Olympus Mons, Mars: Detection of extensive preaureole volcanism and implications for initial mantle plume behavior

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ABSTRACT

The early volcanic history and structural development of Olympus Mons, Mars, has been obscured by the formation of the large circum-Olympus aureole deposits in the Early Amazonian. Mars Orbiter Laser Altimeter data reveal an enormous preaureole extrusive flow unit in Amazonis Planitia that is more than 300 km wide and extends ~1800 km radially away from the Olympus Mons aureole. We interpret this volcanic unit to represent proto-Olympus Mons lava flows emplaced during the latest Hesperian or earliest Amazonian. The orientation and localization of the deposits appear to be due to channeling of the flows into a broad depression between the generally north dipping slope of Amazonis Planitia and the southwestward-dipping slope of the Alba Patera flanks. Formation of the aureole blocked this depression and caused subsequent summit flows to pond in the circum-Olympus trough and flow around the aureole lobes. Emplacement of this proto-Olympus flow unit formed a barrier along the northern margin of Amazonis Planitia, causing ponding of later lava flows and outflow channel events debouching there. The large volume and great lateral extent of the unit imply abundant magma supply and high effusion rates during the initial stages of Olympus Mons construction; this unit may be the result of the initial impingement of a melt-rich mantle plume head.

Keywords: volcanism, Olympus Mons, Mars, plumes, lava flows.

INTRODUCTION

Olympus Mons, the tallest known volcano in the solar system, sits on the northeastern flank of the Tharsis rise of Mars. It is surrounded by a several hundred kilometer wide ring of material known as the aureole (outlined in Fig. 1), which is thought to have been caused by massive deformation and landsliding of the edifice flanks (e.g., Morris and Tanaka, 1994; Francis and Wadge, 1983). The early history of Olympus Mons is poorly understood because the aureole deposits have destroyed and obscured evidence of early and flank ing eruptions (Scott and Tanaka, 1986). In their analysis of the Olympus Mons region, Morris and Tanaka (1994) showed that the structure of the aureole deposits is consistent with gravitationally induced collapse, but pointed out that such a mechanism would not be expected to bury the entire precollapse structure. They therefore looked for evidence of preaureole lava flows extending beyond the aureole, but were unable to find such structures in the Viking images (Morris and Tanaka, 1994). Previous maps, generated from Viking images, show Amazonis and Arcadia Planitiae (Fig. 1) to be blanketed by a series of region-wide volcanic units: the five-member Arcadia Formation, a volcanic formation without an apparent source that persisted throughout the Amazonian (Scott and Tanaka, 1986).

This study uses data from the Mars Orbiter Laser Altimeter (MOLA) and images from the Mars Orbiter Camera (MOC) to examine evidence of preaureole volcanism. MOLA data, and the derived data products, have permitted the analysis and detection of a significant number of geologic features that were only hinted at in Viking image data. For example, gradient maps, detrended topography maps, and slope maps generated from MOLA data (e.g., Fig. 2A) have revealed details of the geology and structure of Amazonis Planitia (Fuller and Head, 2002) and shown that it differs from that originally mapped by Scott and Tanaka (1986). Among the new units detected was a very large flow unit extending northwest across Amazonis Planitia and into Arcadia Planitia from the margins of the Olympus Mons aureole (Fig. 1). Here we document the nature and detailed stratigraphic relationships of this unit and examine evidence for its provenance and age.

OBSERVATIONS

General Characteristics

Stratigraphically, the lobate flow unit (Figs. 1 and 2) overlies the Upper Hesperian Vastitas Borealis Formation (Scott and Tanaka, 1986), a unit laterally correlatable with the outflow channels and thought to represent a potentially ice-rich sublimation residue remaining from the outflow events (e.g., Kreslavsky and Head, 2002). The Vastitas Borealis Formation is ~100 m thick and overlies Lower Hesperian ridged plains of volcanic origin (Head et al., 2002); the ridges on the surface of this unit can be seen to protrude through the Vastitas Borealis Formation, but are largely buried by the lobate flow unit (Fig. 2). The eastern contact of the flow unit is the sharp, scarp-like western boundary of the topographically higher Early Amazonian aureole deposits, suggesting that the aureole unit was emplaced on top of the flow unit, and is thus younger. These general relationships place the age of the flow unit as latest Hesperian or earliest Amazonian, older than any mapped deposits from Olympus Mons.

