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"The Diversity of Martian Volcanic features as Seen in the MOC, THEMIS, and MOLA Data Sets"

PRINCIPAL INVESTIGATOR: Peter Mouginis-Mark

Dr. Peter J. Mouginis-Mark
HIGP/POST
University of Hawaii
1680 East-West Road, POST Room 504
Honolulu, HI 96822
(808) 956-8760

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1. Objectives of Completed Research

This one-year project (which included a one-year no-cost extension) focused on the evolution of the summit areas of Martian volcanoes. It extended the studies conducted under an earlier MDAP project (Grant NAG5-9576, Principal Investigator P. Mouginis-Mark). By using data collected from the Mars Orbiter Camera (MOC), Thermal Emission Imaging System (THEMIS), and the Mars Orbiter Laser Altimeter (MOLA) instruments, we tried to better understand the diversity of constructional volcanism on Mars, and hence further understand the eruption processes.

By inspecting THEMIS and MOC data, we explored the following four questions: (1) Where might near-surface volatiles have been released at the summits of the Tharsis volcanoes? Is the trapping and subsequent remobilization of degassed volatiles [*Scott and Wilson,* 1999] adequate to produce eruptions responsible for extensive deposits such as the ones identified on Arsia Mons [*Mouginis-Mark*, 2002]? To answer this question, we investigated the diversity of eruption styles by studying the summit areas of Arsia, Pavonis and Ascraeus Montes. (2) What are the geomorphic characteristics of the valley system on Hecates Tholus, a volcano that we have previously proposed experienced explosive activity [*Mouginis-Mark et al.*, 1982]? Our inspection of THEMIS data suggests that water release on the volcano took place over an extended period of time, suggesting that hydrothermal activity may have taken place here. (3) How similar are the collapse processes observed at Martian and terrestrial calderas? New THEMIS data provide a more complete view of the entire Olympus Mons caldera, thereby enabling the comparison with the collapse features at Masaya volcano, Nicaragua, to be investigated. (4) What can we learn about the emplacement of long lava flows in the lava plains of Eastern Tharsis?

The result of this work provided a greater understanding of the temporal and spatial variations in the eruptive history of volcanoes on Mars, and the influence of the volatiles within the top few kilometers of the volcanic edifice. This relationship in turn pertains to the availability of volatiles (both juvenile magmatic volatiles and ground water contained within the near-surface rocks) and to magma supply rates at appreciable distances (tens to hundreds of kilometers) from the centers of volcanoes. Explosive volcanism on Mars, a major factor in the release of water at the surface, may have been driven not only by volatiles within the parental melt, but also by magma encountering water or ice at shallow depth within the volcano [*Mouginis-Mark et al.,* 1982, 1988; *Crown and Greeley*, 1993; *Robinson et al.,* 1993].

Project 1: Water discharge on the Tharsis Volcanoes

Scott and Wilson [1999] discussed the possibility that the summit areas and rift zones of Martian volcanoes may have accumulated bodies of ice, and that water was retained below a sealing cap of ice. They proposed that water and CO_2 should be expelled from cooling Martian magma chambers as the magma becomes supersaturated in volatiles. These volatiles would then become trapped elsewhere within the near-surface layers of the volcano, providing a volatile source for subsequent activity. Such a process may have taken place several times at a specific volcano, and *Wilson et al.* [2001]

reinforced this idea by arguing that the presence of separate but overlapping calderas on many Martian volcanoes implies major long-term episodicity in mantle magma supply. *Wilson et al.* [2001] hypothesized that the life history of a magma chamber included reservoir formation, growth, degassing and (often) caldera collapse events.

Where magma interacted with volatiles at a shallow depth, explosive eruptions may have taken place. For instance, in *Mouginis-Mark* [2002] we identified a thick (45 - 50 m) layer on the rim of several pit craters close to the summit of Arsia Mons which we proposed was created by explosive eruptions caused by dikes intruded into volatile-rich layers close to the summit. *Scott and Wilson* [1999] have studied the structure of pits close to the summit of Ascraeus Mons, and proposed that they originated in a similar manner, namely from the intrusion of sills into the volatile-rich edifice. Comparable chains of pits exist on the flanks of Pavonis and Arsia Montes, so that similar studies are warranted of the pits on these volcanoes to see if they too show evidence of layered deposits. This model of volcano evolution would be greatly enhanced if we can find further evidence for volatiles having existed close to the summit of each volcano, which is what we will search for in this task.

