Lava Tubes in the Solar System

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Abstract

All of the major planets and satellites have been visited by spacecraft except Pluto and its moon, Charon. Results show that volcanism is important in the surface evolution of nearly all planets, although the type of volcanism varies considerably. The inner solar system is dominated by basaltic volcanism and lava tubes or channels have been identified on Mars, Moon, and possibly Mercury. The other solar objects of geologic interest, the satellites of major planets, consist of mixtures of ice and rock. Unusual styles of volcanism include eruptions of sulfur, water-slush, or methane ices, some of which form flow channels as seen in spacecraft images. Depending upon their rheological properties, these materials may also form tubes.

Venus is the last terrestrial planet to be explored geologically. It has often been described as the sister planet to Earth because of its similarity in size, density, and proximity in the solar system. Because Venus is completely shrouded by dense, hot clouds, its surface is hidden from view by conventional cameras. Its geological diversity is currently being revealed by the U.S. Magellan mission. Launched in 1989 and beginning operation in August 1990, this mission involves a sophisticated radar imager that is systematically mapping the surface of Venus at a resolution better than 100 meters. Preliminary results show that volcanism dominates many areas. Thin flows hundreds of kilometers long are seen, many of which originated from calderas, small pit craters, or fissures. Some of the flows were clearly emplaced through lava channels, parts of which are discontinuous and suggest roofing to form lava tubes.

Introduction

With the flyby of the Voyager 2 spacecraft past Neptune in the fall of 1989, the geological reconnaissance of the Solar System is nearly complete, with parts of all major planets and satellites photographed except for the Pluto-Charon system. Analysis of photogeological results for solid-surface planets and satellites shows that the principal processes in surface evolution are impact cratering, surficial processes (such as landslides and weathering), tectonic deformation, and volcanism. Impact cratering and surficial processes effect the planet from sources external to the planet; volcanism and tectonic deformation result from internal processes and are primarily manifestations of heat loss from the interior.

Most of the larger planets and satellites and some of the smaller satellites of the outer planets show evidence for volcanism. Dark regions on the Moon, called maria, are known to be of volcanic origin; similar plains regions seen on Mars and Mercury are also the result of eruptions. Radar images of Venus obtained from the Magellan mission show huge mountains and vast plains that are of volcanic origin. Many of the satellites of Jupiter, Saturn, Uranus, and Neptune exhibit smooth plains that are the consequence of liquid materials erupted from their interiors onto the surfaces to form plains that mantle older terrains.

The Moon

Mapping shows that mare lava flows cover about 17% of the surface of the Moon. The total volume of volcanic rock, however, probably constitutes less than 1% of the crust, with most of the material being composed of impact-produced brecciated rocks. Nonetheless, mare lava flows dominate the near side of the Moon and contain a variety of volcanic features and flow structures (Wilhelms, 1987). Samples of the Moon returned by the United States Apollo program and the Soviet unmanned Luna series have shown that the mare lavas are composed of basaltic rocks. Although very similar to basalts on Earth, they tend to be more titanium-rich and were erupted more than one billion years ago. Estimates of the viscosities of the lavas at the time of their eruption show that they were extremely runny, having the consistency of motor oil at room temperature.

In December 1990, the Galileo spacecraft flew past the Moon and returned the first new information for the far side in more than two decades (Belton et al., 1992). The data revealed the presence of numerous iron-rich deposits in the highland terrain that constitutes most of the far side. Many of the areas showing this distinctive signature appear to be mare deposits that have been mantled by impact generated debris. Mapping the location of these areas, termed "cryptomaria," is showing that volcanism on the Moon is more extensive than previously considered.

