VOLCANISM ON MARS

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GLOSSARY

Amazonian The youngest of the geologic epochs on Mars identified through geologic mapping of superposition relations, and the areal density of impact craters.

caldera An irregular collapse feature formed over the evacuated magma chamber within a volcano.

central volcano Emplacement of volcanic materials from a centralized source vent rather than along a distributed line of vents.

composite volcano A volcano consisting of intermixed effusive lava flows and pyroclastic materials. Flank slopes are typically $>10°$, or more than twice as steep as the flanks of a shield volcano.

Fossae Descriptor applied to an aligned series of fractures in a planetary surface.

Hesperian The intermediate geologic epoch on Mars identified through geologic mapping of superposition relations, and the areal density of impact craters.

Icelandite Volcanic rock with silica content comparable to an andesite, but which did not form as a result of subduction or orogenic processes.

Mons Descriptor applied to a large isolated mountain on a planetary surface.

Noachian The oldest of the geologic epochs on Mars identified through geologic mapping of superposition relations, and the areal density of impact craters.

Patera Descriptor applied to an irregular or complex crater with scalloped edges, surrounded by shallow flank slopes.

pseudocrater A "rootless vent" created by the interaction of lava with groundwater or wet sediments beneath the flow.

shield volcano A broad volcanic construct consisting of multitudes of lava flows. Flank slopes are typically $\sim 5°$, or less than half as steep as the flanks on a composite volcano.

SNC meteorites A group of meteorites thought to originate on Mars, due to a relatively young age and trapped gases very like the atmosphere of Mars. The acronym is derived from the names of the three meteorites that define the major subdivisions identified within the group: S, Shergotty; N, Nakhla; C, Chassigny.

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Tholus Descriptor applied to an isolated domical small mountain or hill, usually with slopes much steeper than that of a patera.

volcanic plains Planar mappable units interpreted to consist of volcanic materials, usually with individual flow margins resolvable within the unit.

yardang A rounded erosional landform produced by wind-driven sand. Some yardang fields on Mars are interpreted to be formed in wind-eroded pyroclastic deposits.

I. INTRODUCTION

The advent of spacecraft exploration revealed that Mars possesses some of the most dramatic volcanic features found anywhere in the solar system. How did a planet half the size of the Earth generate volcanoes like Olympus Mons, which is several times larger than the largest volcanoes on Earth? This question is just one example of the issues currently being investigated as part of the relatively recent scientific endeavor called "Comparative Planetology." This article will summarize the basic information presently known about volcanism on Mars. The reader can then compare the Martian volcanoes to the numerous volcanoes studied in great detail here on the Earth as well as to volcanoes observed on other planetary bodies.

Two generalizations can be made before we investigate the Martian volcanoes in greater detail. Volcanoes on Mars appear to be broadly similar in overall morphology (although different in scale) to volcanic features on Earth, so there is no direct evidence for Martian eruptive processes that are somehow significantly different from the volcanic styles and processes known on Earth. This inference strengthens our confidence in using the basic approach of attempting to understand the Martian volcanoes in terms of traditional volcanology. Next, the Martian volcanoes occur on terrains of various relative ages (discussed below), so that volcanism represents a dominant geologic process throughout much of Martian history. This is in contrast to volcanism on the smaller body of Earth's Moon, where volcanic activity was confined to roughly the first third of lunar history (see "Volcanism on the Moon"). Comparative planetology thus supports the concept that volcanism is the primary mechanism for a planetary body getting rid of its internal heat, where smaller bodies tend to lose their internal heat more rapidly than larger bodies (Jupiter's moon Io appears to contradict this trend because this object, the size of Earth's Moon, is the most volcanically active body in the solar system, but this activity is powered by unique gravitational tidal forces within the Jovian system; see "Volcanism on Io"). Next we review some important background information before examining the types of volcanic features present on Mars.

II. BACKGROUND

The first direct evidence of the importance of volcanism on Mars came during the Mariner 9 orbital mission. A massive global dust storm obscured the entire Martian surface when Mariner 9 arrived at Mars on November 14, 1971, but as the weeks passed, the dust slowly began to settle. The first surface features at equatorial latitudes to become visible through the dust pall were four dark "spots" in the region of the planet that telescopic observers called Tharsis. Gradually these spots were revealed to each be topped by a complex crater assemblage, the first clue that four huge volcanoes were present in the Tharsis area. By chance, the three previous fly-by Mariner missions failed to image this area in detail sufficient to show these large volcanoes. Mariner 9 continued to map the entire Martian surface until October 12, 1972, revealing that Tharsis was not alone in containing impressive volcanic constructs. The Mariner 9 view of Mars was updated significantly with the improved resolution of the cameras on the two Viking Orbiter spacecraft that operated at Mars from June 19, 1976, to August 17, 1980. The ~55,000 Viking Orbiter images led to refined interpretations for many Martian features, but they did not significantly alter the first global perspective of Mars revealed by the Mariner 9 images.