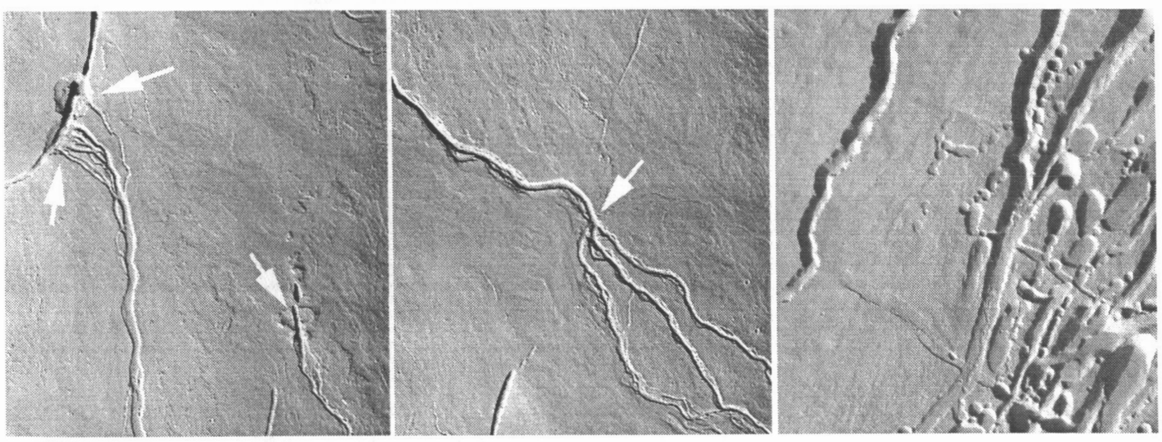

Fig. 1: Examples of valleys and graben found on the flanks of Ascraeus Mons, showing that water most likely flowed from some of these features. At left, arrows point to places where fluids most likely emerged on surface. Center image shows a distributary channel system (arrowed) with associated water flow. At right, none of these collapse pits appear to have released water. The location, range of elevations on edifice where pits occur, and the sizes and distance downslope that the water flowed, will all be identified in this work. All images are 17 km across. THEMIS frame numbers, left to right, V08155020, V08155020, and V07245001.

We found some evidence within the THEMIS data set to support the idea that intrusions released volatiles at certain locations and not in others along the Tharsis Ridge rift zone (Fig. 1). An important observation would be to find places where water has leaked out of fractures high on the sides of the volcanoes. Such "leaky fractures" have been found in places such as Cerberus Fossae [*Berman and Hartmann*, 2002; *Burr et al.*, 2002; *Plescia*, 2003] and at the foot of Olympus Mons (Mouginis-Mark, 1990), but to date there have been no examples documented at high elevations. The examples shown in Fig. 2a and 2b are thus highly unusual. Finding additional examples, and observing the elevation of the fracture, as well as the distance from the rift axis, will help further constrain our ideas for the hydrogeology of Martian volcanoes [*Head and Wilson*, 2002]. Key measurements that we will make under this work will include (1) the range of elevations where water appears to have reached the surface; (2) dimensions (width and depth) of possible source fractures and pits; and (3) the distance of the water source from the summit caldera and from the rift axis on the volcano. We also note that there are collapse pits in the flanking rift zones but not within the caldera of Arsia Mons, which has significance in our work on gas segregation in non-vertical dikes [*Mitchell et al.*, 2002].

Project 2: Mapping the Valleys on Hecates Tholus

The volcano Hecates Tholus provides good evidence for explosive volcanism [*Mouginis-Mark et al.*, 1982, 2000] by virtue of the widespread mantle of material that has buried impact craters on the upper western flanks of the volcano. One of the most enigmatic aspects of this volcano is that it has a very well developed system of valleys on its flanks [*Reimers and Komar*, 1979; *Gulick and Baker*, 1990]. In our earlier study [*Mouginis-Mark et al.,* 1982] we interpreted the valley system to comprise a large number of unconnected stream segments, but now our inspection of THEMIS images (Fig. 2) reveals that many of the individual valleys are much longer than previously believed, and have a variable depth of incision along their length that appears to be related either to local topography or to strength differences in the country rock. Our early analysis of these valley systems has been published in *Mouginis-Mark and Christensen* [2005].