Although most of the lava flows on the Moon were emplaced as vast flood lavas which generated huge pools of molten magma, some of the flows, particularly in the later stages of eruption, were emplaced through open rivers of lava or through closed systems of lava tubes (Figure 1). These ancient lava channels and partly collapsed lava tubes are seen today as lunar sinuous rilles (Figure 2) like lava tubes and channels found on Earth, with many lunar sinuous rilles exceeding 100 kilometers in length and 1 kilometer in width. Despite the differences in scale between the lunar and terrestrial features, the mechanics of eruption, flow emplacement, and lava tube formation are considered to be similar based on the assumption that it is the rheological property of

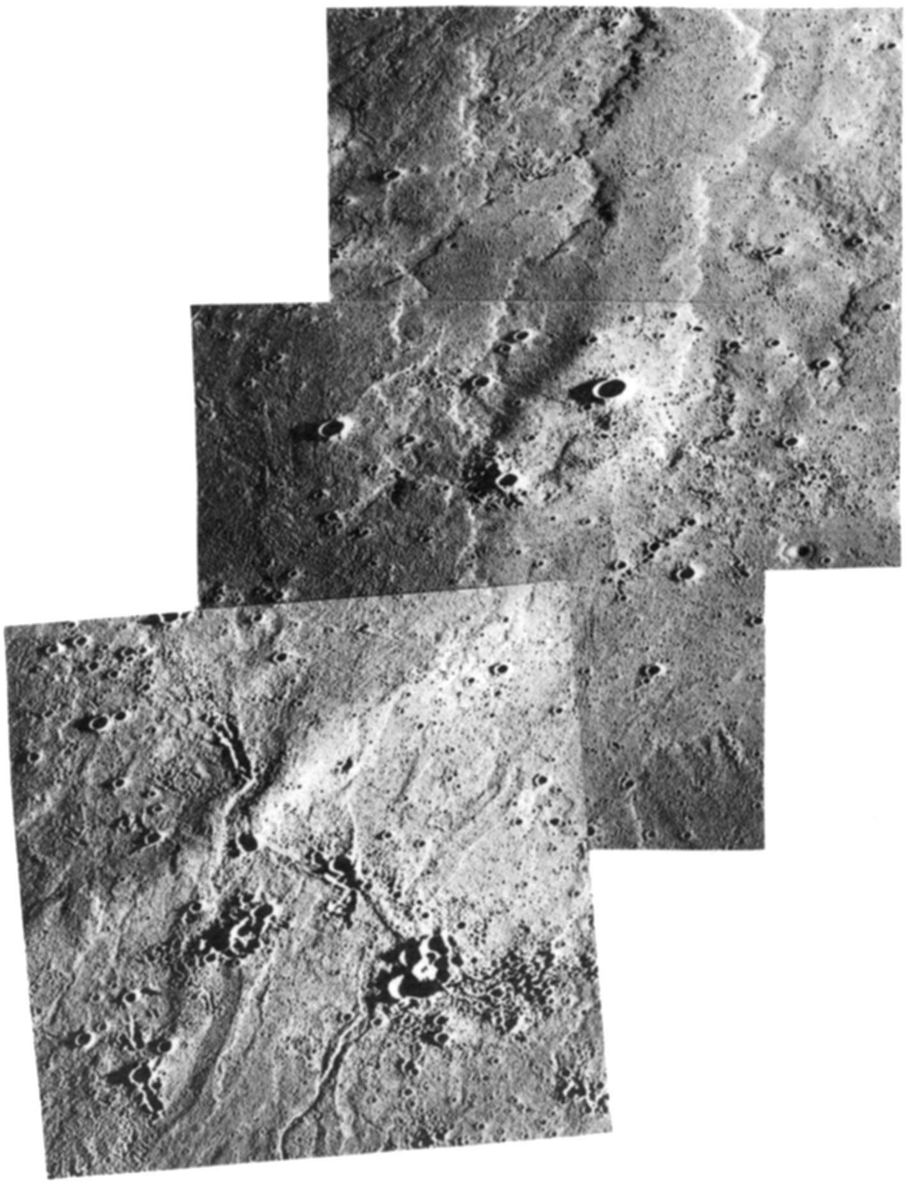

Figure 1—Mosaic of photographs taken by the Apollo 17 astronauts from orbit around the Moon, showing the southwestern part of Mare Imbrium. Some of the flows seen here can be traced more than 1,000 kilometers north (toward top) from vent areas south of the area shown here. Initially, the flows were fed through lava channels and lava tube systems (NASA AS 17-155-23714 to 23716).

the lava and the style of eruption that lead to the formation of lava tubes and channels.

