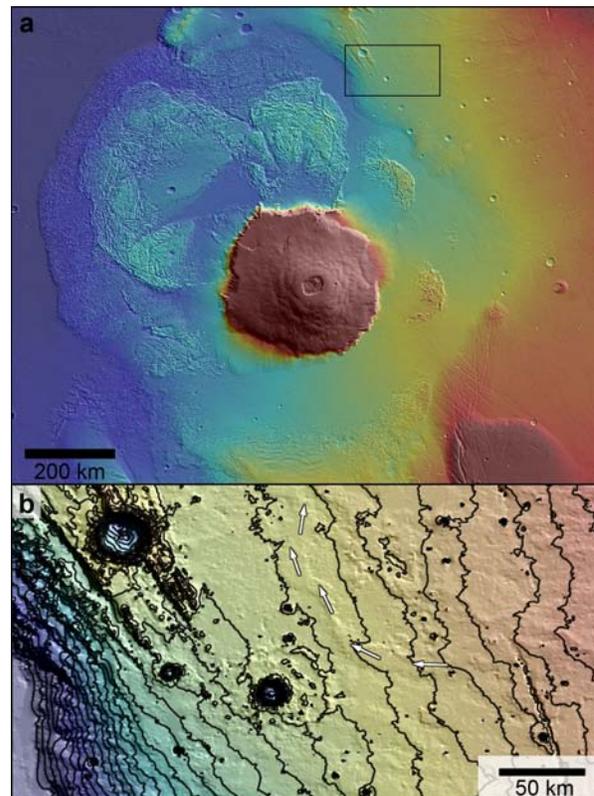


**THE FORMATION HISTORY OF OLYMPUS MONS FROM PALEO-TOPOGRAPHY.** L. M. Jozwiak<sup>1,2</sup>, R. J. Isherwood<sup>2</sup>, and J. C. Andrews-Hanna<sup>2</sup>, <sup>1</sup>Dept. of Earth, Atmospheric, and Planetary Sciences, MIT, Cambridge, MA, ljozwiak@mit.edu, <sup>2</sup>Dept. of Geophysics, Colorado School of Mines, Golden, CO, jcahanna@mines.edu.

**Introduction:** The Olympus Mons shield volcano on the northwestern edge of Mars' Tharsis rise is the largest volcano in the solar system. Its volcanic history is intimately tied with the volcanic and geodynamic history of Tharsis and of Mars as a whole. Previous studies used crater counting to estimate the age of the flanks of Olympus, with typical values of ~200 Myr [1]. However, establishing the formation history for Olympus Mons is complicated by the fact that each volcanic eruption resurfaces the flanks, erasing the previous crater record. Here we place constraints on the bulk formation history of Olympus Mons by reconstructing the paleo-flexural history of the surrounding region. Crater retention ages from lava flows on the flexural trough surrounding the edifice that pre-date the trough are used to constrain the onset of volcanic loading. Crater retention ages from the aureole deposits are used to constrain the age at which a significant fraction of the edifice was in place. These two ages bracket the main constructional period of Olympus.

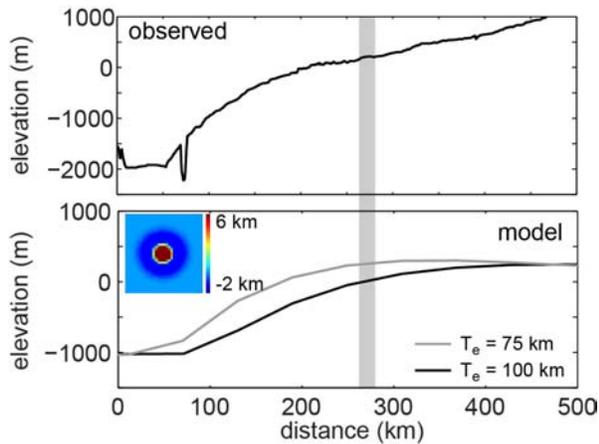
**Paleo-topography of the Olympus Mons flexural trough.** The concept of paleo-topography is used in terrestrial geodynamics to reconstruct the vertical motions of the lithosphere [2], but has seen less use in planetary applications [3]. Our paleo-topographic reconstructions are predicated on the fact that fluids (e.g., lava) flow along the path of steepest descent. Olympus Mons is surrounded by a large flexural trough that has been partially infilled with volcanic eruptions (Figure 1a). We surveyed the outer inwards-facing flanks of the trough in MOLA topography using ENVI and ArcGIS to identify topographically discordant flows whose paths deviated significantly from the down-slope direction. Lava flows follow sinuous paths down-slope, with the flow vectors oriented within  $\pm 10^\circ$  of the path of steepest descent. Several topographically discordant flows were identified on the slopes of the flexural trough that deviated from the downslope direction by more than this natural variability. In the northeast quadrant of the Olympus Mons flexural trough, one lava flow was observed to be flowing  $78^\circ$  away from the current down-slope direction, as determined by fitting a plane to the local topography (Figure 1b). The implication is that this lava flow formed before the flexural trough altered the region's topography.

