Chapter 41

Volcanism on Mars

James R. Zimbelman
Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC, USA

William Brent Garry and Jacob Elvin Bleacher
Sciences and Exploration Directorate, Code 600, NASA Goddard Space Flight Center, Greenbelt, MD, USA

David A. Crown
Planetary Science Institute, Tucson, AZ, USA

Chapter Outline

GLOSSARY

AMAZONIAN The youngest geologic time period 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, which includes the potential for a significant role for explosive volcanism.

central volcano Edifice created by the emplacement of volcanic materials from a centralized source vent rather than from along a distributed line of vents.

composite volcano A volcano that consists of intermixed lava flows and pyroclastic deposits. Flank slopes are typically $>10°$, or more than twice as steep as the flanks on a typical shield volcano.

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

HESPERIAN The intermediate geologic time period on Mars identified through geologic mapping of superposition relations and the areal density of impact craters.

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

NOACHIAN The oldest geologic time period 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.

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

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

SNC meteorites A group of igneous meteorites that originated on Mars, as indicated by a relatively young age for most of these meteorites, but most importantly because gases trapped within glassy parts of the meteorite are identical to the atmosphere of Mars. The abbreviation is derived from the names of the three meteorites that define major subdivisions identified within the group: S, Shergotty; N, Nakhla; C, Chassigny.

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

volcanic plains Planar mappable units interpreted to consist of volcanic materials, often with individual lava flow margins resolvable on the plains surface.

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

1. INTRODUCTION

Spacecraft exploration has revealed abundant evidence that Mars possesses some of the most dramatic volcanic landforms found anywhere within the solar system. How did a planet half the size of Earth produce volcanoes like Olympus Mons, which is several times the size of the

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largest volcanoes on Earth? This question is an example of the kinds of issues currently being investigated as part of the space-age scientific endeavor called "comparative planetology." This chapter summarizes the basic information currently known about volcanism on Mars.

The volcanoes on Mars appear to be broadly similar in overall morphology (although, often quite different in scale) to volcanic features on Earth, which suggests that Martian eruptive processes are not significantly different from the volcanic styles and processes on Earth. Martian volcanoes are found on terrains of different age, and Martian volcanic rocks are estimated to comprise more than 50% of the Martian surface. This is in contrast to volcanism on smaller bodies such as Earth's Moon, where volcanic activity was mainly confined to the first half of lunar history (see "Volcanism on the Moon"). Comparative planetology supports the concept that volcanism is the primary mechanism for a planetary body to get rid of its internal heat; smaller bodies tend to lose their internal heat more rapidly than larger bodies (although, Jupiter's moon Io appears to contradict this trend; Io's intense volcanic activity is powered by unique gravitational tidal forces within the Jovian system; see "Volcanism on Io"), so that volcanic activity on Mars would be expected to differ considerably from that found on Earth and the Moon.

2. BACKGROUND

The first evidence of the importance of volcanism on Mars came during the Mariner 9 mission, the first spacecraft to be placed in orbit around another planet. Mariner 9 arrived at Mars on November 14, 1971. The first surface features to become visible were four dark "spots" in the region of the planet that telescopic observers called Tharsis. These spots were revealed to each have complex crater assemblages at their summits, which was the first indication that four huge volcanoes are located in the Tharsis region. Mariner 9 eventually mapped the entire Martian surface, showing that the Tharsis region was not the only location with clear evidence of volcanism. This initial Mariner 9 view of Mars has been updated by the steadily improved spatial resolution of cameras and other instruments carried on two Viking orbiters, the Mars Global Surveyor, Mars Odyssey, the Mars Express orbiter, and most recently the Mars Reconnaissance Orbiter.

The distribution of volcanoes on Mars is not uniform; there are several regions where central volcanic constructs are concentrated (Figure 41.1). Many of the largest volcanic constructs have been given names by the International Astronomical Union (Table 41.1), the only organization that can designate official names for features on planetary surfaces. The largest concentration of Martian volcanoes is within 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 250° E longitude. The "Tharsis Rise" represents crust that is elevated ~10 km above the Martian datum level, which is twice the elevation of the highest portions of the cratered highlands that dominate the southern hemisphere of Mars.

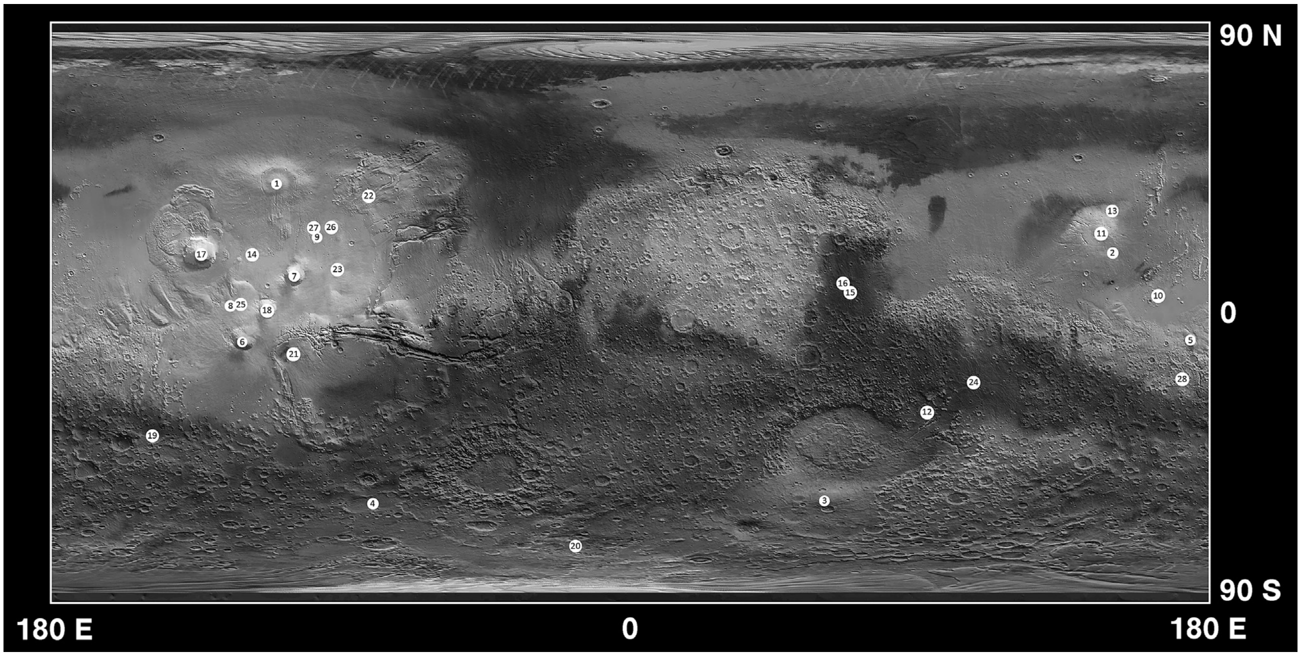

FIGURE 41.1 Location map of major named volcanic features on Mars. Numbers correspond to features listed in Table 41.1. Base map is shaded relief MOLA topography with superposed THEMIS TES albedo. NASA/JPL-Caltech/ASU.