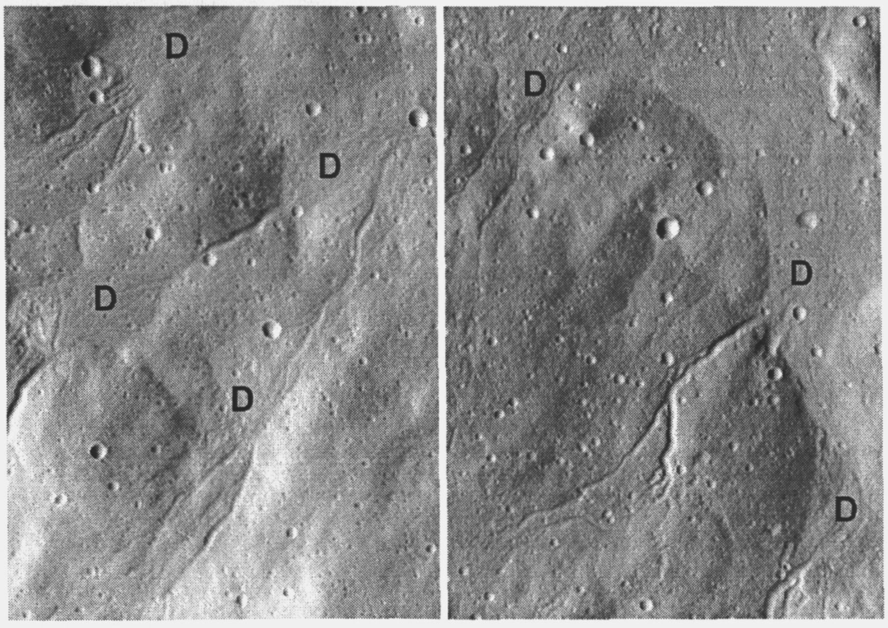

Fig. 2: The eastern flank of Hecates Tholus has already been well imaged by THEMIS, and shows that most of the isolated valley segments originally seen in Viking images [*Mouginis-Mark et al.*, 1982] are in fact inter-connected. Local topography appears to have promoted deep valleys on steeper slopes and the formation of small deltas ("D") on the shallower slopes. Images are both parts of THEMIS image V02716007. See Fig. 3 for location.

The identification of the total length of each valley, the frequency of braiding within individual valleys, and the existence of valleys that cross the surrounding lava plains are high priority goals for this task. The formation of these features would require long-lived surface water flow during a single event, and a protracted period of valley formation, respectively. In turn, if such discoveries can be made, this will have implications for the local climate and volatile budget of the volcano [*Mouginis-Mark et al.,* 1982; *Gulick,* 1998]. Other models, including the idea that the valleys were produced by rainfall, also need to be considered.

We looked at as much of Hecates Tholus as is possible using the available MOC and THEMIS images to better constrain the spatial extent and maturity of the valley system. We created a mosaic of the entire volcano using daytime IR THEMIS images (Fig. 3a) and there are several parts of the volcano that have either been imaged at 18 m/pixel or 36 m/pixel by the THEMIS VIS instrument (Fig. 3b).

