INVESTIGATION OF A LANDSLIDE MECHANISM FOR THE FORMATION OF THE OLYMPUS MONS SCARP AND AUREOLE LOBES. S. Musiol[1], D. A. Williams[2], S. van Gasselt[1], T. Platz[1], A. Dumke[1], and G. Neukum[1], [1]Freie Universität Berlin, Institute for Geological Sciences, Planetary Sciences and Remote Sensing, Malteserstr. 74-100, 12249 Berlin (stefanie.musiol@fu-berlin.de), [2]School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287-1404.

Introduction: Olympus Mons (OM) has an up to 9 km high circumferential scarp and aureole lobes with runout distances of more than 700 km. These are exceptional features that most other Martian volcanoes do not have. It is generally accepted today that the formation of the scarp and aureole lobes are correlated. Early attempts to explain these features proposed gravity spreading and thrust sheets [1,2,3], subglacial eruptions [4,5], volcanic spreading [6,7], and mass wasting [8,9,10]. Large volcanoes such as OM are known to deform the elastic lithosphere by loading [11]. Furthermore, they are subject to internal deformation by lateral spreading [12]. Stresses induced by these processes could lead to earthquakes and volcanic eruptions triggering flank failure [12]. The questions addressed in this work are a) whether the OM basal scarp and aureoles can be explained by a landslide mechanism and b) how the very long runout distances of the aureole deposits can be explained.

Methods: For our data integration, organization and analysis we utilized ESRI's Geographic Information System (ArcGIS). The image basis consists of data from the HRSC (High Resolution Stereo Camera) on Mars Express with a spatial resolution of 25 m/px and from the CTX (Context Camera) on Mars Reconnaissance Orbiter with a spatial resolution of 6 m/px. The images were projected using Mars Transverse Mercator projection with a center longitude of 134°W. Gridded topography data of the MOLA (Mars Orbiter Laser Altimeter) on Mars Global Surveyor with a spatial resolution of 463 m/px and topography data derived from HRSC stereo data with a spatial resolution of 100 m/px have been used for terrain-model analysis and morphometry. For volume determination an equal-area sinusoidal projection was used for which the margins of the aureole of interest were digitized and the area of the digitized polygon was determined. Heights of an aureole section were averaged to obtain a mean thickness which was subsequently multiplied with the area. In order to characterize the structural inventory of OM, mapping was performed.

Results: In general, OM upper flanks are under a state of compression, as evidenced by the presence of terraces (Figure 1) interpreted as thrust faults [13]. In contrast to this, a number of extensional features are visible on the lower flanks, such as concentrically oriented grabens and fractures, partially buried below thick stacks of lava. Radially oriented scarps and elevated blocks on the lower flanks (Figure 1) were interpreted as tear faults [6]. The blocks are partly rotated and could be related to complex listric fault systems with synthetic and antithetic faults. On top of the blocks we found normal faults. Near the eastern base of the scarp a number of wrinkle ridges, small channels, ridges, and possible strike slip faults are observed. Wrinkle ridges are the surface expression of thrust faults forming in a layered unit on top of a décollement [14]. The caldera of OM is characterized by concentric grabens and wrinkle ridges, partly radially oriented.

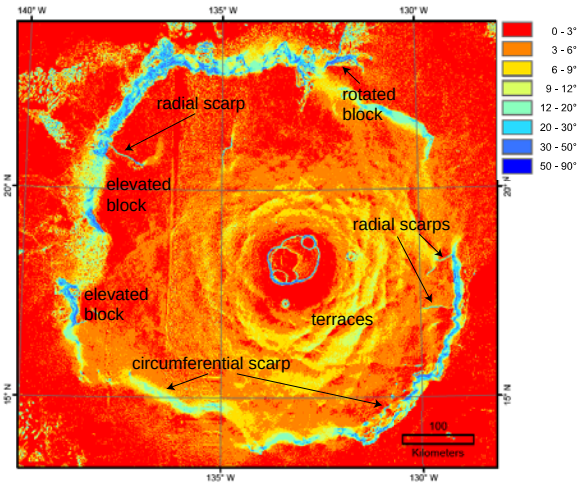

Figure 1. Slope map derived from HRSC stereo data. Lava covered circumferential scarp shows slope values of 10-20°, exposed scarp shows slope values >20°.

The volume of the northwestern aureole lobe (Figure 2) amounts to 2.9×10^5 km³, a factor of 1.5 larger than the estimated volume of 1.97×10^5 km³ as given by [8]. In order to estimate in how far this volume could be derived from a collapsed scarp of a possible larger proto-OM, we extended the lower scarp as shown in Figure 3 to give a possible proto-OM cone. We computed the volume of the dashed part in Figure 3 from MOLA topography data and we used a scarp height h of 8.5±0.5 km, a distance d from the center of the caldera to the scarp of 300±20 km, a scarp angle α of 20°±10° and a lower flank angle β of 2°±1° for our calculations. The result of $4.9\times10^5\pm3.2\times10^5$ km³ fits to the aureole-lobe volume within uncertainties. The possible proto-OM cone extended up to a distance of 543±25 km from the volcano center (Figure 2), making an emplacement mechanism likely as suggested by [8],

i.e. a rockslide removed material from OM outer flanks, which once extended beyond the present base.