The distribution of volcanoes on Mars is not uniform; there are four regions where central volcanoes are concentrated (Fig. 1). Twenty-three volcanic constructs have been given names (Table I) by the International Astronomical Union, the only organization that can officially designate names for planetary features. The largest concentration of Martian volcanoes occurs in the Tharsis region, where the volcanoes are distributed on and around a 4000-km-diameter bulge in the Martian crust, centered on the equator at 110°W longitude. This bulge has lifted the crust to an elevation ~10 km above the Martian datum, twice as high as the highest portions of the cratered highlands that dominate the southern hemisphere of Mars (shaded portion of Fig. 1). The "Tharsis Bulge" is surmounted by three volcanoes collectively called the Tharsis Montes (5, 6, and 16 in Fig. 1), aligned along a N40E trend that includes addi-

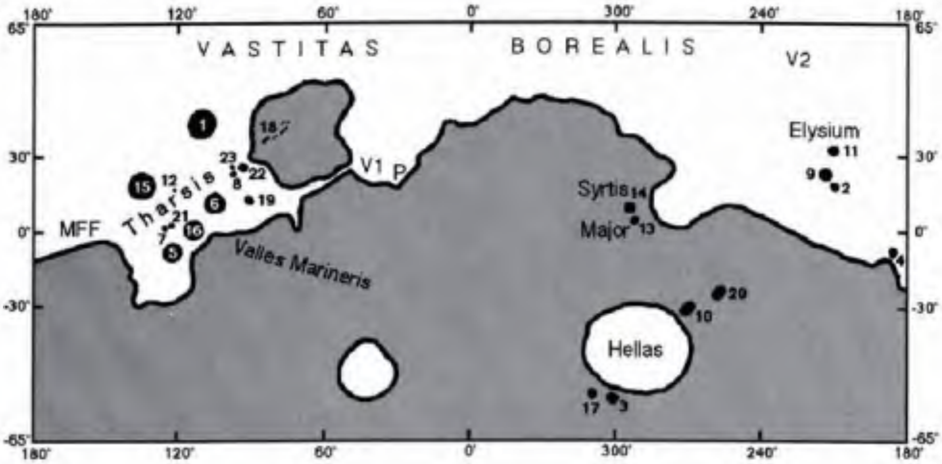

FIGURE 1 Location map for named central volcanoes on Mars. The black areas indicate various volcanic centers, with numbers keyed to Table I. The shaded area represents densely cratered materials typical of the highlands that dominate the southern hemisphere. Letters indicate landing sites (V1, Viking 1; V2, Viking 2, P, Mars Pathfinder) and the Medusae Fossae Formation (MFF). Mercator projection.

tional volcanic centers northeast of the Tharsis Montes. The Tharsis Montes and nearby Olympus Mons (15 in Fig. 1) are the four tallest features on Mars, the summit calderas of which were first imaged by Mariner 9 above the dusty lower atmosphere. Outside of the Tharsis area, Martian central volcanoes are confined to the Elysium, Syrtis Major, and Hellas regions (Fig. 1), all named for broad bright or dark surface markings visible with Earth-based telescopes. In addition to the named central volcanoes, broad expanses of regional plains exist across Mars, many of which include compelling evidence that they were formed by the emplacement of numerous individual volcanic flows.

The Mariner 9 and Viking images showed the physiographic makeup of the entire surface of Mars. Through careful observation of the superposition and cross-cutting relationships of distinctive material units, a global geologic sequence has been developed. The areal density of impact craters present on the various material units allows the relative stratigraphy to be established even where units are not in contact with each other. The convention defined for three major divisions of Martian geologic history are the Noachian (oldest), Hesperian (intermediate age), and Amazonian (youngest) epochs, providing a broad temporal sequence in which we can discuss the various Martian volcanoes. Unfortunately, the absolute age of these Martian epochs is very unconstrained at present; various models of the impact flux on Mars allow the Amazonian period to be from millions to billions of years in age. Most planetary scientists likely would accept that Amazonian materials represent events late in Martian history, but ages for documented samples collected from regionally expansive terrains are needed to constrain the precise time range covered by the cratering record on Mars. In spite of this uncertainty in absolute age, the geologic stratigraphy provides a robust framework in which the relative ages of various materials, including both central volcanoes and regional volcanic plains, can be evaluated.

Remote-sensing data provide information about Martian materials that is complementary to the photogeologic interpretation of spacecraft images. Reflected visual and infrared light provides compositional information by the wavelengths at which some of the light is selectively absorbed. Earth-based telescopic studies can not resolve individual volcanoes but reflectance spectra indicate that bright regions are covered with a dust that includes considerable oxidized iron whereas the dark regions are less dusty and may include pyroxene-bearing material such as mafic volcanic rock like basalt. Thermal infrared measurements by the Viking orbiters indicate that the Martian surface is coated with particulate materials, ranging from micron-sized dust covering practically all of surface in the bright regions to sand-sized particles mixed with larger unresolved blocks in the dark regions. Significantly, the Viking thermal measurements showed no "hot spots" attributable to internally generated heat anywhere on the planet. Radar signals transmitted from Earth and reflected from the Martian surface have shown that some individual volcanoes, such as the Tharsis Montes, display strong scattering behavior. The scattered radar signals indicate