A current debate for lunar sinuous rilles centers on the role of erosion by flow through tubes. Some planetary scientists suggest that the sinuous rilles are primarily the consequence of erosion by flowing lava, while others maintain that they are predominantly constructional features.

The only lunar sinuous rille visited on the surface of the Moon was the Hadley Rille, located on the eastern margin of the Imbrium basin on the lunar near side (Figure 3). The Apollo 15 mission landed on lava plains between the rille and the Apennine Mountains to the east. Samples collected by the Apollo astronauts show that the lavas that spilled from the bank of the rille are basaltic. Photographs taken of the interior walls of Hadley Rille show distinctive horizontal layers that are typical of those seen in the relatively thin lava flow units associated with most lava tubes and channels on Earth. Recent work by Spudis et al. (1988) indicates a complex geologic history for the development and evolution of Hadley Rille.

The Moon was the first extraterrestrial planetary object examined for volcanic features and much of what is known about lava tubes in the Solar System context has been derived from the study of lunar sinuous rilles. Hadley Rille and dozens of similar features show that many of the lava flows on the Moon were emplaced through unitary lava tubes and channels. Mapping their origin and tracing their pathways enable eruptive vents to be identified. These mapping projects contribute to the understanding of lunar surface history.

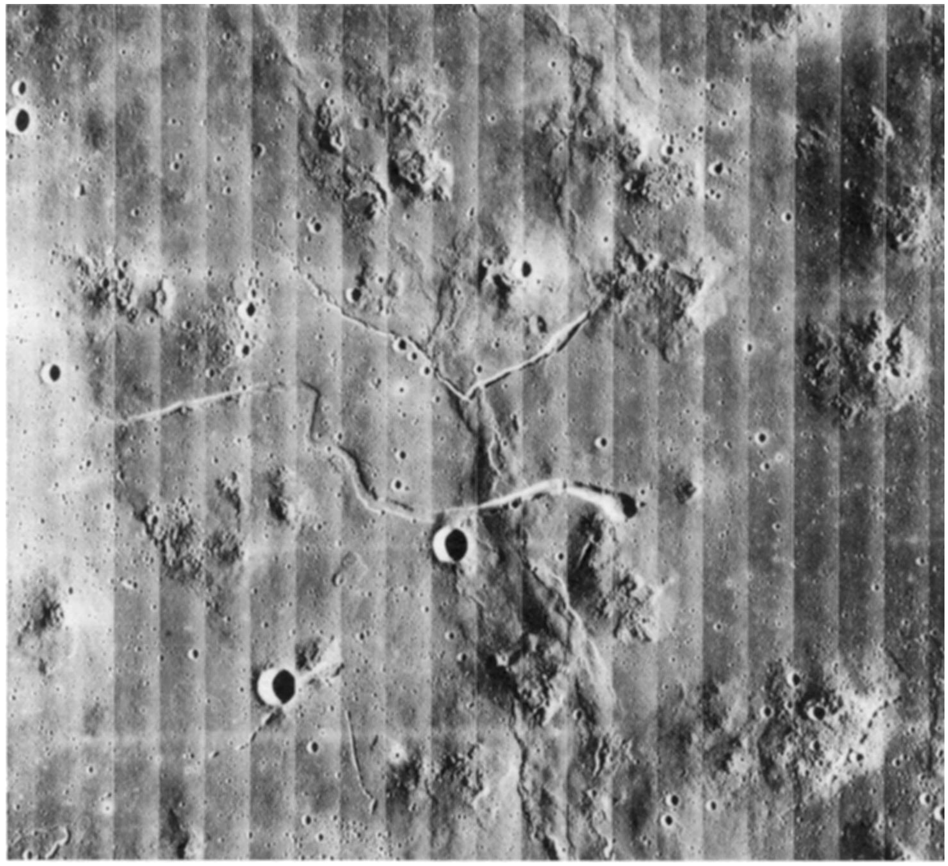

Figure 2—Lunar Orbiter (robotic spacecraft) image of the lunar Marius Hills region, showing several sinuous rilles and partly-collapsed lava tubes (lower left) that emplaced lavas in the mare regions (NASA LO V-M-213, sun illumination from the right, north to the top, areas shown is about 60 kilometers by 55 kilometers).