TABLE 41.1 Major Volcanic Centers on Mars

Number[1]	Name[2]	Location[2]	Diameter[2] (km)	Relief[3] (km)
1	Alba Mons	41.1, 249.3	1100	5.8
2	Albor Tholus	18.9, 150.5	160	4.2
3	Amphitrites Patera	−58.7, 60.9	130	0.5−1.5
4	Aonia Tholus	−59.0, 280.0	60	–
5	Apollinaris Mons	−9.1, 174.8	280	5.4
6	Arsia Mons	−8.3, 239.9	470	11.7
7	Ascraeus Mons	11.9, 255.9	460	14.9
8	Biblis Tholus	2.5, 235.6	170	3.6
9	Ceraunius Tholus	24.0, 262.8	130	6.6
10	Cerberus (region)[4]	5, 262	700	–
11	Elysium Mons	25.0, 147.2	400	12.6
12	Hadriacus Mons	−31,3, 91.9	450	1.1
13	Hecates Tholus	32.1, 150.2	180	6.6
14	Jovis Tholus	18.2, 242.6	60	1.0
15	Meroe Patera	7.0, 68.8	50	(<0.5)[5]
16	Nili Patera	9.0, 67.2	70	(<0.5)[5]
17	Olympus Mons	18.7, 226.2	610	21.1
18	Pavonis Mons	1.5, 247.0	370	14.0
19	Sirenum Mons	−38.2, 212.2	120	–
20	Sisyphi Tholus	−75.7, 341.5	30	–
21	Syria Mons	−13.9, 255.7	70	–
22	Tempe (region)[4]	35, 275	300	–
23	Tharsis Tholus	13.3, 269.3	150	7.4
24	Tyrrhenus Mons	−21.6, 105.9	270	1.5
25	Ulysses Tholus	3.0, 238.5	100	1.5
26	Uranius Mons	26.9, 267.9	270	3.0
27	Uranius Tholus	26.3, 262.4	60	2.9
28	Zephyria Tholus	−19.8, 172.9	40	–

[1]*See Figure 41.1 for locations on a global map.*
[2]*Name, center location, and feature diameter (rounded to 10 km) from the Gazateer of Planetary Nomenclature Web site (8/2013).*
[3]*Relief derived from MOLA data, from Table 1 of Plescia (2004).*
[4]*Many small volcanic centers occur within a broad region. Cerberus Tholi are several separate small volcanic centers with radiating flows, each 20−50 km in diameter. The Tempe region includes E. Mareotis Tholus (Figure 41.5), Issedon Tholus, N. Mareotis Tholus, and W. Mareotis Tholus as named volcanic features.*
[5]*Estimated relief of the individual constructs, not of the Syrtis Major region as a whole, as shown in Table 1 of Plescia (2004).*

The Tharsis Rise is surmounted by three large volcanoes that are collectively called the Tharsis Montes, aligned along a N40E trend that includes additional volcanic features northeast of the Tharsis Montes. Olympus Mons (Figure 41.2) is larger than any of the three Tharsis Montes, at least in part because it is located on the flank of the Tharsis uplift, but it still reaches heights comparable to that of the tops of the Tharsis Montes. Outside of the Tharsis region, Martian **central volcano**es are present in the Elysium, Syrtis Major, and Hellas regions, all named for broad bright or dark areas visible to astronomers using Earth-based telescopes. In addition to the regions with large

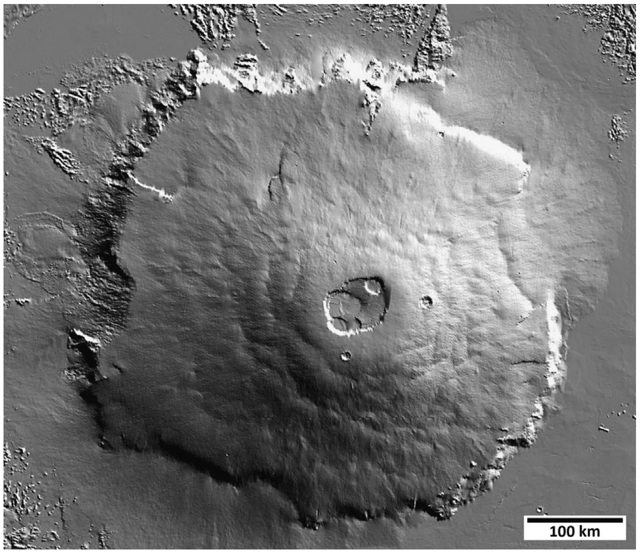

FIGURE 41.2 Olympus Mons, the largest shield volcano on Mars. Shaded relief version of MOLA topographic data. NASA/JPL-Caltech/GSFC.

central volcanoes, broad expanses of regional plains are present across Mars, many of which show compelling evidence that the plains were formed by the emplacement of numerous lava flows.

Through careful observation, a global geologic sequence has been mapped across Mars. The areal density of impact craters on the various material units allows a relative stratigraphy to be established even where units are not in physical contact with each other; recent consensus among the researchers who count impact craters led to absolute ages that can be associated with a statistically significant areal density of impact craters. Three major divisions are now recognized for the geologic history of Mars: the **Noachian** is the oldest era, and it includes materials from the formation of Mars to ~3.8 Ga; the **Hesperian** is an intermediate era where water was quite abundant across the planet, covering rocks emplaced between ~3.8 and ~3.0 Ga; and the **Amazonian** is the youngest era, with rocks emplaced from ~3.0 Ga to the present. The eventual collection of documented samples for precise age-dating will hopefully refine and calibrate these broad age designations.