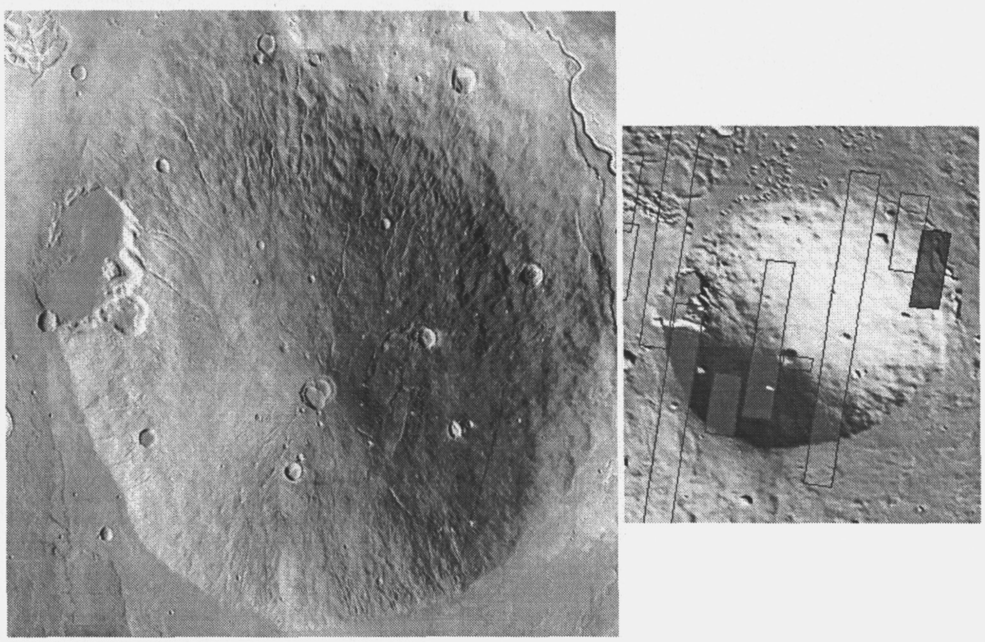

Fig. 3: Coverage of Hecates Tholus is already excellent from THEMIS. At left (a) we show a mosaic that we have produced from daytime IR images (100 m/pixel resolution). At right (b) is a map from the THEMIS web site showing the coverage of the VIS images. The shaded area on the eastern (right) side of the volcano marks the location of the image shown in Fig. 3. The shorter segments in Fig. 3b are data acquired at 19 m/pixel, while the longer segments show the 38 m/pixel coverage.

Our observational data on the distribution and size of the valleys on Hecates Tholus enabled us to make inferences about the origin of the water that carved the valleys and, potentially, the hydrothermal system that released the water. Although we were not able to fully study these valleys in the one year of this project, we hope that in the future the work can help resolve which (if any) of these ideas are valid:

(1) A dike approaches the surface with magma traveling almost vertically from the chamber, producing a thermal anomaly that is symmetrical to the edifice. Our models

give the time required for a given batch of magma to pass through the system and its survival against cooling can be studied using the heat loss calculations. The end product is an estimate of the depth of the magma chamber (from the cooling calculations) and its size (from the erupted volume and the criterion of *Blake* [1981] that an elastic magma reservoir can erupt no more than about one third of one percent of its volume). Knowing where the valleys originate on the volcano with respect to distance from the summit will help constrain the intrusion size.

(2) A dike approaches close to the surface but magma motion is largely lateral and no purely magmatic eruption occurs; however, some initial, transient, thermal interaction between magma and shallow volatiles occurs, and an explosive phreato-magmatic eruption results. This could be relevant to the formation of ash deposits on Hecates Tholus [*Mouginis-Mark et al.,* 1982]. The details depend to some extent on whether the volatiles are solid or liquid. Because little or no juvenile magma is subsequently erupted, the deposits of the phreato-magmatic eruption are preserved.

(3) A sill intrudes beneath, but close to, the volatiles within the lower flanks of a volcano so that it interacts thermally with volatiles [*Gulick*, 1998]. At least some of the source areas for valleys on Hecates Tholus are similar to valleys on Earth that are produced by ground water sapping [*Kochel et al.*, 1988], so that we can consider the rate and duration of water release as additional constraints on valley formation and magma/volatile interaction. Options include (a) the volatiles are solid: slow melting of the solid and seepage of the resulting liquid occur; compaction of the layers that contained the volatiles and possibly collapse or subsidence at the surface take place; (b) the volatiles are liquid, and heating causes vaporization and local pressure increase within the aquifer. This in turn produces lateral fluid migration, again with possible visible surface effects.