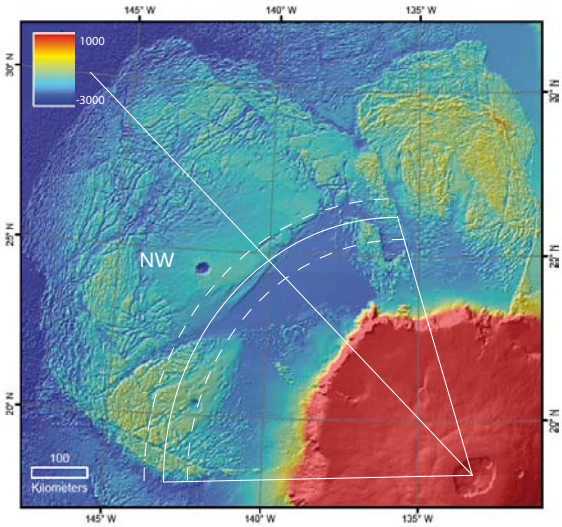

Figure 2. Color-coded MOLA topography map. Northwestern (NW) aureole lobe is indicated as well as dimensions of possible proto-OM cone segment and location of profile shown in Figure 3.

The classification of the OM scarp and aureole lobes based on morphology could be analogous to submarine landslides on Earth [15]: parts of the scarp show amphitheater-heads and the aureole lobes show characteristics of a debris avalanche, i.e. long runout, partly intact sliding blocks, and faulted surface. The aureole lobes extend much farther towards the northwest than to the south and east, suggesting that mass transport was controlled by regional topographic gradients (<0.5°). The coefficient of internal friction, defined as the ratio of fall height to distance travelled by the avalanche [16], is a measure for the efficiency of transport. The northwestern aureole lobe of OM has a maximum runout distance of 660 km and an associated scarp height of 8.5 km leading to a low coefficient of internal friction of 0.01, which indicates that the aureole material moved as a very mobile flow.

Conclusions and next steps: Many aspects of OM features suggest a landslide mechanism for the formation if its scarp and aureole lobes. Landslides on extremely low slopes (<1°) are known to occur only in submarine environments on Earth, the largest landslides even occur on the lowest slopes [17]. Earth analogs such as Hawaii and the Canary islands are known to be sites of large submarine landslides. Elevated pore pressures and weak sediment layers play an important role in their formation [17]. An understanding of OM aureoles and scarp could help resolve the question of the former existence of an ocean within the northern lowlands. Future investigations will concentrate on numerical modeling of slope stability, failure mechanisms, and Earth analogs.

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References: [1] Harris, S. A. (1977) JGR, 82, 3099-3107. [2] Francis, P. W. and Wadge, G. (1983) JGR, 88, 8333-8344. [3] Tanaka, K. L. (1985) Icarus, 62, 191-206. [4] Hodges, C. A. and Moore, H. J. (1979) JGR, 84, 8061-8074. [5] Helgason, J. (1999) Geology, 27(3), 231-234. [6] Borgia, A. et al. (1990) JGR, 95, 14357-14382. [7] McGovern, P. J. and Morgan, J. K. (2009) Geology, 37, 139-142. [8] Lopes, R. et al. (1982) JGR, 87, 9917-9928. [9] McGovern, P. J. et al. (2004) JGR, 109, E08008. [10] Shea, T. and van Wyk de Vries, B. (2008) Geosphere, 14, 657-686. [11] McGovern, P. J. and Solomon, S. C. (1993) JGR, 98, 23553-23579. [12] Morgan, J. K. and McGovern, P. J. (2005) JGR, 110, B05402. [13] Byrne, P. K. et al. (2009) EPSL, 281, 1-13. [14] Montési, L. G. J. and Zuber, M. T. (2003) JGR, 108, 1-22. [15] Moore, J. G. et al. (1989) JGR, 94, 17465-17484. [16] Selby, M. J. (1993) Oxford University Press. [17] Masson, D. G. (2006) Phil. Trans. R. Soc. A, 364, 2009-2039.

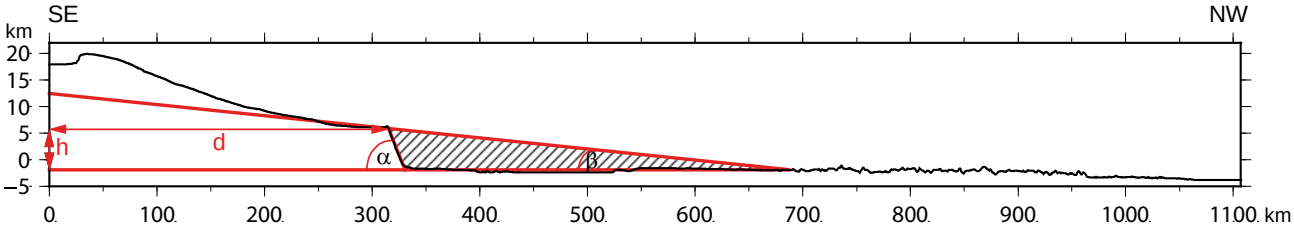

Figure 3: Section through OM shown in Fig. 2 with parameters used to determine volume and inferred proto-OM extension (dashed).