Mars

More than half a dozen spacecraft have been sent to Mars over the past two decades and a tremendous wealth of information has been returned from the red planet. Most of the information has come from the United States Mariner 9 and Viking missions, both of which operated during the 1970s (Carr, 1981). More than half of the surface of Mars is seen to be covered with volcanic materials of one form or another (Figure 4; Greeley and Schneid, 1991). Although information on the composition of the volcanic flows and deposits is very limited, x-ray fluorescence measurements obtained by the Viking lander spacecraft, multispectral remote sensing observations of the surface, and various geophysical models all suggest that the predominant rocks are basaltic. However, some models also incorporate ultramafic materials, such

Figure 3—Apollo 15 mapping camera photograph of the Hadley Rille (115 kilometers long) and the Apollo 15 landing site ("A"); "H" marks the mountain block that is part of the ancient lunar crust. Sun illumination is from the left, north is to the top (NASA AS 15-414).

as komatiitic lava flows. Komatiitic lava flows are characterized as magnesium-rich and were common in the early history of the Earth. Studies suggest that they were extremely fluid and flowed as fast-moving, turbulent masses. This characteristic poses intriguing problems in the consideration of lava tube and channel formation, and komatiitic lavas are being studied by planetary scientists for comparisons with features seen on Mars and Venus.

Although the most impressive volcanic features on Mars are the enormous shield volcanoes, such as Olympus Mons and the other volcanoes of the Tharsis region, various plains-producing lava flows compose most of the surface area of the volcanic materials. Many of the lava flows that built both the shield volcanoes and the plains were emplaced through lava tubes and channels, as shown in Figure 5. In these high resolution images, obtained from the Viking Orbiter spacecraft, open channels and roofed channel segments are clearly visible. Some of the volcanoes, such as Alba Patera, are enormous structures covering thousands of square kilometers and are composed of individual lava flows fed through extensive tube and channel systems.

The Mars Observer mission, to be launched by the United States in 1992, will carry an array of instruments to provide new and important information on the geology of Mars. Of particular interest for the study of lava tubes and channels is the imaging system that will be capable of obtaining pictures with a resolution of ~1.5 meters for any place targeted on the surface of the planet. In addition, the Thermal Emission Spectrometer will obtain measurements that will allow the compositions of the martian lavas and other volcanic deposits to be assessed.

In 1994, the Soviets are scheduled to launch an ambitious mission to Mars that will include not only measurements made from orbit, but also small simple probes that will land in at least four different locations. A high priority target for one lander is a young volcanic terrain. The goal is to obtain