Remote sensing instruments provide data about Martian materials that are complementary to the photogeologic interpretation of spacecraft images. Reflected visual and infrared light provide compositional information by the specific wavelengths at which some of the light is selectively absorbed. Earth-based telescopic studies cannot resolve individual volcanoes on Mars, but reflectance spectra indicate that bright regions, where the largest Martian volcanic provinces are found, are covered with dust that includes considerable oxidized iron, whereas the dark regions are less dusty and show evidence of pyroxene-bearing materials that are common in mafic volcanic rocks such as basalt. Thermal infrared measurements indicate that most of the Martian surface is covered by particulate materials, ranging from the pervasive micron-sized dust to sand-sized particles mixed with larger blocks in the dark regions. Importantly, no thermal measurements from anywhere on Mars have revealed "hot spots" that might be attributable to internally generated heat.

A major advancement in understanding the entire Martian surface was the collection of millions of individual reflected laser points by the Mars Orbiter Laser Altimeter (MOLA). MOLA provided the first global topographic map of Mars where all of the points were tightly constrained by their distance from the center of mass of the planet. Both heights and slopes can be determined accurately from the MOLA measurements, which led to substantial improvements in our understanding of the shapes and topographic characteristics of Martian volcanoes. A shaded relief version of the global MOLA data set is the base map used in Figure 41.1.

Radar signals sent from antennas both on Earth and on spacecraft have shown that some individual Martian volcanoes, like the Tharsis Montes, display very strong scattering behavior. The scattered radar signals indicate the presence of considerable surface roughness at the 10 cm to meter scale on the Tharsis Montes volcanoes, an attribute that may also apply to other Martian volcanoes but the smaller size of other constructs complicates a clear inference of their properties. West of the Tharsis Montes, an area of several million square kilometers displays no reflected radar signal, nicknamed "Stealth" after this extremely low radar reflectance property. Stealth may represent a deposit that is sufficiently thick so that radar signals are absorbed rather than scattered, or Stealth may also have an unusual surface texture that efficiently scatters the radar signals away from the receiving antennas.

3. LARGE CENTRAL VOLCANOES

The four prominent volcanoes in the Tharsis region are some of the largest known volcanoes in our solar system. Olympus Mons (17 in Figure 41.1 and 41.2) and the three Tharsis Montes volcanoes are analogous to **shield** volcanoes here on Earth, except on a much larger scale. The sizes of these volcanoes are so grand (basal diameters are hundreds of kilometers) compared to the overall size of Mars and the slopes along the flanks are so low ($\leq 5°$) that an astronaut hiking up the flank would not be able to see the top over the horizon due to the curvature of the planet. Olympus Mons has a basal diameter of 500 km, and 25 km in vertical relief, that would dwarf Mauna Loa volcano here on Earth. The term "**mons**" refers to a large isolated mountain. The four volcanoes contain similar morphologic and structural features that suggest similar processes through their geologic history. A central **caldera** is located at the summit of each volcano. The overlapping nature of the summit pits (which are complex, sometimes nested calderas) indicates that a magma chamber may have been evacuated multiple times within the constructs.

At first glance, the primary flanks of these volcanoes may appear relatively featureless, but high-resolution images from recent missions reveals amazing details of an array of lava flow morphologies (e.g., channeled flows, tube-fed flows, small shields) that have constructed and shaped these shields over time. Irregular channels and canyons are eroded into the shield materials on the northeast, and southwest flanks of Arsia, Pavonis, and Ascraeus Montes (6, 18, and 7 in Figure 41.1) are structural remnants of a series of breaches that created rift aprons comprised of long lava flows and small shields. Lava flows from the rift aprons are hundreds of kilometers long and surround the base of the main flanks as well as extend toward the perimeter of the Tharsis Rise. The volume of material erupted from the rift aprons is generally at least an order of magnitude less than the volume erupted to form the main flanks of the Tharsis Montes, and is more widely spread across the top of the Tharsis Rise. Several researchers have noted morphologic differences between the rift aprons and the main constructs, suggesting that the rift aprons may represent an eruptive episode very distinct from that which formed the bulk of the shield constructs.

The Elysium region is another important volcanic center on Mars, located to the west of the Tharsis Rise. The Elysium volcanic region includes Elysium Mons, Hecates Tholus, and Albor Tholus (11, 13, and 2 in Figure 41.1). Surrounded by the low plains of the northern hemisphere of Mars, Elysium Mons is similar in scale to the Tharsis volcanoes, but with a different topographic profile. The summit of the Elysium Mons construct is relatively steep (slopes up to 12°), giving the profile a more conical appearance, as compared to the low slopes near the summits of the four large shield volcanoes in Tharsis. While the overall profile may be different, high-resolution images show that flow morphologies on Elysium Mons (channeled flows, tube-fed flows) are similar to those observed on the Tharsis volcanoes. Lava flows from Elysium Mons are quite extensive, extending more than 700 km from the summit, which is surmounted by a single caldera about 14 km in diameter, although the floor of the caldera preserves subtle details that suggest repeated collapse occurred prior to the last lava infilling.

Alba Mons (formerly Alba Patera; 1 in Figure 41.1) is a broad volcanic construct north of the Tharsis Montes, but the morphology of the Alba structure is atypical of that of other shield volcanoes on Mars. The diameter of Alba Mons is similar in scale to that of Olympus Mons, but the overall height is lower and slopes are quite gentle ($\leq 1°$), giving the volcano a relatively flat, less dramatic profile than its Martian counterparts. A caldera complex is present at the summit of a central edifice that was constructed on an extensive apron of early-phase lava flows that extend nearly 1000 km from the summit region. High-resolution images and topography show that Alba Mons is comprised of long lava flows and tube-fed flows much like the Tharsis and Elysium volcanoes; however, the Alba eruptions resulted in a very different final morphology. Compelling features present near Alba Mons are the dense swarm of arcuate fractures (graben) that surround this volcano, some of which are partially filled by subsequent eruptions.