Task 3: Rheology of a long lava flow at Pavonis Mons, Mars

During the emplacement of a lava flow, three physical processes can be important: 1) changes in viscosity, (2) the formation of channels, levees, or stationary margins that divide the flow into active and inactive components, and (3) a loss of volatiles that cause a change in the density of the lava [cf., *Walker*, 1973; *Crisp and Baloga*, 1994; *Zimbelman*, 1998]. It is particularly difficult to determine the relative roles of these processes because they can occur simultaneously in active flows. Furthermore, for flows on Mars, the application of numerical models is best achieved when the entire flow length is considered, rather than just the distal portion.

The objective of this task was to determine whether lava channel formation within lava flows is correlated either with distance from the vent and/or with local topographic slope. Dimensions of lava flows can be used to unravel the relative roles of viscosity changes, the formation of lateral levees, stationary margins and stagnant zones. In *Baloga et al.* [2003], we developed a new formula for the relative change in viscosity of the flow on the basis of a steady state Newtonian flow rate. Our approach featured a new length scale that described the transfer of lava from the active advancing component to the passive margins of the flow. Thickening and widening of the flow with distance are predicted in this model for a single, coherent, isothermal, viscous flow. In *Baloga et al.* [2003], we studied a single lava flow to the north of Pavonis Mons volcano to explore the motion of the flow, particularly with respect to the formation and evolution of lava channels and the thickening of the flow. Numerous measurements were made across and along the length of the flow, using the 128th degree MOLA digital elevation model. We discovered that none of the physical processes that cause large viscosity increases in terrestrial flows [*Moore*, 1987; *Crisp et al.,* 1994; *Crisp and Baloga*, 1994] seem to have occurred with the Pavonis flow. This style of emplacement may explain why many of the long, sheet-like flows on the plains of Mars often exhibit an unexplained lack of thickening with down-flow distance.

Project 4: Comparison of Martian and Terrestrial Calderas

The structure and morphology of Martian calderas have been well studied through analysis of the Viking Orbiter images [*Mouginis-Mark*, 1981; *Wood*, 1984; *Mouginis-Mark and Robinson*, 1992; *Crumpler et al.*, 1996], and provide important information on the evolution and eruptive styles of the parent volcanoes. Using Viking data it has been possible, for numerous calderas, to define the sequence of collapse events, identify locations of intra-caldera activity, and recognize post-eruption deformation for several calderas. Inferences about the geometry and depth of the magma chamber and intrusions beneath the summit of the volcano can also be made from image data [*Zuber and Mouginis-Mark*, 1992; *Scott and Wilson*, 1999]. In at least one case, Olympus Mons, analysis of compressional and extensional features indicates that when active, the magma chamber was located within the edifice (i.e., at an elevation above the surrounding terrain). The summit areas of Olympus and Ascraeus Montes provide evidence of a dynamic history, with deep calderas showing signs of having been full at one time to the point that lava flows spilled over the caldera rim [Mouginis-Mark, 1981]. In our new work under this project, we explored the structure of the Olympus Mons caldera and compared our observations to those that we made at Masaya volcano, Nicaragua [*Mouginis-Mark et al.,* 2005].

Mouginis-Mark and Rowland [2001] reviewed the geomorphic information for Martian calderas that can be determined from the Viking Orbiter data. They made certain predictions about what might be learnt from analysis of higher spatial resolution data provided by the Mars Orbiter Camera (MOC) and the visible camera that is part of the Thermal Emission Imaging System (THEMIS), as well as the analysis of digital topographic data from the Mars Orbiter Laser Altimeter (MOLA). MOC images have a spatial resolution of ~1.5 to 6.0 m/pixel, and THEMIS visible wavelength images have a resolution of 19 m/pixel; in both instances, this coverage is much better than the 40 – 200 m/pixel data that were typically obtained by the Viking Orbiters. As this work will show, these data do indeed provide a wealth of new information on the structure and evolution of calderas on Mars, and importantly this new information makes direct comparison between calderas on Earth and Mars more instructive. Nowhere is this opportunity for utilizing terrestrial analogs greater than with the four giant shield volcanoes in the Tharsis region of Mars; Olympus, Arsia, Pavonis and Ascraeus Montes. In *Mouginis-Mark et al.*

[2005], we concentrate on these four volcanoes and identifies clear differences in the subsidence and/or infilling history of each. For each key caldera feature we have identified a terrestrial analog. Coupled with field observations of these analogs, MOC, MOLA and THEMIS observations provide new insights into the subsurface structure and magma supply rate for each Martian volcano.