TABLE 1 Named Volcanic Centers on Mars

Number	Name	Center	Horizontal scale[a] (km)	Relief[b] (km)
1	Alba Patera	40°N, 109°W	450	~4
2	Albor Tholus	19°N, 210°W	160	~5
3	Amphitrites Patera	59°S, 299°W	130	<1
4	Apollinaris Patera	8°S, 186°W	180	~5
5	Arsia Mons	9°S, 120°W	350	~11
6	Ascraeus Mons	11°N, 104°W	350	~17
7	Biblis Patera	2°N, 124°W	150	~4
8	Ceraunius Tholus	24°N, 97°W	150 × 100	~5
9	Elysium Mons	25°N, 214°W	300	~12
10	Hadriaca Patera	30°S, 266°W	180	<1
11	Hecates Tholus	32°N, 210°W	170	~6
12	Jovis Tholus	18°N, 117°W	60	~2
13	Meroe Patera	7°N, 291°W	50	<1
14	Nili Patera	9°N, 293°W	60	<1
15	Olympus Mons	28°N, 133°W	500	~25
16	Pavonis Mons	0°N, 113°W	350	~10
17	Peneus Patera	57°S, 307°W	120	<1
18	Tempe Fossae[c]	36°N, 86°W	3 × 1	≪1
19	Tharsis Tholus	13°N, 91°W	170 × 110	~6
20	Tyrrhena Patera	22°S, 253°W	180	~1
21	Ulysses Patera	3°N, 122°W	100	~2
22	Uranius Patera	26°N, 93°W	150	~1
23	Uranius Tholus	26°N, 98°W	60	~4

[a] Approximate horizontal dimension (maximum and minimum values for elongate features).
[b] Estimated relief from summit to the surrounding terrain; from U.S.G.S. (1991).
[c] Largest of several small features along Tempe Fossae (Fig. 4).

considerable surface roughness at the 10 cm to meter scale on the surface of the Tharsis Montes, something that may likely also apply to other volcanoes but which are too small to be clearly resolved with Earth-based radar. West of the Tharsis Montes, a region of several million square kilometers returns no radar signal back to Earth; this area has been nicknamed "Stealth" after its very low radar reflectance properties. Stealth could be a deposit sufficiently thick so that the radar signal is fully absorbed, such as through deposition of pyroclastic materials associated with the nearby volcanoes, or Stealth also might have unusual relief that efficiently scatters the radar signals away from the antennas on Earth.

III. Large Central Volcanoes

Olympus Mons and the three Tharsis Montes each have shapes typical of a basaltic shield volcano on Earth, but at non-Earth-like scales (Fig. 2). The flanks of the four mountains have maximum slopes of ~5°, with shallower summit and basal slopes, much like the shape of the subaerial portion of the Mauna Loa shield volcano. The great bulk of the Mauna Loa volcano, which with its subaqueous mass comprises the largest mountain on Earth, is still dwarfed by any one of these four mountains, but particularly by Olympus Mons with its 500-km diameter and 25-km vertical relief. The four Tharsis

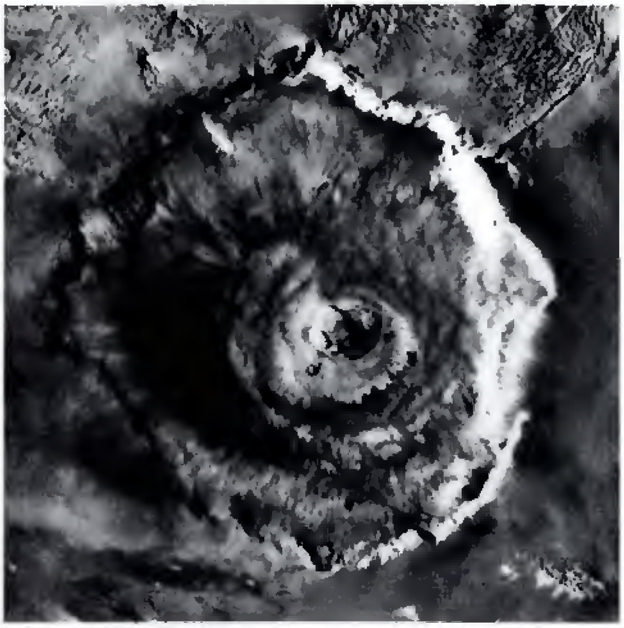

FIGURE 2 Olympus Mons, the largest central volcano on Mars (15 in Fig. 1 and Table I). Olympus Mons has shallow flank slopes typical of a shield volcano. The volcano has 25 km of relief from its summit to the plains surrounding the basal scarp, which is ~600 km in diameter and from 3 to 6 km in height. (Viking Orbiter image 646A28, courtesy of NASA.)

shield volcanoes are so large that their size is not fully appreciated without considering the curvature of the Red planet; an astronaut on the surface anywhere near these mountains could not see their summits because this would be beyond his (or her) local horizon!

The great size and height of the four large Tharsis volcanoes generated considerable discussion about their potential source regions. If bouyancy is assumed to be the sole driving force for a typical basaltic magma on Mars, the summits of the four large Montes volcanoes indicate their sources lie at depths >120 km, potentially implying a thick lithosphere in the Tharsis region. Interestingly, older Martian volcanoes generally display reduced relief (when compared to the Tharsis shields), so lithospheric thickness may have increased throughout Martian history. When combined with the lack of any obvious nearby plate tectonic features such as subduction arcs or transform faults, the great bulk of these mountains may result from mantle sources that released their magma at one location without the lithospheric movement we associate with plate tectonics on Earth. In this light, it is interesting that the volume of Olympus Mons is roughly comparable to the integrated volume of the Hawaiian-Emperor seamounts. The descriptor "Mons" refers to a large isolated mountain, and all four Tharsis shield volcanoes clearly deserve this designation.