4. PATERAE AND THOLI

The descriptor "**patera**" refers to an irregular or complex crater, often with scalloped edges; these complex craters often are surrounded by slopes that are considerably less than the slopes encountered on shield volcanoes. Such features contrast greatly with impact craters or basins of comparable size, so that a volcanic caldera origin is the consensus interpretation. Another distinctive class of volcanic construct, which is consistently smaller than features of the mons type, has the descriptor "**tholus**" that is applied to an isolated domical small mountain or hill, usually with slopes much steeper than the shallow slopes around a patera. Both paterae and tholi (the plural form of these terms) are generally smaller than 200 km in diameter (Table 41.1).

Former paterae in the Tharsis region were recently renamed either Tholus or Mons. Uranius Mons (26 in Figure 41.1) is now recognized by orbital elevation measurements to be considerably larger than the previously named Uranius Patera, which had been applied to features that are now seen to be at the summit of a much broader regional rise that is part of the volcano structure. Tholi are very abundant in the Tharsis region (8, 9, 14, 23, 25, and 27 in Figure 41.1). Slopes on tholi tend to be steeper than those of the large Tharsis shield volcanoes, but the slopes are typically not as steep as those on Elysium Mons. Ceraunius Tholus (9 in Figure 41.1) has sinuous channels carved into the flanks of the volcano, implying that significant effusive (and erosive) flows occurred after the bulk of the construct had formed (Figure 41.3). Some early researchers concluded that such erosive channels on tholi and paterae flanks may be due to pyroclastic flows, while others prefer to interpret the channels to be the result of concentrated fluvial activity that postdates the volcanic activity.

The Elysium region includes two tholi in addition to Elysium Mons (2, 11, and 13 in Figure 41.1); this group represents a substantially lower areal density of volcanic centers than the numerous constructs in the Tharsis region, but Elysium is the second highest volcanic rise on Mars. Hecates Tholus (13 in Figure 41.1) has numerous channels on its flanks and portions of the summit area with few

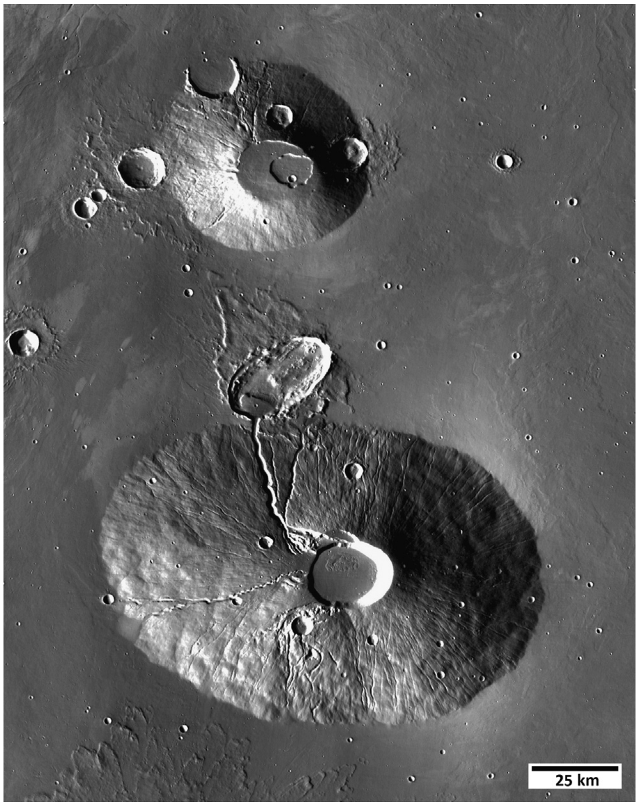

FIGURE 41.3 Ceraunius (bottom) and Uranius (top) Tholi. Channels have been eroded into the flanks of Ceraunius Tholus, with a possible "lava delta" at the mouth of one channel, emplaced within an elliptical impact crater north of the volcano. Portion of THEMIS Daytime IR mosaic. NASA/JPL-Caltech/ASU.

preserved impact craters; both characteristics have been interpreted to be the result of pyroclastic activity late in the history of this volcano. Meroe and Nili Paterae (15 and 16 in Figure 41.1) are near the summit of a broad 4-km-high rise that is associated with the classical low-albedo region named Syrtis Major, where remote sensing reveals the presence of both olivine and pyroxene. Apollinaris Mons and Zephyria Tholus (5 and 28 in Figure 41.1) are located on the broad boundary between the southern cratered highlands and the northern lowland plains; both volcanoes are not too far from the landing sites of the Spirit and Curiosity rovers. Six volcanic centers (including paterae, tholi, and mons) have been identified within the intensely cratered (old) southern highlands (3, 4, 12, 19, 20, and 24 in Figure 41.1), so volcanic activity was significant through essentially all of the history of Mars.

5. HELLAS HIGHLAND VOLCANOES

The cratered highlands surrounding the Hellas basin in the southern hemisphere of Mars exhibit a variety of volcanic landforms, most notably ancient, eroded volcanoes (formerly called highland paterae) and vast plains

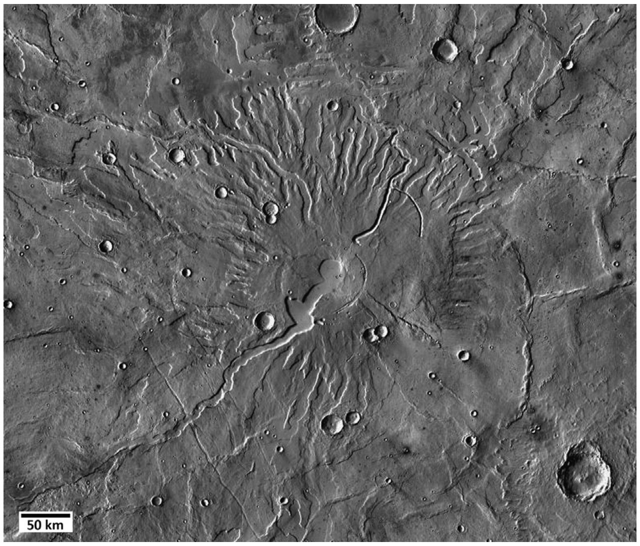

FIGURE 41.4 Tyrrhenus Mons, a low-profile volcano that likely includes pyroclastic deposits on its flanks. Portion of THEMIS Daytime IR mosaic. NASA/JPL-Caltech/ASU.