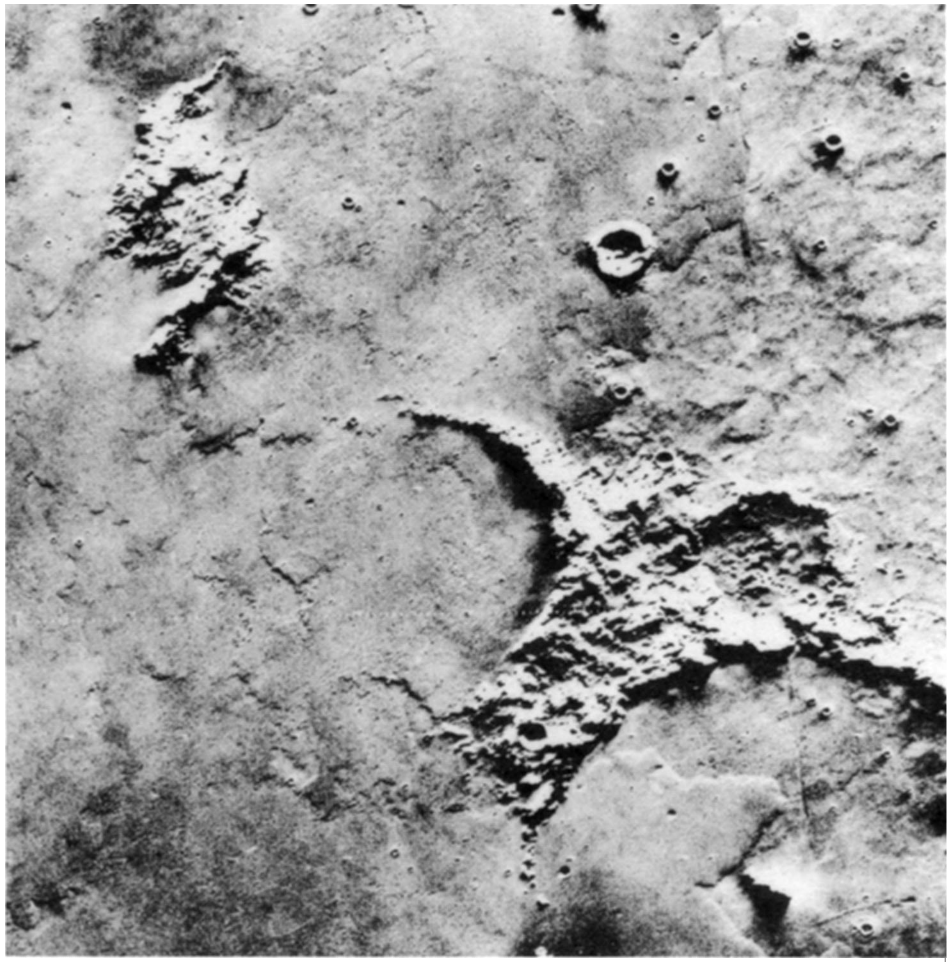

Figure 4—View of Mars taken by the robotic Viking Orbiter spacecraft, showing vast lava plains that have nearly completely flooded and buried older terrain. Best estimates of compositions suggest that these flows are basalts; area shown is about 150×170 *kilometers (NASA Viking Orbiter frame 056A14).*

in-situ measurements of the composition of the lava flows and high resolution images from the surface. At the same time, a German built, high-resolution camera will obtain stereoscopic images from the Soviet orbiter. Images from this system will enable photogrammetric measurements and construction of topographic maps over lava tube systems and volcanic terrains.

The information to be obtained from the American and Soviet missions has the potential for making significant contributions to the study of martian lava tubes. Data on lava compositions, images of collapsed tube segments and possible tube entrances, and topographic information will aid in understanding the formation and evolution of the martian surface. Mars remains one of the most important planets for understanding the evolution of the inner Solar System.

Mercury

The only geological information available for Mercury came from the Mariner 10 spacecraft that flew in the early 1970s and observed about half the surface. Photographs of Mercury and limited remote sensing information show various smooth plains that are significantly younger than the rest of the surface of the planet (Greeley, 1987). It is only by circumstantial evidence, however, that these areas are considered to be volcanic, and the types of features, such as sinuous rilles seen on the Moon and Mars, generally are not seen on Mercury.

For many years an advanced mission to Mercury was deemed impossible or very difficult from an engineering perspective. Recent studies, however, show that it is feasible to place a spacecraft into orbit around Mercury. Such a mission could obtain not only high resolution images for suspected volcanic areas of the surface, but also to observe the other 50% of the planet which remains totally unknown at this time.

Venus

Venus has been called the sister planet of Earth because both planets are nearly the same size and density, and occupy the same general location in the Solar System. Venus, however, is completely enveloped in clouds and its surface is not visible to conventional cameras. The clouds, composed of droplets of sulfuric acid, create a greenhouse ef-