The lower flanks of the Tharsis Montes have been buried by plains-forming flows emanating from the volcanoes themselves or vents in between them. Only Olympus Mons is surrounded by an arcuate scarp nearly 600 km in diameter and with 3–6 km of vertical relief (Fig. 2). The origin of the basal scarp at Olympus Mons remains controversial, but several enormous fan-shaped deposits northwest of the volcano have been interpreted to be gravitationally driven landslides, perhaps aided by volatile lubrication along the detachment surface. High-resolution Viking images show multitudes of interwoven lava flows extending down the flanks of Olympus Mons and over the basal scarp, spilling onto the surrounding plains. Many of the individual flows have medial channels similar to channel-fed lava flows on terrestrial volcanoes. Thermal infrared data indicate that all four of the volcanoes are thoroughly coated with fine windblown dust, severely limiting any information about the volcanic rocks that can be learned from most remote-sensing techniques.

As noted earlier, all four shield volcanoes are surmounted by summit calderas. Olympus and Ascraeus Montes have complex calderas revealing multiple episodes of collapse whereas Arsia and Pavonis Montes have only a single collapse rim preserved at present. Geophysical modeling of fractures around the caldera on Olympus Mons verifies that these features are consistent with collapse into evacuated magma reservoirs within the shield construct. By analogy to terrestrial shield volcanoes, these intermediate magma chambers may have been periodically replenished from a larger magma source located beneath the volcanic pile.

A separate volcanic center with its own crustal bulge (but one considerably smaller than the Tharsis Bulge) is present in the Elysium region (11 in Fig. 1). Elysium Mons is the largest construct in the region, and it has some important distinctions from the four Tharsis shield volcanoes. Elysium Mons has considerably steeper flank slopes (up to 12°) than the Tharsis shields, surmounted with one major caldera (although the floor preserves subtle details that suggest repeated collapse prior to the last lava infilling). The shape of Elysium Mons is somewhat reminiscent of conical composite volcanoes typical of subduction margins such as the Andes or the Cascades, but there are no associated features (such as a nearby trench) to indicate that subduction is in any way responsible for this Martian volcano. Following Mariner 9, Elysium Mons was compared to the volcano Tibesti in Africa, where an intracontinental hot spot is a more likely analog than an active plate margin. While there are some vocal supporters of possible subduction on Mars, the consensus impression since Mariner 9 has been the apparent dearth, if not total absence, of any classic plate tectonic features on Mars.

Alba Patera, north of the three Tharsis Montes (1 in Fig. 1), represents another important exception to the broad shield morphology. This volcano is only slightly smaller in horizontal dimension than Olympus Mons, but it lacks the dramatic relief present on the Tharsis shields and Elysium Mons (Table I). Early results from the Mars Orbital Laser Altimeter on the Mars Global Surveyor spacecraft indicate that this volcano has flank slopes ≤1°, much less than the already shallow 5° flanks of the shield volcanoes. Even more unique is a band of dense fractures that makes almost a complete ring around this shallow-sloped construct. Some researchers have compared this tectonic pattern to that which would surround a core of competent rock that is subjected to intense regional stress; such an interpretation would imply that Alba Patera was completely solidified well before the regional stress pattern was imposed. Crater densities indicate that Alba Patera has been exposed to the impacting bombardment longer than either the Tharsis shields or Elysium Mons, but some volcanic effusion may have postdated the stress that produced the distinctive arcuate band. Recently, it was proposed that Alba Patera may be a Martian example of a Venusian corona (see "Volcanism on Venus"); such an interpretation has profound implications for crustal thicknesses on Mars during an epoch when other comparable thin-lithosphere features are not readily apparent. As we shall see next, Alba Patera is not representative of the majority of features that have been given the name "patera."

IV. Paterae and Tholi

Alba Patera is the largest member of a class of volcanic construct on Mars that is quite distinct from the Mons-type volcanoes. The descriptor "Patera" refers to an irregular or complex crater with scalloped edges that is surrounded by shallow flank slopes. These features contrast greatly with impact craters or basins of comparable size, and a volcanic caldera is the consensus interpretation. Another distinctive class of volcanic construct, which is consistently smaller than the Mons type, has the descriptor "Tholus" applied to an isolated domical small mountain or hill, usually with slopes much steeper than those of a patera. Both Paterae and Tholi (other than Alba Patera discussed above) are generally smaller than 200 km in diameter (Table II).