containing wrinkle ridges that cover low-lying regions in rugged, cratered terrain. Hadriacus Mons and Tyrrhenus Mons (12 and 24 in Figure 41.1) are located northeast of the Hellas basin. Tyrrhenus Mons (Figure 41.4) is found within the ridged plains of Hesperia Planum, interpreted in the early days of Martian exploration to consist of flood basalts analogous to the lunar maria. Hadriacus and Tyrrhenus Montes display central caldera complexes surrounded by relatively flat-lying layered deposits that are heavily dissected by radiating valleys. Recent high-resolution images confirm earlier suggestions that the flanks of these volcanoes are friable in nature and dissected by fluvial processes, although the exact styles and rates of erosion are yet to be determined. Formation of the flanks of these volcanoes has been attributed to large explosive eruptions in Late Noachian (Tyrrhenus) and Early Hesperian (Hadriacus) time that would have emplaced pyroclastic flow deposits in thick sequences around the eruptive vents for hundreds of kilometers. Later effusive volcanic activity may have occurred at the summit regions of both volcanoes and also formed a large field of lava flows that extend from Tyrrhenus Mons to the southwest.

To the south and southwest of the Hellas basin, the ridged plains of Malea Planum bury the basin rim and cover the cratered highlands. Similar in surface morphology and extent to Hesperia Planum, Malea Planum is attributed to voluminous flood volcanism. Within Malea Planum, four major volcanic features have been identified. Amphitrites Patera (3 in Figure 41.1) is the summit depression of a shield-like edifice similar to Tyrrhenus and Hadriacus Montes, with radiating channels characterizing its flank materials. However, in the case of Amphitrites Patera, its surface shows scalloped and pitted textures, and pedestal and ejecta flow craters attributed to periglacial modification of unconsolidated volcanic materials, perhaps similar to the pyroclastic deposits forming Tyrrhenus and Hadriacus Montes. Malea, Peneus, and Pityusa Paterae are large, caldera-like depressions within the ridged plains that also show evidence of surface modification by periglacial activity. Malea and Pityusa Paterae have been compared to large calderas on Earth such as Yellowstone, and have potentially been the source regions for large quantities of lava flows and/or pyroclastic deposits. The volcanic features within Malea Planum are similar in age to those found to the northeast of Hellas, suggesting that this region of Mars was a major volcanic center in ancient times.

6. SMALL CONSTRUCTS

Much knowledge has been gained about small volcanic constructs across Mars from the study of data collected during the post-Viking era. Although Mariner and Viking data revealed tremendous insights into the construction of large volcanoes on Mars, few volcanoes were conclusively identified with diameters of tens of kilometers. However, it was speculated by many researchers that fields of small constructs at this size should exist. Perhaps the most beneficial data to advance our knowledge of these features was the MOLA topography. Even the early, coarser gridded data products showed numerous structures with diameters of tens of kilometers and heights of several hundred meters. Similar structures on Earth have been named low shields due to their low profile and typically form due to dominantly effusive eruptions of lava from point or linear vents. The collection of higher-resolution image data sets over more extensive areas of Mars also reveals steeper-sided cones with diameters of up to several kilometers and heights of several hundred meters (Figure 41.5). Although apparently less common, these features are thought to represent slightly more explosive episodes that produced cones. A third group of small constructs includes fissures with little to no topographic relief, but which appear to link to extensive surface flow units.

Low shields and fissures are now known to be common features across the plains of the Tharsis province, and are also found in very close proximity to the larger central constructs in this region. Both the Tempe Terra and Syria Planum regions of Mars were long known to include several small constructs. Post-Viking era data show that small constructs are more plentiful in these regions than previously thought (Syria includes more than 200 small constructs), and that they are common in other portions of Tharsis, dominantly among and to the east of the Tharsis Montes, southeast of Olympus Mons, and south of Alba Mons. Although each vent represents an eruption point of lava at the surface that built a construct, or "topographic cap" several hundred meters in height and tens of

FIGURE 41.5 E. Mareotis Tholus, with a 2-km-long summit vent. A circular impact crater is southwest of the elliptical summit vent. Mars Orbiter Camera, MOC2-64 (image 50704fsub2). NASA/JPL-Caltech/MSSS.

kilometers in diameter, the flow fields associated with these features can extend for much greater distances. Where constructs are located in closely spaced groups, the flow fields coalesce to form extensive **volcanic plains**. Impact craters have been counted on the flanks of some of the larger low shields across the Tharsis province, and ages associated with these features place them in the Amazonian, among the youngest volcanic features in the region. However, some low shields are extensively buried, nearly completely, by plains lavas that are considered to be older, and both the Syria and Tempe vent fields are considered to be pre-Amazonian in age. As such, it is not clear if the development of fields of low shields and fissures represents a style of Martian volcanism that was dominant during the latter part of the planet's history or if this style of volcanism has occurred throughout the planet's evolution.

Post-Viking image data have also enabled the study of much smaller domes, cones, and mounds across Mars. These features tend to be hundreds of meters to several kilometers across and hundreds of meters in height. The cones can be generally divided into two groups based upon the interpretation of their formation, including: (1) volcanic cones (cinder and/or spatter), and (2) volcanic rootless constructs (VRCs). Several individual volcanic cones have been identified in high-resolution images across Mars, but only two groups have been identified and studied in more detail. These groups are located in western Tharsis and Utopia Planitia near the north pole of Mars. Ages for these two fields have been estimated at Amazonian and Late Noachian to Early Hesperian, respectively. Some of these features are associated with small lava flows, sometimes from breaches in the structure or from the base. The limited number of these fields suggests that this style of volcanism was never dominant on Mars, or that it was more common in the Noachian and much of the evidence has been buried by younger deposits. VRCs are thought to form when lava flows were emplaced across surfaces that were rich in subsurface ice deposits. As heat is transferred from the active lava through the basal crust, the frozen volatiles begin to melt and can form steam. If pressure is able to build up, local explosive events can occur that excavate the substrate and eject overlying lava to form piles or cones. These cones will be near circular if the lava flow is no longer moving, but can also be fork-shaped if the flow was advancing, as the rootless explosions took place and material was deposited onto a surface that transported it away as new explosions continued. Because these features do not mark the location where a rising magma body reaches the surface they are considered to be “rootless” or not directly connected to a magma body beneath it. Unlike the volcanic cones described previously in this paragraph, VRCs are not typically the source of effusive lava-flow deposits, are located in groups of hundreds to thousands (as opposed to tens of features), are found within a single extensive lava flow, and tend to be smaller in both diameter and height. Because VRCs require the presence of ice-rich materials, their presence and age can be used to infer information about a region’s paleoenvironment. As such, it is critical to be able to accurately decipher volcanic cones from VRCs.

