Prodigious ash deposits near the summit of Arsia Mons volcano, Mars

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[1] Mars Orbiter Camera images are used to identify widespread material interpreted to have formed via explosive volcanism on Arsia Mons volcano, Mars. This material crops out in cliff sections associated with pit craters in layers ~45–50 m thick. The large range of elevations where the material is found (6.2–17.5 km) suggests locally-derived materials, although extensive reworking has produced a wide variety of dune forms. Two possible styles of volcanism appear possible for generating this material: (1) explosive volcanism associated with pit crater formation due to the release of magmatic gases, or (2) the interaction between dikes and volatile-rich substrates. Although the best examples occur on Arsia Mons, pit craters on Ascraeus Mons also suggest explosive activity. The absence of comparable features on Olympus Mons indicates that the eruptive histories of the larger Tharsis shields were more diverse than has been inferred from Viking Orbiter images. *INDEX TERMS:* 5480 Planetology: Solid Surface Planets: Volcanism (8450); 6225 Planetology: Solar System Objects: Mars; 8450 Volcanology: Planetary volcanism (5480)

1. Introduction

[2] Images from the Mars Orbiter Camera (MOC) have radically changed our perception of geologic processes on Mars, including the styles of volcanic activity [*Malin and Edgett*, 2001]. One such earlier paradigm that is investigated here is the idea that the Tharsis Ridge volcanoes (Arsia, Pavonis and Ascraeus Montes) preserve no evidence of explosive activity. Contrary to Viking-based observations that indicated that these constructs are built from multiple lava flows originating either at the summit or on the upper flanks [e.g., *Carr et al.*, 1977; *Mouginis-Mark*, 1981; *Wilson and Head*, 1994], examination of MOC images of Arsia Mons (9.5°S, 121.2°W) reveals the existence of spatially extensive, fine-grained material. An origin by explosive volcanism is proposed here for this material.

[3] The idea of extensive explosive volcanism within Tharsis is not new. Circumstantial evidence had been identified from Viking Orbiter images [*Edgett*, 1997; *Edgett et al.*, 1997; *Wilson et al.*, 1998], with the recognition of inactive eolian dune fields in SW Tharsis. *Edgett* [1997] suggested that explosive volcanism produced the large quantities of sediment that now form these dunes. Explosive eruptions may have been associated with the formation of small cones (possible cinder cones) in the summit region of Pavonis Mons, and within the caldera of Ulysses Patera. *Scott and Wilson* [1999] proposed that the channels on the SSW flank of Ascraeus Mons were formed by low-energy fluvial processes that resulted from the intrusion of sills into volatile-rich layers of the volcano. Although this interaction between intrusions and sub-surface volatiles was an integral part of the *Scott and Wilson* [1999] model, they did not, however, identify any eruptive deposits that may have been associated with this activity. Recent analysis of Mars Global Surveyor data [*Hynek et al.*, 2002] has also supported the interpretation that there are extensive deposits of fine material in this region of Tharsis.

2. New Observations

[4] High-resolution (2.85–5.71 m/pixel) MOC images of the upper flanks of Arsia Mons (Figure 1) show that extensive deposits of fine-grained material exist at elevations between 5.4 and 16.4 km above datum. These deposits can be recognized as a thick layer around the rim of pit craters on the N and S rims of the caldera (Figures 2a and 2b). In rare instances (e.g., Figure 2a), topographic data from the Mars Orbiter Laser Altimeter (MOLA) experiment cross the cliff section, allowing layers thickness to be estimated at ~45–50 m. Surficial deposits can also be recognized as thick, morphologically bland, units within cliff sections that separate more resistant layers (Figure 2c), and as dark dust landslide scars in the interior of a graben (Figure 2d). Although conceivably of eolian origin, these fine materials