Paterae in the Tharsis region (7, 21, and 22 in Fig. 1) tend to have caldera diameters more than half as broad as the overall construct. This observation led some researchers to conclude that such paterae may be the summits of shield volcanoes whose lower flanks have been buried by more recent volcanic plains, which seems quite reasonable for the Tharsis region, where volcanic plains are abundant and likely quite thick. Tholi in the Tharsis region (8, 12, 19, and 23 in Fig. 1) tend to have slopes steeper than those of the shields but usually not as steep as Elysium Mons. Some volcanoes (e.g., Ceraunius Tholus) have sinuous channels carved into their flanks, implying significant effusive (and erosive) flow after the bulk of the construct formed (Fig. 3). A few researchers have interpreted the erosive channels on tholi and paterae flanks to be due to pyroclastic flows. The buried-

FIGURE 3 Ceraunius Tholus, a volcanic dome with an elongate crater from an oblique impact at its northern base (8 in Fig. 1 and Table I). The volcano is noncircular, with dimensions 150 × 100 km. At least one sinuous channel carved into the volcano was active after the oblique impact since a riverlike "delta" formed in the crater where its rim was breached by the lava channel. (Viking Orbiter image 516A24, courtesy of NASA.)

shield interpretation for paterae has difficulty accounting for the close proximity of both broad patera and steep tholus in the Tharsis region (8, 22, and 23 in Fig. 1), where the tholi volcanoes may indicate either effusive or compositional properties quite different from those of paterae volcanoes.

The Elysium region has paterae and tholi as well, although fewer than in the Tharsis region (2, 4, and 9 in Fig. 1). These volcanoes have both scoured flanks and, on Hecates Tholus, a portion of the summit area where very few impact craters are preserved. Both characteristics have been interpreted to result from pyroclastic activity: erosive pyroclastic flows to generate the flank scours and an inferred ash deposit following a plinian-style eruption at the summit of Hecates Tholus. Neither of these interpretations should be considered proof of pyroclastic activity, but they do suggest an increased possibility for a pyroclastic component associated with paterae- and tholi-style eruptions, as compared to Mons-style volcanoes.

FIGURE 4 Tyrrhena Patera, one of the low-profile paterae in the southern highlands near the rim of the Hellas impact basin (20 in Fig. 1 and Table I). The radiating pattern of channels has eroded into material ~180 km in diameter, interpreted to be ash deposited around the volcanic vent. (Viking Orbiter image 87A14, courtesy of NASA.)

V. Highland Paterae

Paterae located in the cratered highlands of Mars deserve special treatment because they appear to have several characteristics distinct from those of the small volcanoes in the Tharsis and Elysium regions. The highland paterae are concentrated in two regions: a linear trend of four volcanoes on the outer rim of the Hellas impact basin in the southern hemisphere (3, 10, 17, and 20 in Fig. 1), and two vents relatively recently identified within the classical dark region of Syrtis Major in the northern hemisphere (13 and 14 in Fig. 1). Both regions include evidence that suggests that pyroclastic materials comprise an important fraction of the products produced by these highland paterae, suggesting that volcanism in the highlands may have involved eruptions fundamentally different from those that produced the broad Mons volcanoes, the shallow paterae, or the steep tholi.

The four paterae on the rim of the Hellas basin are notable in that all possess very shallow flank slopes, likely much less than the shallow 1° flanks of Alba Patera. The Hellas volcanoes are more noteworthy for their intensely eroded appearance than for any obvious construct around the central vent (Fig. 4). The channels cut deeply into the flanks of the Hellas paterae have been interpreted to indicate removal of friable material concentrated around the central vent, possibly through either fluvial or volcanic processes, or both. The logical way to build up a broad low-profile deposit of friable materials around a volcanic vent is through deposition of pyroclastics. Currently, it is not clear if pyroclastic flows or falls are the dominant agent for emplacement of the ash, and both processes appear to be viable candidates. What is apparently rare at these volcanoes is a significant effusive lava flow component. The top of the friable deposit at each volcano appears to be more competent, forming a caprock between channels eroded into the deposit; this resistant zone may be case-hardened or indurated friable materials, or it may involve some effusive lava flows, but this is difficult to resolve with current data. All four Hellas volcanoes represent a substantially different style of eruption and emplacement than the other central volcanoes discussed above, suggestive that the magma involved may have somehow been different (increased volatile content?) from the effusive lavas that dominate the more recent Martian volcanoes.

Nili and Meroe Paterae were only recognized as being volcanic vents in the 1980s, long after Mariner 9 and the early Viking images established the presence and types of the other volcanic centers. Both paterae are near the center of the Syrtis Major dark region that has been observed telescopically from Earth for several centuries. Remote-sensing data of the Syrtis Major region indicate the dark materials are significantly less oxidized than the bright dusty portions of the planet, with strong indications of a mafic chemistry that likely includes a pyroxene component. When the volcanic vents were identified, researchers proposed that the dark material in Syrtis Major may in fact be wind-transported mafic volcanic ash. Viking images in Syrtis Major reveal abundant dark dunelike features, supporting the concept that wind action in crucial to the story of this area. The action of the wind on the individual ash particles may help to remove an oxidation coating as the grains bounce into each other.

VI. Small Constructs

Mars has numerous occurrences of small domes, some of which may have a volcanic origin. Unfortunately, these features are mostly small enough that Viking imaging data are not sufficient to provide definitive evidence for their origin. One of these features that is big enough to show some important physical characteristics is found in the Tempe region, within a zone of fractures called Tempe Fossae (Fig. 5). Here an oblong low mound is present around an elongated summit depression (between the arrows in Fig. 5). The depression follows the trend of the surrounding fractures, so that structural control likely played a role in determining where vented materials could reach the surface. The vast majority of these features are smaller than the Tempe example; typically, the individual domes are <1 km in diameter and at most a few hundred meters in height. A popular interpretation of their origin is that of cinder cones, with the variation that some may be pseudocraters where a lava flow interacted with either a shallow water layer or wet sediments. There are literally thousands of these features in various places throughout the northern lowlands of Vastitas Borealis (Fig. 1), so that either a cinder cone or pseudocrater origin would imply abundant water–lava interaction across the northern plains. An alternative nonvolcanic interpretation is a periglacial feature such as a pingo (an ice-cored mound).