The third class of small volcanic constructs on Mars includes fractures or fissures to which channel networks are connected. This type of feature is identified in both Tharsis and Elysium and has been a source of debate in both regions as to their origin. The channel networks are typically sinuous, sometimes branching, and display features such as steep walls, wall terraces, a lack of topographic lava flow levees, and the branching channels can form terraced islands. Due to the similarity of these characteristics to terrestrial fluvial channel systems, some researchers have proposed an origin via the release of subsurface water, possibly by melting of subsurface ice due to interaction with ascending magma, and erosion by overland flow. However, as detailed image and topographic data become available for these features some researchers have suggested an origin associated with volcanic emplacement of sheet lavas. This remains a topic of current study. Yet, in either style of suggested formation, these features likely represent a site where ascending magma caused the formation of a new feature on the surface of Mars.

7. VOLCANIC PLAINS

Volcanic plains comprise some of the most extensive geologic units on Mars outside the cratered highland terrain. The plains appeared to be quite featureless in moderate to low resolution images from the Mariner and Viking missions, but when viewed in higher resolution images from those missions and post-Viking-era missions a variety of features are observed. Post-Viking observations show that in some cases fields of small constructs, including low shields and low-relief fissures, are the sources for some of the extensive plains units. Although not all plains units have obvious sources, likely due to burial, it seems that the link between fields of small constructs and plains units is likely to have been common, thereby differentiating these two volcanic units from the larger central vent constructs. Perhaps the best example of this relationship is the Cerberus **Fossae** and associated Athabasca Valles lava flows in the Elysium region. Although the origin of Athabasca Valles is thought to involve magmatic melting of ground ice and water release from the Cerberus Fossae, high-resolution image data have shown that this same system was subsequently the site for eruption of flood lavas that flowed down the Athabasca Valles system and resurfaced the Cerberus Palus plains. These volcanic deposits are considered to be Late Amazonian in age, covering $>250,000\ km^2$ with $>5000\ km^3$ of lava. Comparable relationships between plains units and small constructs also exist in the Tharsis region and interpretation of the complex morphologies in these flow fields is a current research focus in Martian volcanology, particularly attempting to disentangle the complex relationships between possible fluvial and volcanic features.

The most obvious features in the volcanic plains away from the small constructs are abundant lobate margins surrounding individual packages of material that appear to have been emplaced through flow of fluid materials (Figure 41.6). The lobate margins can be sufficiently thick (various measurements indicate lobe thicknesses of tens of meters to greater than 100 m) that the flowing material is widely accepted to be lava rather than something like water-rich debris flows. Stacked sequences of such flow units likely make up the bulk of the topographic bulges that surround both the Tharsis and Elysium volcanic centers.

Volcanic plains also comprise regionally extensive units in locations that presently do not include major or small 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. These plains units display wrinkle

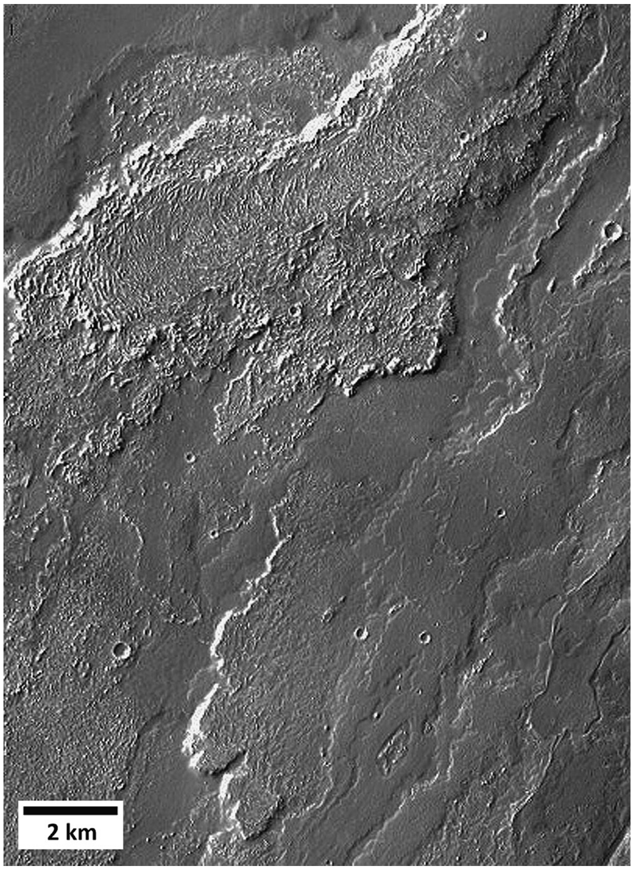

FIGURE 41.6 Lava flows west of Arsia Mons. Portion of THEMIS VIS frame V46368003. NASA/JPL-Caltech/ASU.

ridge morphologies that are less abundant or absent from other plains deposits surrounding the Tharsis and Elysium volcanic centers. Both the Lunae Planum and Hesperia Planum volcanic plains have crater densities that suggest they were emplaced during the Hesperian. As such, these plains are significantly older than some of the younger volcanic plains units in and around the Tharsis and Elysium volcanic centers. Thus, substantial outpourings of plains-forming lava flows, likely from vents that are themselves buried by thick stacks of flows, were significant events during the Hesperian and Amazonian periods.

The volcanic plains of Mars display flow features that can be broadly divided into simple and complex flow units. 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 comprises 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 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 (Figure 41.6), with numerous finger-like flow lobes traceable in some cases for many hundreds of kilometers. Continued examination of higher resolution image data might show that the older plains display comparable complex morphologies, or these units might be so old that these morphologies are obscured by erosion or burial by sediments.

8. MEDUSAE FOSSAE FORMATION

Some plains units are quite problematic in origin. Such 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 (MFF) is the largest such enigmatic deposit that overlies both the northern lowland plains units and the transitional terrains along the margin of the old southern cratered highlands. Spread along the Martian equator south of both the Tharsis and Elysium regions, MFF materials occur within a region that spans more than 100° of longitude (nearly 6000 km). MOLA data show that MFF materials range in thickness from tens of meters in western exposures to more than 3 km in eastern exposures, while orbiting sounding radar investigations reveal that the MFF deposits overlie units conformable with both lowland plains and cratered highlands.