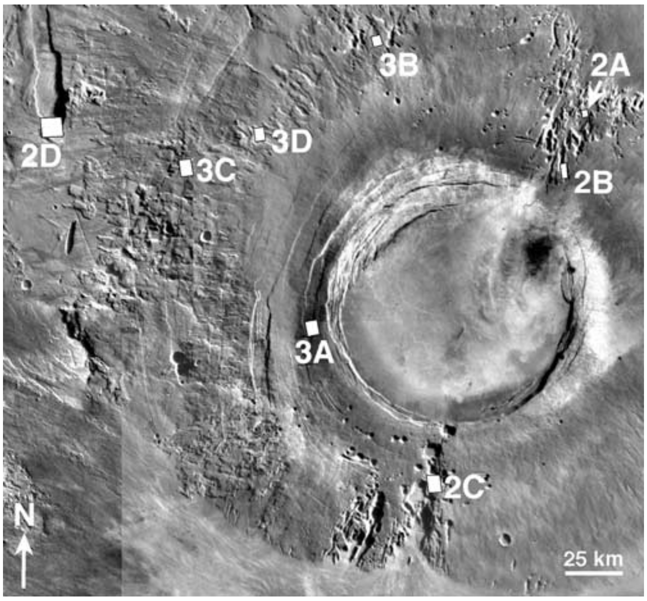

Figure 1. Location image for MOC high resolution images (Figures 2 and 3) obtained on the upper flanks of Arsia Mons. Mosaic of MOC wide-angle images. Field of view is from 6.9°S–12.0°S, 118.8°W–124.2°W.

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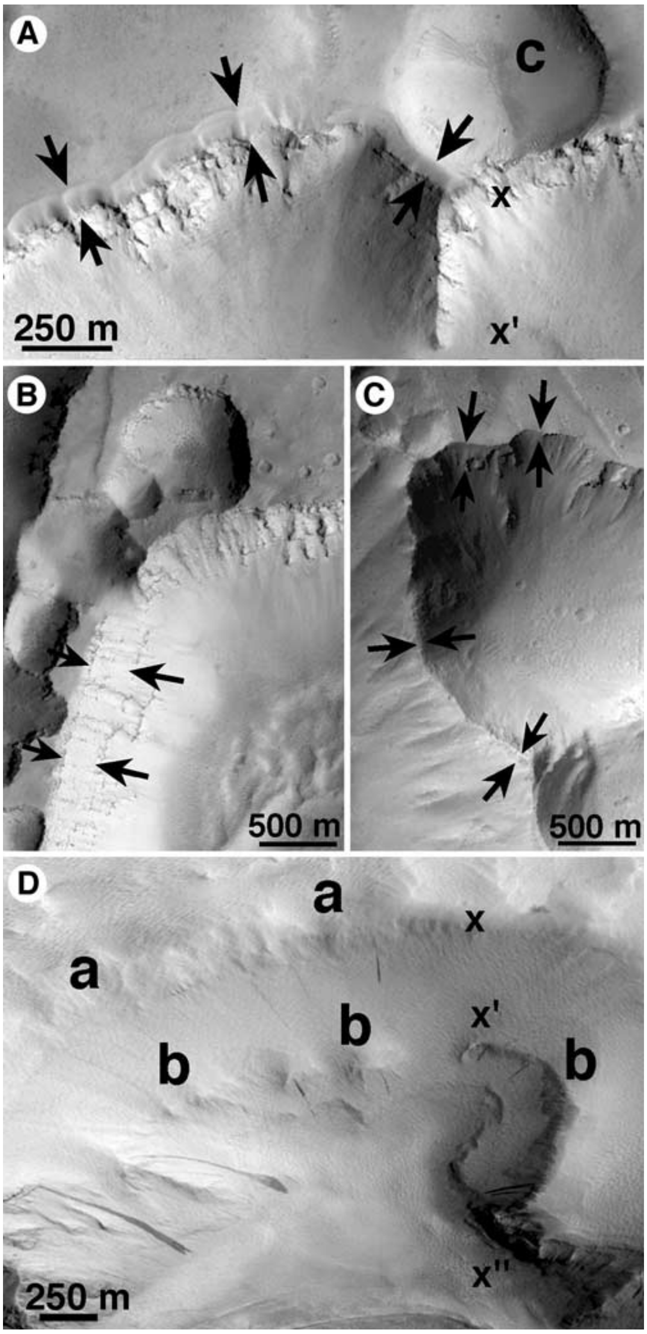
are sufficiently thick and widespread that a locally derived volcanic origin appears more likely. No eroded landforms have been identified nearby that could have been the source of these fine materials, and the elevation of the deposits (as much as 17 km above Mars datum) would suggest that erosion by the wind would be very inefficient [*Greeley and Iversen*, 1985, p. 89–92]. However, locally this material has been reworked to form dunes at a variety of scales from the limit of resolution to star-shaped dunes a few hundred meters in width (Figure 3). In no instances can fresh lava flows be seen in these MOC images, so that it seems likely that the mantle of fine material exceeds several tens of meters in thickness even where sections are not available. Furthermore, the number of superposed impact craters is very small (e.g., Figure 3b), implying that the deposits are either very young or were recently mobile.