Morphology

The preaureole Olympus Mons flow unit is extremely long (~1780 km) and wide (310–420 km), with a maximum thickness of ~100 m; as exposed, it is the longest flow unit yet detected on Mars, longer than any identified in the flow catalog of Peitersen et al. (2002). The flow unit is on a very shallow slope (~0.0038); the substrate decreases in elevation only 120 m over the unit’s 1800 km extent. It is approximately constant in width, suggesting preferential forward advance instead of lateral spreading. The regional topography appears to be channeling the flow, inhibiting lateral movement in favor of forward flow. The nearly constant width along the flow unit is common for long (>50 km) flows, according to a study of 145 martian and terrestrial lava flows (Peitersen et al., 2002).

The surface of the flow unit shows a rough, rubbly texture (Fig. 3A), occasionally interrupted by round depressions meters to tens of meters across (e.g., Fig. 3B). These depressions are not seen in MOC images to the north and south, suggesting that they are unique to this flow unit. Possible origins include impact craters, collapse depressions, or deflation pits. Global MOLA roughness data reveal the presence of a very young, latitudinally dependent, fine-grained mantling deposit overlying much of the flow unit (Kreslavsky and Head, 2000); MOC images show extensive eolian modification of the surface. These data indicate that the current surface has been altered in the ~3 b.y. since its emplacement, explaining why the flow unit was not recognized in Viking images, which show only the extensively modified surface.

Flow units on Mars can be formed by lava flows, lahars (e.g., Christiansen, 1989), or a combination of both (e.g., Tanaka et al., 1992; Russell and Head, 2001). Christiansen (1989), using Viking images, mapped lahars whose overall morphology is broadly similar to the preaureole flow unit. Russell and Head (2001),...
using MOLA data and MOC images, have examined the region and interpreted the broad, lobate structures as lava flows and the narrower, higher-relief units as lahars. The broad, lobate morphology of the preaureole flow unit therefore appears more consistent with a lava-based than a lahar-based origin. MOLA data further suggest that the preaureole flow unit is composed of a series of discrete lava flows. The data reveal a few discernable flow margins on the surface of the unit (mapped in Fig. 2). Figure 3C, MOC images taken across a crater rim, reveals laterally extensive layers in the crater walls. These could be a result of ejecta layering, but their cohesiveness and differential weathering patterns are more suggestive of solid rock units. Their overall morphology is similar to layers seen in MOC images elsewhere and interpreted to be lava beds (e.g., McEwen et al., 1999). They also resemble exposed cliffs within the Columbia River Basalt Group. It should be noted, however, that apparent layers within the Columbia River Basalt Group are often entablature tiers, i.e., laterally persistent patterns of cooling joints (e.g., McMillan et al., 1989); the layers visible in Figure 3C may similarly represent cooling effects instead of a series of discrete flow events.

The southern portion of the flow unit forms two rectilinear depressions in northeastern Amazonis Planitia (centered at 32°N, 150°W). The western margin of these basins is approximately parallel to the wrinkle ridges that sweep across this region (mapped in Fig. 2; see also discussion in Head et al., 2002), suggesting that the southernmost flows abutted a wrinkle ridge and were deflected to form the enclosed basins. These southernmost flows may be the oldest in the flow unit; the uppermost flows (mapped individually in the southwest corner of Fig. 2) appear to curve around these basins.

The flow unit is surrounded by closely associated smooth plains (Fig. 2) that also overlie the Vastitas Borealis Formation. MOC images show several features interpreted to be related to ice or water. At the margins of the flow unit, subparallel meandering channels carve through the substrate (e.g., Fig. 3D), and are interpreted to represent melting and mobilization of ground ice. The meandering planform of the channels and the extensive eolian reworking suggest that the smooth plains are easily eroded. We interpret these deposits to be related to the emplacement of the flow unit, most likely resulting from melting of the underlying ice-rich sediments of the Vastitas Borealis Formation during emplacement of the superposed flow unit, causing melting and drainage out along the flow margins.