The final category of distinct volcanic landforms on Mars consists of about two dozen deeply dissected conical hills scattered throughout the highlands. These features typically are <30 km in diameter and were only recognized as potentially of volcanic origin through careful study of the extensive Viking database. There are no names given to these features, nor is there any obvious pattern to their occurrence throughout the highlands. The dominant characteristic is deep scours present on all of their flanks, similar to the scoured exteriors of some paterae that are thought to have been subjected to pyroclastic flows. Assuming they are volcanic in origin, they appear to represent yet another distinct style of volcanic deposit confined to the old densely cratered highlands of Mars. The eroded domical hills cannot be dated by crater density due to their small areal extent, but their presence solely within the ancient materials of the cratered highlands leads most researchers to assume an old age for these features.

FIGURE 5 Small volcano (between arrows) located along Tempe Fossae (18 in Fig. 1 and Table I). Solar illumination from the left indicates an elongate mound built up around a very elliptical depression, probably analogous to a Strombolian eruption along a linear vent. The feature is ~3 km in length and likely <300 m in vertical relief. (Viking Orbiter image 627A28, courtesy of NASA.)

VII. Volcanic Plains

Volcanic plains comprise some of the most extensive geologic units on Mars outside of the cratered highlands. The plains tend to be quite featureless at moderate to low resolution, but in high-resolution images, these plains display numerous lobate margins surrounding individual packages of material that appear to have been emplaced through flow of fluid materials (Fig. 6). The lobate margins are sufficiently thick (various measurements indicate lobe thicknesses of tens to hundreads of meters) that the flowing material is widely accepted to be lava rather than something like a water-rich debris flow. Volcanic plains surround both the Tharsis and Elysium volcanic centers, and a stacked sequence of such flows likely accounts for a significant part of the topographic bulges surrounding these centers. Volcanic plains also comprise regionally extensive units in locations that presently do not have visible volcanic constructs. In particular, the plains of the Lunae Planum area east of the Tharsis region and the Hesperia Planum plains northeast of the Hellas basin extend over many thousands of kilometers, and both of these plains have crater densities that indicate a Hesperian age that must be older than the volcanic plains around Tharsis and Elysium. Thus substantial outpourings of plains-forming lava flows, likely from vents that are themselves buried beneath the thick pile of flows, were significant events during both the Hesperian and Amazonian epochs.

FIGURE 6 Lava flow margins on the Elysium plains near Hecates Tholus. Image width ~54 km, centered on 32.2°N, 213.5°W. (Viking Orbiter image 651A10, courtesy of NASA.)

The volcanic plains of Mars display flow features that can be divided into at least two broad categories: simple and complex. This distinction follows from an extension of George Walker's classification of terrestrial lava flows by the cooling units preserved in the volcanic sequence, with simple flows representing a single cooling unit of great extent (and probable large volume of effusion) and complex flows representing an intermixed sequence of discrete flow lobes that each comprise individual cooling units. Some plains units are nearly featureless in terms of detail visible in even the highest resolution orbital images, and many of these plains units may eventually turn out to be volcanic in origin, even though at present they are not readily placed within the simple or complex designation. Many of the volcanic plains that fill the floors of impact basins (like Hellas) or that lack clearly resolvable individual flows over wide areas are considered to be simple in the sense that the volcanic emplacement most likely was sufficiently rapid or prolonged to allow the plains to be considered as representing one major cooling unit. The younger volcanic plains around Tharsis and Elysium are primarily complex (as in Fig. 6), with numerous finger-like flow lobes traceable in some cases for many hundreds of kilometers. As orbital image resolution improves, as with the Mars Orbiter Camera on the Mars Global Surveyor spacecraft, some of the older volcanic plains likely may turn out to be made up of a series of complex flow lobes like the ones that surround Tharsis and Elysium.

Not surprisingly, some plains units are problematic in origin. These units tend either to be relatively featureless or to have such complicated surface exposures that their origin remains the subject of considerable controversy. The Medusae Fossae Formation southwest of the Tharsis region (MFF in Fig. 1) deserves a brief discussion here because although its origin remains controversial, one of the contending hypotheses is that this material is the result of massive pyroclastic eruptions. The Medusae Fossae Formation consists of several discrete layers of material that is very friable (eroded by the wind into huge fields of yardangs) but locally prominent caprock units help preserve the underlying materials. This observation has been compared to the welded and nonwelded zones present within many ignimbrite deposits on Earth. A significant problem with this hypothesis is that there is no indication of the possible source vent or vents, which is troubling if volcanic eruptions laid down ash that in places is over 2 km thick and that extends over several million square kilometers along the Martian equator, following the boundary between the southern cratered highlands and the northern lowland plains. The prospect of large ash-producing eruptions in this part of the planet is strengthened by recent remote-sensing observations that an area west of Arsia Mons and east of the majority of the Medusae Fossae Formation displays the unique property that Earth-based radar signals are not reflected from this broad area. "Stealth" has been interpreted to be associated with pyroclastic eruptions from vents west of the Arsia Mons volcano, which lends some support to possible major ignimbrite eruptions in the area.