3. Styles of Eruption and Candidate Vents

[5] It is not clear what style of volcanism produced the mantling deposits identified here. No obvious vent structures are revealed in MOC images of the pit craters or graben. Nothing reminiscent of spatter ramparts or positive-relief features can be seen on the rims of any of the pit craters shown in Figure 2. As has been proposed for the pit craters on the perimeter of Alba Patera volcano [*Scott and Wilson*, in press], explosive volcanism associated with pit crater formation on Arsia Mons may have been sufficiently vigorous that the pyroclasts and lithics were distributed over a very wide area and cannot be identified in MOC images. At least two alternative styles are possible: (1) explosive volcanism due to magma fragmentation via the release of magmatic volatiles, and/or (2) phreato-magmatic activity due to the interaction of intrusions with a near-surface volatile layer. Because of the limited spatial coverage of individual MOC images, it is not possible to trace any of the mantling deposits for more than a few kilometers; no thinning of a deposit as a function of radial distance from a source has been observed.

[6] It is proposed here that the source of the deposit was close to the summit of Arsia Mons. The pit craters on the volcano bear a strong morphological similarity to craters on the flanks of Alba Patera, Mars, some of which *Scott and Wilson* [in press] propose were produced by explosive eruptions generated by the interaction of a dike and ice-

Figure 2. (opposite) (a) Extensive mantling material (between arrows) surrounds the rims of numerous pit craters on the N. flank of Arsia Mons. MOLA data collected from orbit m0701588 crosses the right side of the image and shows that the elevation change between points x and x′ is 399 m, implying that this topmost layer may be ∼45–50 m thick. The rim elevation is ∼13.8 km above datum. Note the extensive fill materials within crater “c”. Part of MOC image m0701587. South, and the rim crest, is at the top of image. (b) Massive units of morphologically bland material (between arrows) crop out in the walls of a depression at ∼15.5 km elevation on the northern flank. Part of MOC image m0306911, north to top. (c) A mantle of material with large local variations in thickness (between arrows) is seen at an elevation of ∼15.8 km. Eolian material is not expected to collect in this manner, so that an air-fall origin from an eruption appears more likely. Part of MOC image m0300412, north to top. (d) Dark slides, interpreted elsewhere on Mars to be dust landslides [*Malin and Edgett*, 2001] are common features on the western flanks of Arsia Mons, where a 12 km-wide graben is located at an elevation of 6.2 km. Two distinct levels (“a” and “b”) can be seen within this 1.0 km-high cliff section (top of cliff is towards top of image), suggesting that more than one unconsolidated unit exists. MOLA data collected from orbit m1301793 show that the upper rim (x) is at an elevation of 6,242 m, the middle bench (x′) is at 5,650 m, and the foot of the scarp (x″) is at 5,362 m. Part of MOC image m1301793, south to top. See Figure 1 for locations.