Although only one large-scale caldera collapse event at a basaltic shield has occurred in the historic record (the 1968 collapse of Fernandina caldera, Galapagos; *Simkin and Howard* [1970]), fieldwork on terrestrial calderas continues to provide insight into these dynamic features that can be applied to comparable features on Mars. Few of the terrestrial examples have been studied with the goal of furthering an understanding of their planetary analogs, thereby opening the possibility of future productive analysis of calderas on basaltic volcanoes on Earth. This work concludes with a more detailed description of the caldera at Masaya volcano, Nicaragua. Here, multiple collapse events and ease of access allow for detailed study of numerous collapse and infilling events and the ways in which they interact. Many features at Masaya assist in understanding the dynamics of Martian caldera floors. The terrestrial features and insights presented here can be used as guides and analogs when examining Olympus Mons, where the Martian lakes and pit craters may have formed in a similar way. There are, however, some drawbacks. If Nindiri crater is an analog to the summit of Olympus Mons, extensional features should be found around the perched outer perimeter of the crater and compressional features towards the center. Much of the surface of each of the Nindiri lakes is buried by more recent units or tephra, making it difficult to construct a geologic map of the 1570 – 1670 units and the 1852 ponded lava flow within Nindiri. This creates problems when trying to identify any extensional and compressional features that may have formed due to continuing subsidence of the under-lying surface. However, some surfaces are accessible from the southern or northern rims. Here parts of the lake surface exposed at these locations have numerous surface features that warrant close inspection as they may have Martian analogs.

Some volumetric and thermal constraints can also be placed on the sequence of events. As at Masaya, by calculating the time it takes for a lake of a given thickness to completely cool below the brittle-ductile transition, the maximum time can be calculated during which plastic deformation can occur (i.e., plastic deformation could only occur while the lake core was still partially molten). This time estimate is relevant to other Martian lava lakes that underwent plastic deformation, which should be recognized as bowl-shaped surfaces in the MOLA elevation measurements. For instance, the caldera floor of Ascraeus Mons reveals several thinner ponded lava flows compared to Olympus Mons. Five prominent layers can be identified within a 315 meter-high section of the wall of the Ascraeus Mons crater. This implies an average thickness of the ponded lavas of ~63 meters. Given the Alae relationship of Peck (1978) this thickness would take ~70 years to freeze. Reconstructing an original diameter of ~20 km for this crater (number 3 of *Mouginis-Mark*, 1981) implies an average volume for each ponded layer of ~19.8 km^3. Using the same hypothetical dimensions for an equivalent lava flow on the flanks (i.e., 50 m thick and 10 km wide) as Olympus Mons would suggest that a single intra-caldera eruption of Ascraeus Mons might have produced a flow ~40 km long, which is typical of lava flows observed on the flanks [*Zimbelman*, 1985].

2. Publications from this MDAP project

We published three papers during the award period, which provided new insights into the diversity of volcanism on Mars, and the distribution of Martian volatiles in space and time:

Baloga, S. M., P. J. Mouginis-Mark, and L. S. Glaze (2003). The rheology of a long lava flow at Pavonis Mons, Mars. *J. Geophys. Res.* 108 (E7), 5066, doi: 10.1029/2002JE001981.

Mouginis-Mark, P. J. and P. R. Christensen (2005). New observations of volcanic features on Mars from the THEMIS instrument. *J. Geophys. Res.* **110**, No. E8, doi: 10.1029/2005JE002421.

Mouginis-Mark, P.J., A. J.L. Harris, and S.K. Rowland. Terrestrial analogs to the calderas of the Tharsis volcanoes of Mars. "*Environments on Earth: Clues to the Geology of Mars*", in press, August 2005.

Two conference talks were also given:

December 7th, 2002 "Masaya Volcano, Nicaragua: A Terrestrial Analog for the Evolution of Martian Calderas". Fall 2002 AGU meeting, San Francisco.