VIII. COMPOSITIONAL CONSTRAINTS

Compositional information for Mars is available from three different sources: remote-sensing data (from either spacecraft instruments or Earth-based telescopes), on-site analyses by instruments on spacecraft that have returned data from three landing sites on Mars, and a special group of meteorites for which there is compelling evidence that these rocks were blasted from the surface of Mars and eventually fell to Earth. Each of these data sources has unique advantages and disadvantages as well as various limitations to the utility of the data. Here we will explore each data type for its implications for volcanic materials on Mars.

Remote-sensing studies of Mars began with telescopic measurements of various properties of the Martian surface and atmosphere, and since the 1960s these data have been augmented with higher spatial resolution data from a host of instruments on spacecraft that either flew by or orbited the planet. Earth-based instruments can achieve very high spectral resolution but only with relatively low spatial resolution on the planet (covering an area that may be hundreds of kilometers across). Spacecraft instruments tend to achieve substantially improved spatial resolution, but often this has come at the expense of spectral resolution. The ubiquitous Martian dust complicates this effort at any spatial resolution, masking significant portions of the surface within the instrument field of view and generally decreasing the contrast of the already subtle spectral features being sought. In spite of this handicap, remote-sensing data have shown that the dark regions of the planet have strong mafic affinities. Unfortunately, only the Syrtis Major volcanoes are present within a dark region, and the spectral information of other volcanic centers is effectively masked (at visual and thermal wavelengths) by the dust. Tens of microns of dust can strongly affect visual reflectance, and only 2 cm of dust can totally obscure even competent bedrock from thermal infrared observations.

The first concrete compositional information obtained for Martian materials came from an X-ray fluorescence instrument that was flown on both the Viking 1 and Viking 2 landers. In spite of the fact that the landers set down over 6000 km apart, the composition of the Martian fines at both sites was remarkably uniform (Table II), which in itself was a strong indication of the homogenizing influence of the regular global dust storms. Although repeated attempts were made to obtain a rock fragment with the Viking sample arm, no Martian rock was analyzed by the Viking instruments (centimeter-sized fragments all turned out to be indurated clods of dust). This situation changed dramatically in July of 1997 when the Mars Pathfinder mission successfully landed near the mouth of the Ares Vallis canyon and deployed the first mobile vehicle on Mars, the Sojourner rover. Sojourner had a spectrometer that the rover was able to place directly on several Martian rocks, as well as on the fine-grained materials between the rocks. The fines at the Pathfinder site were generally quite consistent with the fines observed at the Viking sites (Table II; note the differing sums for columns 2 and 3), but the rocks show distinct chemical differences from the fines ("Yogi" and "Barnacle Bill" in Table II). Images of the rocks at the Pathfinder site give a strong impression of being volcanic in origin, with ubiquitous pits that are likely vesicles. Assuming the rocks are volcanic, the compositions obtained from the Sojourner spectrometer imply they may be basaltic andesite. If the anomalously large sulfur content for the rocks is assumed to be contamination by dust on the rock surface, the measured silica contents become lower limits and at least some of the rocks may turn out to be andesites (e.g., "Barnacle Bill"), although recently the term Icelandite has been applied to these silica-enhanced rocks in an attempt to eliminate the subduction-related processes usually associated with the term andesite. Indeed, there is no evidence in or near the Pathfinder site for orogenic generation of andesite lavas, but fractional crystalization within isolated pockets of basaltic or basaltic andesite magmas could have generated some Icelandite-like rocks. The Pathfinder results are undergoing further refinement in association with the instrument calibration, so these results may be subject to revision at a later date.

The very best chemical information about Martian materials comes from 12 very special meteorites. These meteorites are considered to be from Mars because gases implanted in them during the shock of their ejection from their parent body is essentially identical to the atmosphere of Mars as measured by the Viking landers and unlike gases obtained from any other terrestrial or

TABLE 11 Chemical Compositions of Selected Martian Materials

Oxide	*Viking 1/Viking 2 fines*[a]	*Pathfinder fines*[b]	*Pathfinder "Yogi"*[c]	*Pathfinder "Barnacle Bill"*[c]	*Shergotty meterorite*[d]
SiO_2	43.3	49.0	55.5	58.6	51.4
Al_2O_3	7.1	8.4	9.1	10.8	7.1
FeO^e	17.4	16.1	13.1	12.9	19.4
MgO	6.0	7.9	5.9	3.0	9.3
CaO	5.7	6.3	6.6	5.3	10.0
K_2O	0.0	0.2	0.5	0.7	0.2
TiO_2	0.5	1.2	0.9	0.8	0.9
SO_3	7.5	5.4	3.9	2.2	0.1
Na_2O	—	3.0	1.7	3.2	1.3
Cl	0.5	0.5	0.6	0.5	—
Total	88.0	98.0	97.8	98.0	99.7

[a] Average of two samples of fines from Chryse (Viking 1) and four fines samples from Utopia (Viking 2); from Table 6.1 of Frankel (1996).