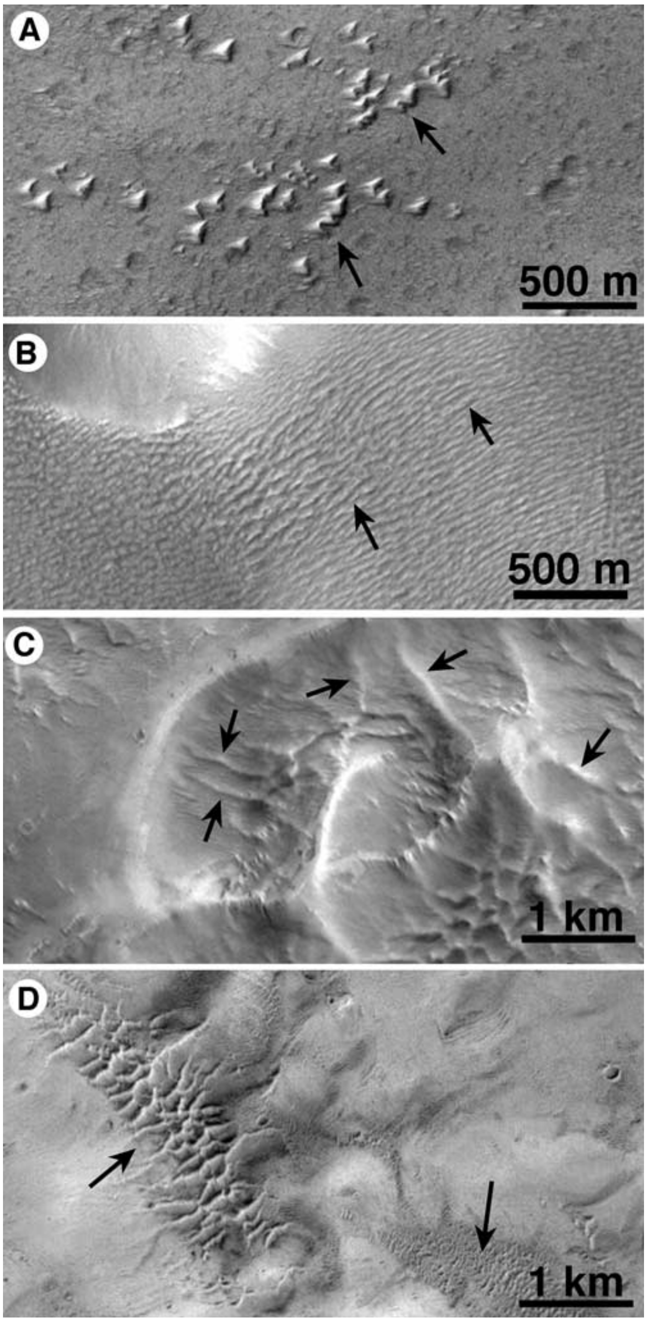


Figure 3. A wide variety of dunes (arrowed) characterize much of the flanks of Arsia Mons between 10.5–17.0 km above Mars datum, suggesting that the fine materials are locally remobilized but not removed from the summit of the volcano. Parts of MOC image m2200273 (a), m0300414 (b), m1101805 (c), and m1800038 (d). North is toward the top of all figures. See Figure 1 for locations.

rich permafrost. A common origin for the Arsia Mons and Alba Patera pits appears to be probable. Indeed, many of the Arsia Mons pits are located along the proposed "rift zone" that extends along the axis of the Tharsis Montes Ridge [*Crumpler and Aubele*, 1978; *Scott and Wilson*, 1999]. Thus intrusions into, or eruptions through, volatile-rich layer(s) at a depth of a few tens to a few hundreds of meters may have resulted in large-scale phreato-magmatic activity at high elevations close to the volcano summit.

4. Explosive Volcanism on Other Tharsis Volcanoes?

[7] It is possible that whatever mechanism was responsible for the production of the mantling deposits on Arsia Mons could well have operated on the other large Tharsis volcanoes. If the fine materials on Arsia Mons were generated by either the intrusions of dikes into a volatile-rich substrate or the explosive release of gas-rich magmas, then a search for comparable pit craters and graben on other volcanoes may also suggest explosive activity. Indeed, the southern flanks of Ascraeus Mons have collapse features that are very similar to those of Arsia Mons (Figure 4). In contrast, Pavonis Mons has less-well developed examples of pit craters, while such features appear to be absent from Olympus Mons.

[8] Whatever style of volcanism produced the mantling deposits, it does not appear to have been constrained by elevation. Pits extend from elevations >17.0 km above datum to 6.2 km above datum on Arsia Mons, from 13 km–6.5 km on Pavonis Mons, and 11.2–5.3 km on Ascraeus Mons (Table 1). This suggests that whatever the source of volatiles (magmatic or locally derived) the explosive eruptions were not simply the result of the low atmospheric pressure associated with the great height of the Tharsis Montes. This observation is consistent with numerical models [*Wilson and Head*, 1994; *Head and Wilson*, 1998] that predict that atmospheric pressure on Mars is always so low that even a very gas-poor (by Earth standards) magma would erupt explosively. Volatiles derived from hydrothermal systems on certain Martian volcanoes [*Gulick and Baker*, 1990], or the cold-trapping of magmatic volatiles near the summit [*Scott and Wilson*, 1999], might be expected on all of the high Tharsis