December 15th, 2004: "Remote sensing studies of Kilauea volcano, Hawaii, as an aid to understanding volcanic processes on Mars, Venus and Io", Fall 2004 AGU Mtg., San Francisco.

3. Implications for Future Research

From our analysis of the THEMIS VIS images of volcanoes on Mars it appears that one of the most important observations is the frequent occurrence of features formed by flowing water in close proximity to eruption sites. The identification of water discharge at high elevations (> 6 km) on Ascraeus Mons is particularly noteworthy, but there also appears to have been abundant water on the flanks of Hecates and Ceraunius Tholi as well as within segments of the Olympus Mons aureole materials. No morphologic evidence has been found in the THEMIS images to identify a source for this water, but snow melt [*Fassett and Head,* 2004] or the remobilization of volatiles released from the degassing volcano [*Scott and Wilson,* 1999] appear to be the most likely. Water close to the summit of a volcano has important implications for affecting the type of eruption, and has been proposed for both Ascraeus and Arsia Montes [*Scott and Wilson*, 1999; *Head and Wilson*, 2002; *Mouginis-Mark*, 2002].

The abundance of water at the summit of Hecates Tholus may also be relevant to the possible explosive eruption style of this volcano. As described by *Mouginis-Mark et al.* [1982], this volcano has some of the best evidence for recent explosive volcanism on

Mars in the form of an asymmetric super-posed impact crater distribution. The area immediately to the west of the summit caldera is devoid of impact craters larger than ~10 m (i.e., the resolution limit of MOC images). The Viking-era interpretation was that this area is mantled by an air-fall deposit that was generated by either a plinian or sub-plinian eruption at the summit of Hecates Tholus. An important, but worrying, component of the model is the cause of the asymmetry, which relies on either a directed blast or strong local winds that preferentially deposit material on only one flank of the volcano. Weathering and erosion, rather than explosive volcanism, may be a way to explain the unusual distribution of sub-kilometer sized impact craters on the volcano.

Alternatively, *Neukum et al.* [2004] have suggested that glacial deposits may also exist on this part of the volcano, providing a non-juvenile source for the volatiles. Snowmelt has also been proposed as a mechanism for valley formation on Martian volcanoes [*Fassett and Head*, 2004], which could explain the protracted period of valley formation that can be inferred from the relative timing of the valleys and the lava flows from Elysium Mons that surround the southern base of Hecates Tholus. We see from the THEMIS VIS images that water was most likely released to the surface close to the summit caldera rim. This implies that a large volatile reservoir existed at the summit, and this reservoir could have been derived from out-gassing of the juvenile magma or from snowmelt. In either the glacial/snowmelt model or the degassing model, a hydrothermal system such as the one proposed by *Gulick* [1998] could have remobilized the volatiles and explain the non-uniform distribution of small impact craters on the flanks for the volcano. Explosive volcanism is, therefore, still a possible style of activity for Hecates Tholus but alternative models including, for instance, glacial erosion or the rotting of surface lava flows by an active hydrothermal system, need to be investigated.

If a non-explosive model for the volatile history of Hecates Tholus were to be found correct, it would raise additional questions about the diversity of eruption style on Mars. Previous discussions of Martian volcanism [e.g., *Francis and Wood*, 1982; *Greeley and Spudis*, 1981; *Wilson and Head*, 1994] have included the possibility of explosive volcanism because the flanks of certain volcanoes (notably Alba Patera, Hecates Tholus, and Ceraunius Tholus) have easily eroded flanks that may comprise ash deposits. Even the flanks of the highland paterae (Hadriaca Patera and Tyrrhena Patera) may be formed from ash [*Greeley and Crown*, 1990; *Crown and Greeley*, 1993]. If this easily eroded material is in fact comprised of hydrothermally altered lava flows, then the range of magmatic compositions on Mars does not need to be as diverse, nor is there the need to include primary melts with high volatile contents.

As of August 2005, the collection of images from THEMIS is continuing. We hope that future data acquisitions will specifically be targeted to create complete high-resolution mosaics of the main volcanic edifices, thereby allowing additional details of the volcanic history and styles of eruption to be investigated.

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