MODELLING SUBSIDENCE DUE TO THE OLYMPUS MONS LOAD USING PALEO-SLOPE INDICATORS. J. Chadwick[1] and P. McGovern[2], [1]Dept. Of Geography and Earth Sciences, University of North Carolina at Charlote, Charlotte, N.C. 28223; djchadwi@uncc.edu; [2]Lunar and Planetary Institute, Universities Space Research Association, Houston TX 77058; mcgovern@lpi.usra.edu.

Introduction: Olympus Mons is an enormous volcanic edifice with a basal diameter over 600 km and a height over 23 km above the adjacent plains. The thickness of the elastic lithosphere (T_e) beneath Olympus Mons has been estimated to be at least 150 km based on the absence of circumferential graben [1, 2]. Analysis of gravity and topography admittance spectra indicates that T_e is > 70 km at Olympus Mons [3, 4].

In addition to graben formation, loading and subsidence of large volcanoes can form moats and potentially influence the orientations of previously-emplaced slope-directed features, such as lava flows or fluvial channels. The flow directions indicated by these features provide a snapshot of the local slope orientation at the time of their formation. If they formed prior to or during an episode of subsidence of a nearby large volcano, the orientation of modern topography may differ from that indicated by these “paleo-slope” features. In this study, deformation due to loading of Olympus Mons was identified by mapping the downslope azimuthal orientations of groups of lava flows and comparing them with modern topographic orientations.

This study of lava flow orientations on the smooth plains around the southern and southeastern sides of Olympus Mons demonstrates how paleoslope data can be used to derive information on the (geologically) recent deformation of Mars. This example exploits the divergence between paleo-slopes and current slopes as derived from the equipotential-referenced Mars Orbiter Laser Altimeter (MOLA) topography dataset [5].

Methods: The procedure for estimating subsidence responsible for the reorientation of topographic slopes relative to paleo-slope features is as follows: We collected digitized azimuths of the downhill directions of lava flows using moderate- and high-resolution spacecraft imagery and MOLA DEM. We then extracted MOLA points within a certain distance of each flow azimuth datum (i.e., the location of the head of the flow) to create a reference surface. We calculated the slope magnitude and azimuth of that plane from MOLA to derive the current values (red vectors in Figure 1). A 30-km search radius was used for each datum in this case. We then calculated vertical displacements resulting from a lithospheric flexure model, a long-wavelength response of the thick Martian lithosphere to the emplacement of volcanic flows on the flanks of Olympus Mons. Here we used the “shallow spherical shell” loading model [6], although there are other models with differing advantages (e.g., the spherical harmonic loading model [7] or the axi-symmetric “thick-plate” formulation [8]. The model inputs are load dimensions (width, height, and shape), and elastic lithosphere thickness Te.

To remove the effects of the loading-induced flexure the vertical displacements of each individual model were subtracted from the MOLA topography, yielding a “pre-deformation” surface. The misfit between the pre-deformation surface downhill azimuth and the flow azimuth (black lines in Figure 1) was then calculated. The loading models with the lowest r.m.s. misfits (over the entire ensemble of flow points) are the preferred models. The resulting downhill azimuths at each flow head datum for such a loading model are shown by the white arrows in Figure 1.

Results: The r.m.s. misfit values between paleoslope azimuths and model predeformation azimuths (in units of degrees) for volcanic loading models were calculated. The results for a truncated (flat-topped) cone load shape (centered on the Olympus Mons caldera) shows a classic tradeoff between the load radius (y-axis) and T_e (x-axis). Best-fit T_e values are generally 100 km or greater, consistent with estimates for T_e from loading models [1, 2] and gravity-topography relationships [3, 4]. The effects of a change in load shape to a standard cone would be to shift the best-fit models upward (bigger load radius) and to the left (lower T_e). This shift is likely in part due to the fact that a regular cone of given radius and height has less volume than a truncated cone; decreasing load height alone gives a similar shift to the upper left. Load center heights of 1 to 8 km were considered, with best fits generally in the 3-5 km range.

Counterclockwise deflection of modern slopes from lava flow orientations around Olympus Mons (Figure 1) is consistent with subsidence centered on the volcano, evidence for a topographic response to the load of this volcano. A 4-km tall, 300-km radius increment of volcanism represents a significant fraction of the volume of the total Olympus Mons edifice: ~3.8 x 10^5 km^3, or about 17% of the edifice by a simple reckoning of the above-base-level material. Accounting for the edifice material filling the flexural depression below the base level, however, will reduce this percentage significantly. Nonetheless, such a load increment represents a major episode in the evolution of the Olympus Mons edifice, one that is now constrained in age by the age of the flow units south of Olympus

Mons. These flows have been determined stratigraphically to overlap in time with those of the lower flanks of Olympus Mons [9]. Crater counts for Olympus Mons lower flank flows from Mars Express data give age ranges of 10^7 – several x 10^8 years in most cases [10]. An age of 3.8 x 10^7 years, squarely in this range, would yield a magma supply rate of 0.01 km^3/yr, about an order of magnitude below the 0.09 km^3/yr mean rate of supply at Kilauea, Hawaii, but comparable to the minimum rate of 0.02 km^3/yr measured in the 1960s [11]. These preliminary results suggest that a plume comparable to a weak version of the one building the Hawaiian Islands on Earth existed in the Martian mantle in the very recent geologic past. The large volume and recentness of the edifice increment calculated here is also consistent with evidence (young faulting) for recent flank spreading of the Olympus Mons edifice [12].