Many alternative hypotheses have been proposed for MFF, but the explanation most consistent with all currently available data is that MFF materials are the result of massive pyroclastic eruptions. MFF exposures consist of layered materials that appear to be very friable, eroded by wind-driven sand into enormous field of **yardangs**, which locally include caprock layers that help to preserve the underlying, more easily eroded materials. MFF materials are clearly easily eroded by windblown sand, but the eroded surface still maintain steep slopes, suggesting that at least some lithification has likely occurred within the materials. These characteristics have been compared to welded and nonwelded zones within many ignimbrite deposits on Earth. A significant issue with the pyroclastic hypothesis is that there is no indication of the possible source vent or vents, which is troubling if explosive eruptions produced more than 1 million km^3 of deposited materials.

The radar "Stealth" region, discussed earlier, has been interpreted to be associated with pyroclastic eruptions from undisclosed vents west of Arsia Mons, which lends support to possible massive ignimbrite eruptions in and around the MFF region. Unfortunately, MFF is within an enormous section of the Martian surface where infrared mapping reveals that a dust mantle, perhaps at least 1 m in thickness, completely masks the underlying rocks, thus effectively hiding MFF materials from remote sensing that could provide some indication of the composition of these friable deposits. It is possible that the Curiosity rover may eventually shed some light on the characteristics of layered materials that might be outliers of nearby MFF materials.

9. COMPOSITIONAL CONSTRAINTS

Compositional information for Mars is available from three different sources: remote sensing data (orbiting spacecraft instruments and Earth-based telescopes), on-site analyses by instruments on landed spacecraft, and the special group of meteorites for which there is compelling evidence that these rocks were blasted off the surface of Mars and eventually fell to Earth. Here we will briefly examine each data type for its implications for volcanic materials on Mars.

Remote sensing studies of Mars began with telescopic measurements of properties of the surface and atmosphere, and since the 1960s, the telescopic data have been augmented with much higher spatial resolution data from numerous instruments on spacecraft that flew by, orbited, or landed on Mars. Earth-based instruments can achieve very high spectral resolution but with only low spatial resolution (typically covering areas hundreds of kilometers across on Mars). Spacecraft have tended to achieve substantially improved spatial resolution, but until recently these data were at relatively limited spectral resolution. The Compact Reconnaissance Imaging Spectrometer for Mars can image the surface of Mars with up to 20-m spatial resolution while also collecting reflectance measurements at hundreds of visual and near infrared wavelengths for each picture element (pixel). The Thermal Emission Spectrometer extended spectral coverage in thermal wavelengths, resulting in global maps of the presence of several minerals across the planet, including olivine and pyroxene in several low-albedo (dark) regions. The primary results of these spectral studies with regard to volcanism are that two types of basalts seem to be common on Mars, a low-silica type similar to tholeittic basalts on Earth and a moderate-silica type that may either be more like terrestrial basaltic andesites or tholeiite-like basalt with a glassy weathering rind with enhanced silica content.

The ubiquitous Martian dust complicates spectral studies of Mars at all spatial and spectral resolutions, masking significant portions of the surface and generally decreasing the contrast of already subtle spectral features being sought. In spite of this dust handicap, spectral studies have shown that the dark regions of the planet generally have a strong mafic affinity. Unfortunately, only the Syrtis Major volcanoes are located in a low-albedo region, so that the spectral information of nearly every other volcanic center is severely masked by dust. Only tens of microns of dust can strongly affect visual and near infrared reflectance, and only 2 cm of dust can totally obscure even competent bedrock from thermal infrared observations.

The first on-site compositional information for Martian materials came from an X-ray fluorescence instrument on the two Viking landers. In spite of the fact that the two Viking landers were more than 6000 km apart, the composition of Martian fine soils was quite similar at both landing sites. Measurements of the fine soil components at subsequent landing site continued this trend (Table 41.2), which is a strong indication of the homogenizing influence

TABLE 41.2 Chemical Compositions of Selected Martian Materials[1]

Oxide	Spirit Fines[2]	Pathfinder Fines[3]	Spirit Basalt[4]	Pathfinder Basalt[5]	Martian Basalt Meteorites[6]
SiO_2	46.2	49.0	45.7	55.5	49.0−51.4
Al_2O_3	10.2	8.4	10.9	9.1	4.8−12.0
FeO	15.6	16.1	18.8	13.1	17.7−21.4
MgO	8.5	7.9	10.8	5.9	3.7−11.0
CaO	6.4	6.3	7.8	6.6	10.0−11.0
K_2O	0.5	0.2	0.1	0.5	0.06−0.25
TiO_2	1.0	1.2	0.5	0.9	0.8−1.8
SO_3	6.3	5.4	1.2	3.9	0.33−0.80
Na_2O	3.0	3.0	2.4	1.7	1.0−2.2
P_2O_5	1.0	–	0.5	–	0.6−1.5
Cr_2O_3	0.3	–	0.6	–	0.014−0.30
MnO	0.3	–	0.4	–	0.45−0.53
Cl	0.8	0.5	0.2	0.6	0.005−0.013
Total	100.1	98.0	99.9	97.8	

[1]Results are rounded to nearest 0.1% for APXS measurements.
[2]MER-A Gusev mean soil; from Table 4.4, Brückner et al. (2008).
[3]Average of three fines samples (A2, A4, and A5) from Pathfinder; from Table I, Reider et al. (1997). Results are reported as normalized to 98.0%, to allow for unreported P_2O_5, Cr_2O_3, and MnO.
[4]Results for "Adirondack_RAT" from Spirit; from Table 4.1, Brückner et al. (2008).
[5]Results for "Yogi" (A7) from Pathfinder; from Table I, Reider et al. (1997). Results are reported as normalized to 98.0%, to allow for unreported P_2O_5, Cr_2O_3, and MnO.
[6]Basaltic Martian meteorites; from Table 4.4, Brückner et al. (2008).

of the global dust storms. Although repeated attempts were made to collect a rock fragment at the Viking landing sites, no Martian rock was successfully analyzed by the Viking lander instruments (centimeter-sized fragments collected by the sample arm all turned out to be indurated clods of fine soil and dust). This situation changed in July, 1997 when the Mars Pathfinder mission deployed the first mobile vehicle on Mars, the microwave oven-sized Sojourner rover. Sojourner had an alpha proton X-ray spectrometer (APXS) that the mobile rover was able to place directly onto several rocks, as well as the fine-grained materials between the rocks. Subsequently, both Mars Exploration Rovers (MERs) Spirit and Opportunity obtained many dozens of APXS measurements of rocks and soil, and the Mars Science Laboratory rover Curiosity is just beginning to build its own library of APXS measurements (as well as utilize the impressive complement of other instruments available on this latest Mars rover). Table 41.2 lists representative composition results for both fine soils and basalts from the Spirit and Pathfinder landing sites.