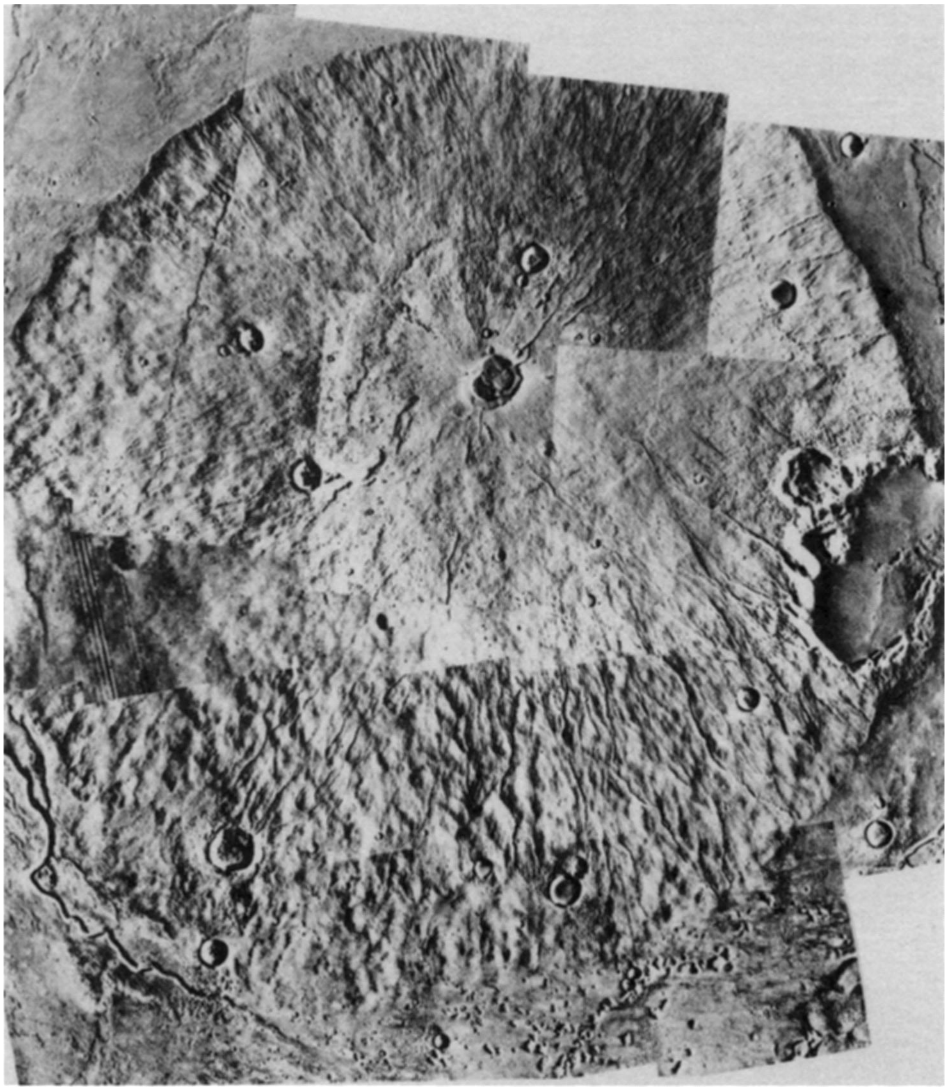

Figure 5—Mosaic of images of the Martian volcano, Hecates Tholus. This shield volcano is more than 200 kilometers across and is composed of hundreds of individual flows, many of which were emplaced through lava tubes and channels. Segments of collapsed tubes are visible as radial patterns around the summit caldera (NASA Viking Orbiter mosaic).

fect, causing the surface temperatures to rise to 450° Celsius, or in excess of the melting temperature of lead.

Venus is the last of the inner planets to be explored geologically. Although the Soviets have landed in more than a dozen locations on the surface and returned information on local rock types (indicating primarily basaltic compositions), the global perspective of the planet has only recently been obtained by the Magellan spacecraft. Launched by the United States and placed in orbit in 1990, Magellan carries a radar mapping system that returned the first high resolution (~75 meters/pixel) radar images of the surface from orbit. Magellan data have revealed Venus to be a geologically diverse planet, dominated by volcanism and tectonism (Saunders and Pettengill, 1991).

Like Mars, Venus exhibits both central volcanoes including shield structures hundreds of kilometers across, and vast plains formed by the accumulation of countless lava flows (Figure 6). Venus exhibits a wider variety of volcanic landforms than Mars, and includes domes that appear to be composed of viscous, pasty lavas and hundreds of fields of cinder cones.