[b] Average of three fines samples (A2, A4, and A5) from Pathfinder; from Table 1 of Rieder *et al.* (1997). Note that results are reported as normalized to 98.0%.

[c] Results of two rocks (A7, Yogi; A3, Barnacle Bill) from Pathfinder; from Table 1 of Rieder *et al.* (1997). Results normalized to 98.0%.

[d] Martian meteorite Shergotty, a basaltic achondrite; from Table V, p. 605, in Kieffer *et al.* (1992).

[e] Total iron, regardless of oxidation state. Reported as Fe_2O_3 for column 2 and FeO for columns 3–6.

extraterrestrial sample. Eleven are igneous in nature and are only one-third the age (1.3 Ga to 180 Ma) of practically all other meteorites, and the twelfth has an older age more typical of most meteorites. Collectively called SNC meteorites, seven are basalts or lherzolites/harzburgites like the Shergotty (S) meteorite, three are clinopyroxenites or wehrlites like Nakhla (N), Chassigny (C) is the sole dunite, and ALH84001 is a ~4.5-Ga orthopyroxenite with veins of carbonate in which are controversial features that may (or may not) be evidence of primitive life from early in Martian history.

The SNC meteorites have told us a lot about Mars in general, but we unfortunately have no evidence for where on the Martian surface they came from. The abundance of volcanic rocks among the available group is consistent with the extensive coverage of Martian volcanic plains discussed above, but the young crystallization ages cannot be used to calibrate the geologic epochs on Mars without knowledge of what specific unit they came from. Some of the nonbasaltic rocks may have come either from slowly cooled cores of thick lava flows where limited fractionation may have taken place or possibly even from a plutonic body. ALH84001 likely came from somewhere in the cratered highlands of Mars, portions of which must date from practically the formation of the planet. In spite of this wealth of chemical detail, it will require the return of documented samples from known localities on Mars before we can relate the rock histories to regional or local geologic materials.

IX. VOLCANIC HISTORY OF MARS

The information presented in this article can be summarized into a general picture of the volcanic history of Mars. Without constraints on the cratering record for Mars, absolute ages cannot be associated with any of these stages. However, the stratigraphy of geologic units at least gives us a fairly clear picture of how volcanic eruptions developed throughout Martian history.

The oldest terrain on Mars is the Noachian densely cratered highlands, and if ALH84001 is representative of this era, at least some magmatic activity took place during this time of intense cratering. Isolated volcanic centers developed within the cratered highlands, most of which are preserved today only as deeply scoured small hills scattered throughout the southern highlands. The Hesperian epoch witnessed massive eruptions of fluid lava that produced volcanic plains that covered extensive portions of the Martian surface. The composition of these plains-forming materials was likely basaltic in nature, although Pathfinder results suggest that more evolved lavas (such as basaltic andesite) also may have been present. Several volcanic centers developed on the rim of the Hellas impact basin and within what is now the Syrtis Major dark region. These volcanoes involved the generation of considerable amounts of ash, leading to a very low overall profile and intense channelization by either fluvial or magmatic fluids. The unique Alba Patera feature may represent a volcano caught in the transition from the more ash-rich eruptions of the highlands to the more lava-rich eruptions typical of most subsequent eruptions.

The late-Hesperian and Amazonian epochs involved voluminous eruptions that resulted in both broad volcanic plains and numerous central volcanic constructs. Volcanic activity concentrated around the Elysium and Tharsis regions; crater densities suggest that effusive activity was most prolonged in the Tharsis region, where some volcanic surfaces are very sparsely cratered and thus may be quite young. Thousands of small domes in the northern lowland plains may be the result of either localized Strombolian activity (cinder cones) or the interaction of lava with water or wet sediments (pseudocraters). Not all of the volcanic activity in the Amazonian period may have been gentle effusion of lava; significant ash deposits may be present west of the Tharsis Montes, although the true nature of these enigmatic materials remains controversial. Volcanic materials are likely still being redistributed by current winds, such as in the Syrtis Major dark region.

X. Future Studies

Several issues about Martian volcanism remain unresolved at present, and hopefully the series of missions NASA has planned for Mars over the coming years will help to address some of these questions. The Pathfinder results have raised the possibility that lavas more evolved than basalt may have been important in Martian history. If this prospect turns out to be true on a global scale, it could have a major effect on our concepts of magmatic evolution on the terrestrial planets. Similarly, the question of the abundance and origin of pyroclastic deposits on Mars remains unclear at present, but this too could have an important influence on issues such as the volatile content of Martian magmas. The absolute age of all Martian terrains, volcanic as well as sedimentary or metamorphic in origin, remains a glaring uncertainty in all studies of the emplacement of volcanic materials on Mars. The return of documented samples from diverse localities on Mars would be the most definitive way to answer these and other outstanding questions about Martian volcanism, and fortunately NASA is actively planning toward that end. The Mars Surveyor program is an ambitious series of landers and orbiters targeted at addressing a host of science questions through repeated visits to Mars, culminating with the return of samples cached by mobile rovers. In preparation for the lander missions, sophisticated remote-sensing data will be collected from new technology sensors in orbit around Mars, as evidenced by the dramatic new data currently being returned by the Mars Global Surveyor spacecraft. All of these new data will undoubtedly add considerable detail to the volcanic history of Mars outlined in this article.

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See Also the Following Articles

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