Images of the rocks at the Pathfinder site support them being interpreted as being volcanic in origin, with ubiquitous pits thought to be vesicles. Spirit and Opportunity have greatly expanded both imaging and chemistry results for what are definitely volcanic rocks, with several distinct "classes" of rock types identified to date. The high sulfur content of both rocks and fines on Mars (Table 41.2) suggests that a thin soil/dust coating may contaminate measurements of uncleaned rock surfaces. Spirit, Opportunity, and Curiosity all carry instruments that can excavate into rock surfaces in order to obtain fresh material for examination. The Spirit basalt values in Table 41.2 are for an APXS measurement that followed grinding on the surface of the rock Adirondack using the Rock Abrasion Tool (RAT); these results show sulfur and silica contents lower than either the soils or uncleaned Pathfinder targets. Chemistry results from post-RAT APXS measurements by the two MERs, or from drilled rock samples examined by Curiosity, are likely to be least affected by possible contamination from surface dust.

The best chemical information about Martian materials comes from a collection of very special meteorites. Over 100 meteorites are now considered to be from Mars because gases implanted in them during the shock that ejected them from their parent body are identical to the atmosphere of Mars as measured by the Viking landers, and unlike gases obtained from any other terrestrial or extraterrestrial sample. The vast majority of these meteorites are igneous in nature, and they are only about one-third the age (1.3 Ga–180 Ma) of practically all other types of meteorites. Collectively called **SNC meteorites**, the majority are basalts or lherzolites/harzburgites like Shergotty (S), some are clinopyroxenites or wehrlites like Nakhla (N), and Chassigny (C) is the sole dunite. ALH84001 is a special case requiring some additional discussion; this orthopyroxenite is the only Mars meteorite that is as old as the solar system ($\sim$4.5 Ga), 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 much about Mars in general, but we unfortunately have no evidence for exactly where on the Martian surface they came from. The abundance of volcanic rocks among the group is consistent with the extensive areas of volcanic plains present on Mars, but their relatively young crystallization ages cannot be used to calibrate the geologic epochs on Mars without knowledge of which specific geologic unit they came from. Some of the nonbasaltic rocks could 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 breached by the impact event that ejected the meteorite. ALH84001 likely came from somewhere in the cratered southern highlands of Mars, indicating that at least portions of the highlands must date from near the formation of the planet. There is no good explanation why the highlands, which cover more than half of the surface of Mars, have thus far produced only ALH84001 as an old Mars meteorite. It will require the return of documented samples from Mars before the precise laboratory techniques that are brought to bear on the Mars meteorites can be related to specific geologic materials or units.

10. VOLCANIC HISTORY OF MARS

The oldest terrain on Mars is the Noachian densely cratered southern highlands. If the meteorite ALH84001 is representative of this era, at least some magmatic activity took place during this time of intensive impact events. Isolated volcanic centers developed within the cratered highlands, preserved today only as deeply scoured features scattered throughout the southern highlands. The Noachian materials give way to Hesperian terrains, where massive eruptions of lava produced volcanic plains that covered large portions of the Martian surface. The composition of these plains-forming materials was likely basaltic, although it is possible that more evolved lavas (basaltic andesite) also may have been common in places. Volcanic centers developed on the rim of the enormous Hellas impact basin, as well as within what is now the Syrtis Major region. These volcanoes appear to have involved considerable amounts of ash production, leading to very low overall profiles, as well as intense channelization of the shallow flanks by either fluvial or magmatic liquids. If the massive MFF deposits are the result of pyroclastic eruptions, then ash production was significant from the Late Hesperian well into the Amazonian. Alba Mons (1 in Figure 41.1) may represent a volcano caught in the transition from more ash-rich eruptions typical of the highlands to the more lava-rich eruptions associated with volcanic constructs in the northern hemisphere of Mars.

Late Hesperian to Amazonian epochs involved voluminous eruptions that produced both broad volcanic plains and numerous central volcanic constructs. Volcanic activity concentrated around the Elysium and the much larger Tharsis regions; impact 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 low-relief craters and domes in the northern lowland plains may be the result of either localized Strombolian activity (cinder cones) or of interaction of lava flows moving over wet sediments (**pseudocrater**s). An ignimbrite origin for MFF materials would imply that pyroclastic activity continued well into the Amazonian.

11. FUTURE STUDIES

The recent rover missions have demonstrated the enormous advantage that mobility provides to the exploration of Mars, particularly when supported by consistently improved orbital capabilities. A staggering amount of data have been collected using the diverse instruments on both the rovers and several orbital platforms, so it seems quite likely that the ongoing comparison of results obtained from all of these recent and ongoing missions should provide new insights into volcanism on Mars during the coming years. The question of the abundance and origin of potential pyroclastic deposits on Mars remains unclear at present, but the ongoing orbiter and rover missions may help to shed light on this issue.

The absolute age of all Martian terrains remains a significant uncertainty in studies of the emplacement of volcanic materials on Mars. An improved understanding of the volcanic structures and deposits on Mars will also provide better constraints on the thermal evolution of the planet. The recent identification of possible ancient explosive volcanic centers in the Arabia Terra region suggests that a reinterpretation of some large (>100 km in diameter) depressions throughout the southern highlands may show some presumed impact features may turn out to be calderas, adding additional information about the transition from explosive to effusive eruptions on Mars.

Martian meteorites will continue to provide valuable new insights into the history of Mars, but unfortunately there has yet to be a definitive link between one or more meteorites and a specific bedrock location 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.

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