**Provenance**

The source and proximal extent of the flow unit are buried by the Olympus Mons aureole. There are two nearby major volcanic edifices, Alba Patera and Olympus Mons (Fig. 1). The flow unit extends approximately radially to Olympus Mons. If it originated at the Olympus Mons summit, it would be on the order of 2500 km long. If it originated from the Alba Patera summit, it would be nearly 3500 km long.

Prior to the emplacement of this unit, the
regional topography was dominated by the regional slope, grading downward to the north from the martian southern highlands toward the northern lowlands (Fig. 1). The flanks of the Alba Patera edifice formed a slope upward to the northeast, and the flanks of the preaureole proto–Olympus Mons volcanic edifice (Morris and Tanaka, 1994) would have formed a similarly steep slope to the southeast. This topography would have preferentially channeled flows extending north from Olympus Mons or southwest from Alba Patera along a relatively narrow trough to the northwest. A flow extending south or southwest from Alba Patera would first have banked against the preaureole Olympus Mons volcanic edifice or the Noachian (i.e., pre-Hesperian) Acheron Fossae (Fig. 1). Reconstructing the likely extent of this preaureole edifice indicates that lava flowing from Alba Patera would have had to climb over the flanks of Olympus Mons to flow into Amazonis Planitia. In addition, the kilometer-scale roughness of the flow unit (Kreslavsky and Head, 2000) supports an origin at Olympus Mons (Fuller and Head, 2002): as discussed in previous papers in more detail, lava flows from a single source typically have internally consistent surface roughness. There are no other preaureole Olympus Mons lava flows to which this flow unit can be compared, but comparison with flows from Alba Patera and the Tharsis Montes shows that those flow surfaces are significantly rougher (at 2.4 km base-length roughness) than this preaureole flow unit. On the basis of these observations, we conclude that the most likely provenance of this flow unit is the preaureole Olympus Mons.

**Stratigraphic Implications**

The flow unit and its surrounding smooth plains overlie the Lower Hesperian ridged plains and the Upper Hesperian Vastitas Borealis Formation, but are truncated by the Lower Amazonian Olympus Mons aureole (Fig. 4A). MOLA data show that the northern margin of the flow unit stands out sharply from surrounding topography, while the southern margin is less distinct (Figs. 2A and 4B). This is consistent with the interpretation that the southern margin was repeatedly embayed and mantled by younger volcanic and outflow events in Amazonis Planitia (Fuller and Head, 2002). MOLA data reveal that the flow unit mapped here crosses the contacts of all five members of the Arcadia Formation, mapped on the basis of Viking data by Scott and Tanaka (1986) and previously thought to have been emplaced throughout the Amazonian. Thus, the Arcadia Formation is in need of redefinition in future studies.

**DISCUSSION**

Several researchers have proposed a gravity-spreading origin for the Olympus Mons aureoles (e.g., Francis and Wadge, 1983; Morris and Tanaka, 1994). Morris and Tanaka (1994) argued that ice-lubricated gravitational collapse implies the presence of an...
existing large volcanic edifice, evidence of which would be lava flows still visible beyond the margins of the aureole; they considered the fact that they had not found any in Viking images to be a weakness of the model. This study therefore strengthens their interpretation and supports their primary conclusion, the collapse of preexisting edifice margins as an origin for the aureole.

The very large volume (50,000–75,000 km$^3$) of the exposed flow unit is approximately half the volume of the Columbia River Basalt Group (Tolan et al., 1989), and this is a minimum estimate, because the flow unit likely originated closer to the Olympus Mons summit region. The lack of such extensive flow units later in the history of Olympus Mons suggests that the early stages of eruptive activity were characterized by a greater magma supply rate and potentially higher effusion rates than later (Wilson et al., 2001). This behavior could be a function of source mantle plume geometry, where early massive flows were fed by a plume head and subsequent lower flow volumes were due to the diminishing volume of the plume tail. This dichotomy in eruptive styles between plume head and plume tail is well documented for terrestrial plumes (e.g., Ernst and Buchan, 2001). Of additional significance is the relationship between plume head size and initial eruption volume. The size of the plume head is primarily a function of the depth at which the plume originated (Campbell, 2001); the enormous volumes of lava erupted here suggest that a source plume may have originated deep in the interior, perhaps at the martian core-mantle boundary.

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