To test this, we used thin-shell spherical harmonic models of the flexural response to volcanic loading at Olympus Mons [4]. The load was iterated to match the approximate topography of Olympus Mons, including

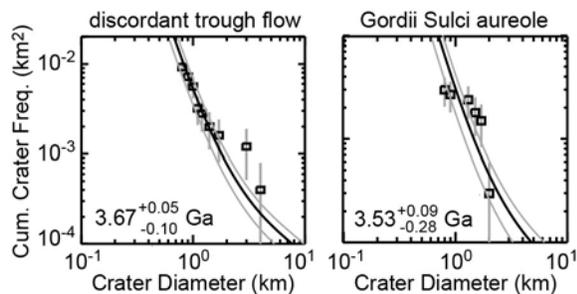


**Figure 1.** (a) MOLA topography of Olympus Mons and the surrounding flexural trough. (b) MOLA topography and contour map showing the topographically discordant lava flow (arrows).

the partial volcanic infilling of the flexural trough. The resulting flexural profiles were compared with the observed topography surrounding the flexural trough. The topographically discordant flow was located at a distance of ~188 km from the trough, measured in the direction orthogonal to the nearest trough segment. Predicted flexural slopes at the location of the flow range from 0.29% to 0.56% for lithosphere thicknesses between 75 and 100 km. These predicted flexural slopes compare favorably with the observed slope at the deviant flow of 0.33%, demonstrating that the observed steep gradient nearly orthogonal to path of the deviant flow is a result of later flexural deformation in response to volcanic loading at Olympus Mons. By comparison, the slope in the down-flow direction is only 0.11%, a factor of three smaller than the gradient towards the trough. Future work will constrain what fraction of Olympus Mons could have been emplaced at the time the flow formed without redirecting it towards the trough, but the magnitudes of the slopes



**Figure 2.** Observed (top) and modeled (bottom) topographic profiles of the flexural trough surrounding Olympus Mons. The location of the discordant flow is indicated in gray, and map of flexure model shown in inset.



**Figure 3.** Crater size frequency distributions and best-fit isochrons for the topographically discordant flow (left) and the Gordii Sulci aureole deposit (right).

clearly argue that the majority of the volcanic edifice post-dated the formation of this deviant flow.

**Constraints from crater retention ages.** The age of the deviant lava flow was derived from counting craters  $\geq 900$  m in diameter in THEMIS IR daytime images [5]. The generated model age of  $3.67^{+0.05}_{-0.10}$  Ga places a constraint on the initiation of significant volcanism and flexural loading at Olympus Mons. On the basis of the paleo-flexure considerations, we conclude that the bulk of Olympus Mons formed after this time.

In order to constrain the end of the primary construction phase, we consider the age of the aureole deposits. These deposits are interpreted to have formed through mass failure of the flanks of Olympus Mons, and thus require that the edifice had attained a significant fraction of its final size (similar aureoles are not found around the smaller Tharsis Montes). In one case, the volume of the aureole deposit can be fit within a concavity in the present-day basal scarp [6].

Three aureole deposits - Cyane Sulci, Sulci Gordii, and Gigas Sulci - were dated, using crater counts derived from THEMIS VIS images. The steep, rough terrain of the aureole deposits imperfectly preserves craters, so that the resultant crater retention ages are

lower bounds. The oldest crater retention age was found for Sulci Gordii, of  $3.53^{+0.09}_{-0.28}$  Ga, in agreement with previous estimates [7]. Using the assumption that the aureole deposits represent flank failure from stresses within the edifice, this age represents the time at which Olympus Mons had reached a significant fraction of its present-day size.

**Conclusions.** From the crater retention ages derived from the topographically discordant lava flow and the aureole deposits, we conclude that the primary volcanic construction of Olympus Mons occurred between 3.67-3.53 Ga. Including the volcanic infill of the flexural trough, we estimate the volume of Olympus Mons volcanics to be approximately  $4.4 \times 10^6$  km<sup>3</sup>. The constraint on the duration of edifice construction of  $14^{+33}_{-19}$  Myr results in an eruption rate of  $\sim 0.3$  km<sup>3</sup>/yr. Volcanic eruption rates at typical terrestrial hotspots are of order 0.03-0.1 km<sup>3</sup>/yr [8]. Thus, eruption rates at Olympus Mons during its primary construction phase are comparable to or slightly greater than eruption rates at terrestrial hotpot volcanoes, suggesting the likelihood of similar geodynamic drivers of volcanism.

Despite the great antiquity of the bulk of Olympus Mons, ongoing volcanic eruptions have been sufficient to resurface the flanks, resulting in crater retention ages of  $\sim 200$  Myr. An upper bound on the rate of late stage volcanism can be calculated by assuming a uniform eruption rate for the entire edifice volume between 3.67 and 0.20 Ga, leading to 0.0012 km<sup>3</sup>/yr. The  $>300$ -fold decrease in the eruption rate after the primary constructional phase may suggest a passive mechanism of maintaining volcanic activity, such as the presence of a pre-existing magma plumbing system facilitating the rise of small amounts of melt to the surface. This formation history parallels that of Tharsis as a whole, which experienced its primary constructional phase in the Noachian [3, 9], despite continued volcanic activity into the Hesperian and Amazonian.

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