the planet, and only in the last few years have we begun to recognize the effect of geologic processes on the development of life; it is therefore not likely that we will have a complete understanding of the Solar System geology after our first brief glance at it.

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[There are many new discoveries in planetary science these days, from new missions, the Hubble Space Telescope, improvements in Earth-based telescopic techniques, and even from old data being re-analyzed. The best way to keep current is to visit the Internet…]

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ERRATA to data tables on companion map I–2447 "Mapping the Solar System." Some early copies of "Mapping the Solar System" had a few errors in the data tables. The correct values are:

Triton—mass 0.0036 (incorrect value is 0.0056)
Oberon—semimajor axis of orbit 583,400 (incorrect value is 387,000)
Pan—orbit period 0.58 (incorrect value is .294)
Callisto—mean radius 2404 (incorrect value is 3404)
Ganymede—mass 0.0249 (incorrect value is 0.0175)

Orthographic projections

SCALES*

1× = 1:100,000,000 (1mm = 100 km; base scale)
2× = 1:50,000,000 (1mm = 50 km)
3× = 1:33,333,333 (1mm = 33.3 km)

*In order to show detail, some of the maps on the front of this sheet are shown enlarged relative to others. The degree of relative enlargement is indicated by an enlargement factor under each body's name. Maps are at the 1× base scale (1:100,000,000) unless noted otherwise.

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—1997

Prepared on behalf of the Solar System Exploration Division, Office of Space Science, National Aeronautics and Space Administration.
Edited by Derrick D. Hirsch; cartography by Roger D. Carroll and Darlene A. Casebier

GEOLOGY OF THE SOLAR SYSTEM
1997

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NW–1997–02–149–HQ