Among the puzzling volcanic features revealed by Magellan are numerous channels, some of which are nearly 7,000 kilometers long. Preliminary analysis reveals several different types of channels, most of which are inferred to be of volcanic origin. One category includes long, narrow channels that have a constant width; they also show breached channel segments where lava flows have spilled onto the surrounding terrain. Although analyses are only preliminary, it is likely that many of the flows were fed through systems of lava tubes, either directly from vents, or as feeder systems from the channels.

The great length of the channels on Venus poses interesting problems for volcanology. Although it is conceivable that conventional flows, such as those composed of basalt, may account for the formation of the channels, other, more exotic lava compositions are also being considered. For exam-

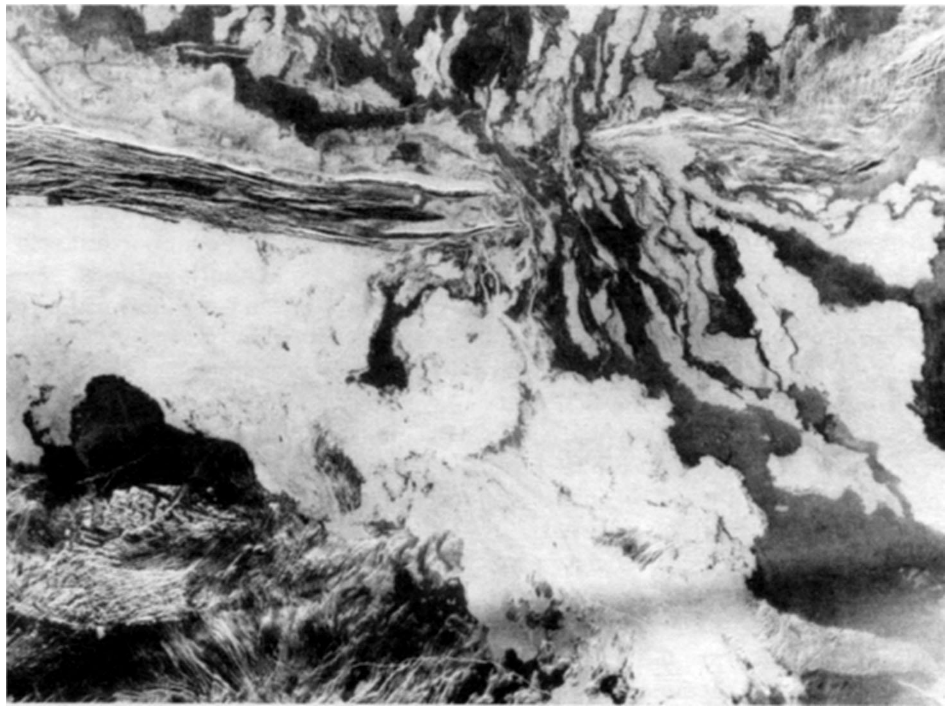

Figure 6—Radar image of the Lada region of Venus taken by the Magellan spacecraft, showing a series of lava flows, some of which were emplaced through channels and networks of lava tubes; area shown is about 550×630 *kilometers (NASA P-38088).*

ple, sulfur compounds are known to exist in the atmosphere of Venus and it is conceivable that some of the flows could be composed of sulfur. Carbonatite is a rare type of lava found in some places on Earth and also has been suggested to exist on Venus. These flows erupt at very low temperatures and, in the Venusian environment, carbonatite and sulfur flows would never solidify, but would continue to flow so long as there was a slope.

The analysis of Magellan images will require many years of study by geoscientists and the wealth of data is only now being realized. As is true for the Earth, Moon, and Mars, study of the volcanic features must include assessment of lava tubes and channels in the emplacement of the extensive lava flows.

Outer Solar System Satellites

The Jovian planets—so named for their resemblance to Jupiter—include Saturn, Uranus, and Neptune as well as Jupiter. All are enormous gaseous planets composed predominantly of hydrogen and helium and lack solid surfaces. Although they are not amenable to geological study, they all have solid-surface satellites, many of which exhibit extensive geological modification.