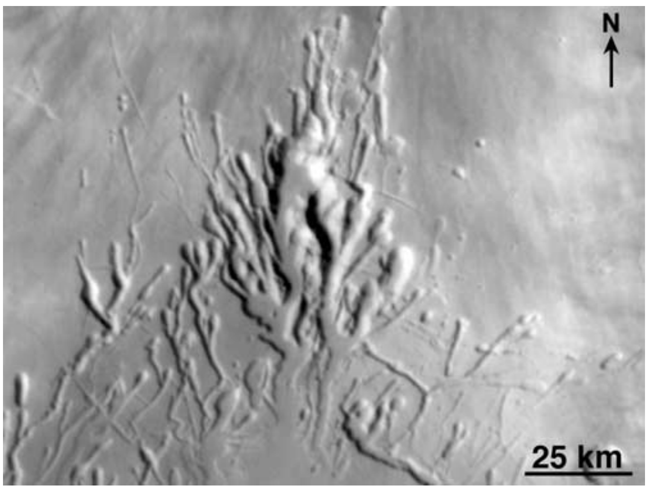


Figure 4. Pits, morphologically similar to those on Arsia Mons, occur on the southern flank of Ascraeus Mons at an elevation of 8–11 km, suggesting that a similar style of volcanism may have occurred on both volcanoes. Part of MOC image m0700307. Field of view is from 8.3°N–9.5°N, 104.5°W–106.0°W.

Table 1. Distribution of Pit Craters on the Flanks of the Tharsis Montes (Elevations in km Above Mars Datum)

	Uppermost pit	Lowest pit	Caldera rim elevation
W Arsia Mons	12.0	6.2	17.6
SW Arsia Mons	17.5	11.6	17.5
NE Arsia Mons	16.0	11.4	16.3
SW Pavonis Mons	13.0	9.2	14.0
NE Pavonis Mons	9.3	6.5	11.9
SW Ascraeus Mons	11.2	8.0	17.3
NE Ascraeus Mons	10.0	5.3	18.0

Although high resolution MOC images are not available for all these features, they may show that the spatial distribution of volatiles was different within each volcano. Note that it is only on SW Arsia Mons that the pits extend all the way to the rim of the summit caldera.

volcanoes so that alternative mechanisms or local variations need to be identified, and an explanation found for why Olympus Mons does not show the same variety of landforms as does Arsia Mons. A possible controlling factor for effusive vs. explosive activity on Mars proposed by *Mitchell and Wilson* [2001] is whether or not the eruptions occurred from near-vertical dikes erupting very near the summit, in which case there would be little chance for gas bubbles and magma to segregate. The alternative situation is when the eruptions originate from highly inclined dikes erupting some considerable way down the rift zone, in which case gas segregation is much easier, with gas leaking out along the strike of the dike and an effusive eruption occurring where the dike reaches the surface.

5. Future Studies

[9] If the deposits identified here are indeed the products of explosive eruptions on Arsia Mons, their occurrence raises several new questions about Martian volcanism that should guide future studies. Specific questions that need further work to answer include: (1) What was the source of the volatiles? Is the trapping and subsequent remobilization of degassed volatiles [*Scott and Wilson*, 1999] adequate to produce these areally extensive eruptions? (2) Are the deposits on Arsia Mons unique, or did explosive activity also occur near the summits of Olympus, Pavonis or Ascraeus Montes? Possible explanations for why such features are not seen on all the high Tharsis volcanoes include different magma degassing histories that did not always develop a trapped volatile layer near the summit, a relative paucity of summit intrusions to remobilize the volatiles, or the fact that more recent lava flows have buried the mantling deposits. (3) Is there any correlation between the materials described here and the "debris blankets" on the NW flanks of Arsia and Pavonis Montes first identified from Viking data [*Carr et al.*, 1977; *Lucchitta*, 1981] and more recently interpreted to be a debris flow [*Baloga et al.*, 2001]? These debris blankets may be comprised of fine materials [*Baloga et al.*, 2001], so that an origin involving the remobilization of explosively-generated ash deposits would be compatible with the MOC observations. (4) Was the explosive phase of volcanism on Arsia Mons only a late-stage event, or did this activity characterize much of the history of this and other volcanoes? More detailed analysis of the relative timing between the ash eruptions and the emplacement of the lava flows seen on most flanks of the volcano is warranted.

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