In general, the model predictions (white arrows Figure 1) match the paleoslopes much better than the current slopes (red arrows in Figure 1), although the goodness of the model fit shows substantial variation over the study area. Areas of misfit for this model may reflect local flow emplacement at different times, when loading conditions on the main edifice were different. Studies of flow unit structure and stratigraphy from geologic mapping can aid in the interpretation of such differences: limiting the set of to-be-fit data based on such criteria may allow significantly improved constraints on load magnitudes and geometries to be achieved. There are additional considerations: we did not explore more complex spatial variations in load dimensions. Structural analysis and mapping of Olympus Mons suggests that the most recent flow units may not be distributed symmetrically about the summit, but rather preferentially elongated along a northeast-southwest axis [13]. Models that account for such complexity by superposing the effects of several smaller symmetric models will be run as this study continues to improve the best-fit results.

References: [1] Thurber and Toksoz (1978), GRL 5, 977-980; [2] Comer et al. (1985), Re. Geophys. 23, 61-92; [3] McGovern et al. (2004), JGR; [4] Belleguic et al. (2005), JGR 110; [5] Smith et al. (2001), JGR 23,689-23,722; [6] Brotchie and Sylvester (1969), JGR74, 5240-5252; [7] Turcotte et al., (1981), JGR 86, 3951-3959; [8] Comer (1983), Geophys. J. R. Astron. Soc., 72, 101-113; [9] Morris and Tanaka (1994) USGS Miscellaneous Investigations Series map I-2327; [10] Neukum et al. (2004) Nature, 432, 971-979; [11] Dvorak and Dzurisin (1993) JGR 98, 22,255-22,268; [12] Basilevsky et al. (2006) GRL; [13] McGovern and Morgan (2009) Geology, 37, 139-142.

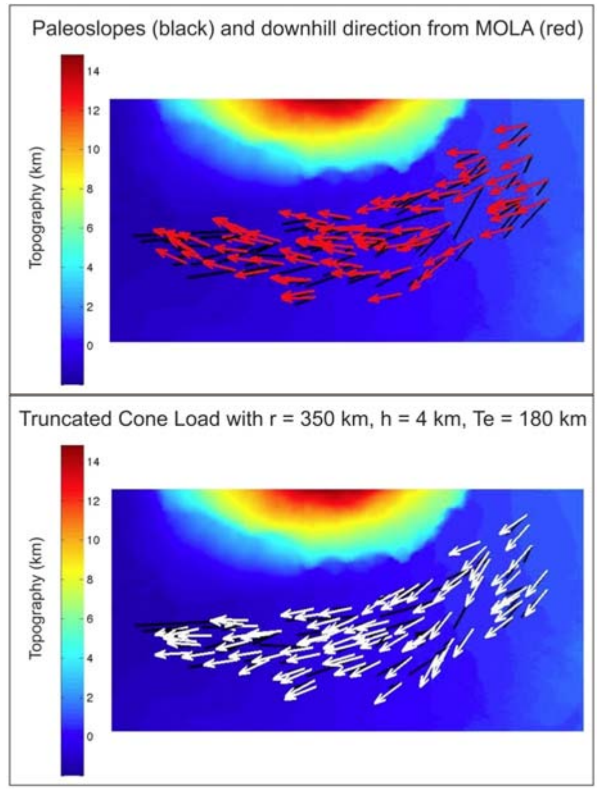

Figure 1. Paleoslope orientations (black lines) connecting the beginning and endpoints of mapped flows. Red arrows show current downhill direction from MOLA. Paleoslopes and predeformation downhill direction (white arrows) from the flexural loading model.

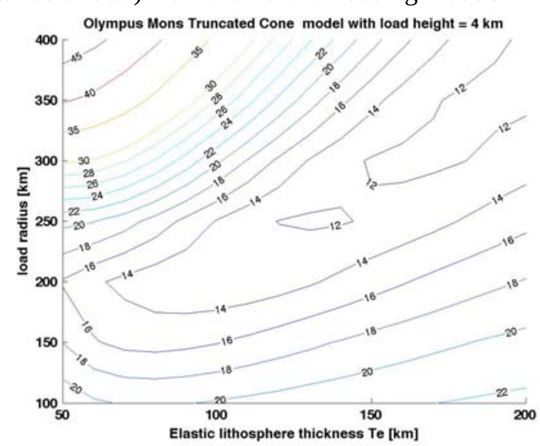

Figure 3. Root-mean-square (r.m.s.) misfits between observed lava flow azimuths and downhill azimuths for a truncated cone load calculated by removing the effects of a loading model from observed topography. Contours are in units of degrees. Model parameters are elastic lithosphere thickness T_e on the x-axis and load radius on the y-axis. Load radii larger than 400 km were not considered because they would cover the flows that are being used to infer paleoslopes. Load height is 4 km.