Jupiter's four large moons were first discovered by Galileo in the early 1600s. They include two objects—Ganymede and Callisto—that are about the size of Mercury, but which have low densities, suggestive of water-ice compositions. The other two moons, Io and Europa, are about the size of Earth's Moon and have densities suggestive of rocky material. Two Voyager spacecraft returned extensive data on the Jupiter system and revealed the first evidence for active volcanism in the Solar System outside of Earth. Voyager images show that eruptions are taking place constantly on Io, with pyroclastic material raining down on the surface nearly everywhere. In addition, high resolution Voyager images show countless flows emanating from enormous calderas. Spectral reflectance data suggest that sulfur is present on the surface of Io and it has been proposed that some of the flows may be composed of liquid sulfur. Although rare and of limited extent, sulfur flows have been observed on Earth and contain small tube-like features. If such features can form at larger scales on Io, they would be important in transporting liquid sulfur lava long distances in the frigid (-140° Celsius) environment of the outer Solar System.

Jupiter's Europa and Ganymede; Saturn's Enceladus, Tethys, and Dione; and Uranus' Miranda are all ice-rich satellites that show large, smooth plains areas. These areas lack abundant superposed impact craters and are considered to be geologically young. The plains are thought by most planetary scientists to have formed by the eruption of slushy ice onto the surface as a consequence of interior heating and melting of ice. Fracture systems seen in association with some of the plains probably served as eruptive conduits to the surface. In some cases, the fractures are ancient features that formed in response to large impact events. In other cases, the fractures appear to have formed in response to internal activity and crustal deformation. Such internal activity and the eruption of liquids onto the surface of some small moons was a surprise to most planetary scientists. Prior to the exploration of the outer Solar System, the degree of internal activity was considered to be a function of planetary mass—large planets would contain more radioactive elements and hence generate more heat and magma. Small objects, such as 500-kilometer-in-diameter Enceladus, were thought to be far too small to generate sufficient heat to melt rocks or even ice. The discovery of active volcanoes on Io (and on Neptune's moon Triton) caused a reassessment of these ideas, and it was recognized that factors other than radioactive heating can generate magma and lead to active volcanism. For example, Io resides in an orbit between Jupiter and another moon, Europa. As such, it is constantly subjected to gravitational tides that push-pull its crust. Frictional heat generated by this tidal stressing is more than adequate to melt parts of Io and to drive the volcanism observed today.

Unfortunately, most images of the outer planet satellites are of low resolution and primarily provide only a reconnaissance of their surfaces. Details of the styles of emplacement and history of the materials that flooded onto the surfaces of these objects must await better data to be obtained on future missions. For example, the Galileo mission, launched in 1989 and currently on its way to Jupiter, will be in orbit around this giant planet for some 20 months beginning in late 1995. During that time it will make repeated passes of the Galilean satellites and obtain images of 10 to 100 times better resolution than the Voyager images. In addition, tentative approval has been given for a joint NASA European Space Agency mission named Cassini. Like the Galileo mission to Jupiter, Cassini will involve a spacecraft placed in orbit around Saturn and will observe not only the giant planet and its rings, but it myriad satellites as well.

Summary

Solar System exploration has demonstrated that volcanism is an important geological processes on the terrestrial planets—Earth, Moon, Mars, and (possibly) Mercury—and on many of the satellites of the outer Solar System. While basaltic volcanism dominates most of the terrestrial planets, exotic (by Earth standards) compositions, such as ultramafic komatiites, sulfur, and carbonatite lavas, may also be found. Lava tubes and flow channels play an important role in the emplacement of many of the lava flows seen on the terrestrial planets. Understanding the origin and evolution of these flow features is critical to the derivation of the evolution of the planets where they are found.

Outer planet satellites include volatile elements such as sulfur, ice, and methane. Understanding the mechanics of eruption and emplacement of volatile and ice-rich materials must await future exploration by spacecraft such as Galileo and Cassini planned for later in this decade and extending into the next century.

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