Heights of Martian Volcanoes and the Geometry of their Calderas from MOLA Data. P. J. Mouginis-Mark[1] and K. J. Kallianpur[1], [1]Hawai‘i Institute Geophysics and Planetology/SOEST, University of Hawai‘i, Honolulu, HI 96822, USA. <pmm@higp.hawaii.edu>

Introduction: We use the 1/32° gridded topographic data from the Mars Orbiter Laser Altimeter (MOLA) to investigate the geometry of Martian volcanoes and their summit calderas. Our objective is to identify details of the structure and style(s) of eruption that are not easy to identify from images taken from the Viking Orbiters and the Mars Orbiter Camera (MOC). We have determined the heights of all of the 18 main volcanoes on Mars, as well as the average depths of their calderas. The topographic variability of the caldera floor has also been examined in detail for signs of post-eruption subsidence. Measurements of Arsia, Ascraeus, Elysium, Olympus, and Pavonis Montes; Albor, Ceraunius, Hecates, Jovis, Tharsis, and Uranius Tholi; and Alba, Apollinaris, Biblis, Hadriaca, Tyrrhena, Ulysses, and Uranius Paterae are included.

Volcano heights and caldera depths were measured using the ENVI software package. To facilitate these measurements, we first created a shaded relief image of each volcano in order to define the break in slope of the flanks around the entire volcano. The elevation of this break in slope varies around the edifice due to, for instance, partial burial of the flanks by lava flows from an adjacent volcano (e.g., the northern slope of Albor Tholus is partially buried by lavas from the southern flank of Elysium Mons). Volcano height is defined here as the maximum elevation of the summit minus the average elevation of the perimeter of the volcano at this break in slope.

Volcano Heights: Our data show that the heights of several Martian volcanoes have been overestimated in the past. Compared to the heights listed by Pike [1], we find that Pavonis Mons is only 8.243 km high (vs. 17.0 km), Arsia Mons is 9.326 km (vs. 18.0 km), Ascraeus Mons is 13.893 km (vs. 19.0 km) and Olympus Mons is 21.611 km (vs. 25.0 km). We also find that a few volcanoes are higher than previously estimated [1]; Ceraunius Tholus is 6.458 km high (vs. 2.5 km), Tharsis Tholus is 7.017 km (vs. 5.0 km), and Uranius Patera is 3.435 km (vs. 2.0 km). The remaining volcano heights are either close to earlier estimates [1], or were not included in earlier analyses by virtue of their small size and/or the lack of suitable Viking data from which to make shadow length measurements.

Caldera Depths: It was previously recognized from stereogrammetric data [2, 3] that the rim crest of the Olympus Mons caldera is highly variable, and so a single measure of rim height is not very informative. We find that the base of the caldera wall is not at a single level, due to several possible reasons, including multiple collapse events or partial burial of the floor by subsequent flows or talus. By using a shaded relief image of the volcano as a guide, we traced the caldera rim crest using the ENVI “region of interest” and “polyline” functions. The average caldera floor height was therefore determined using the “polygon” function within ENVI, tracing the perimeter of the caldera floor from the shaded relief image. Both the average caldera floor elevation and the statistical variation in height were determined. The values of the average caldera depth were derived by subtracting the average floor elevation from the average rim elevation.

Intra-Caldera Topography: Calderas are present on all of the volcanoes considered here, although in a few cases (e.g., the western caldera of Alba Patera) there is morphologic evidence for partial in-filling late in the evolution of the summit of the volcano. Extensive MOLA coverage over these summit regions permits, for the first time, a look at topographic variability within the calderas of volcanoes on Mars, which may reveal subsidence of the caldera floor after the last eruption. These data have important implications for the analysis of the internal structure of the volcano.

Several investigators [4, 5, 6] have recognized that caldera deformation may provide insights into the post-eruption evolution of the magma chamber. In almost all cases, our data show that Martian volcanoes have caldera floors that are not flat or horizontal. This variability may either be due to multiple collapse features lying within the entire caldera (e.g., Olympus and Ascraeus Montes), or to the subsidence of the central portion of a single summit crater (e.g., Apollinaris Patera). Our data show that Tharsis Tholus has the greatest variability in floor topography (1 S.D. = 1,200 m), while Ascraeus Mons (1 S.D. = 1,200 m), Biblis Patera (1 S.D. = 669 m), Olympus Mons (1 S.D. = 464 m), Apollinaris Patera (1 S.D. = 260 m) and Pavonis Mons (1 S.D. = 227 m) also have significant caldera floor variability.

Some of this variability in floor topography derives from the multiple collapse events within the caldera complex. The Olympus Mons caldera is an accumulation of six nested craters, most likely formed during recurrent collapse of the magma chamber following drainage from flank eruptions [3]. The main caldera is ~60 km in diameter, and there are several in the diameter range 30 – 40 km. Two MOLA profiles which traverse the primary crater reveal that the central caldera floor underwent a dramatic subsidence in excess of 1 km. MOLA profile 11358 shows a northward dip from ~18.18°N to 18.4°N, where the floor may have sagged by 150 m. The summit of Ascraeus Mons also displays several discrete centers of collapse [7]. There is a general northward rise in elevation across the caldera floor. Between 11.15°N and 11.37°N, the floor of the caldera slopes upward by about 250 m (~1.1°).

The use of individual MOLA profiles across some of these calderas allows further insight into their characteristics. For instance, the caldera floor of Arsia Mons displays a slight, consistent northward tilt. Subsidence of about 100 m occurred between ~10.2°S and 8.5°S (a slope of ~0.06°). Only when viewed at full resolution can the topographic variability of Arsia Mons caldera be detected. Topographic variability of the caldera floor is of the order of a few meters point-to-point, implying that the floor may have formed as a single flat surface, possibly a lava lake. A possible reason for the lack of deformation could be that the last major collapse event on Arsia Mons was followed by a flooding of lava within the caldera or from the adjacent caldera walls [7].

Discussion: Our estimates of caldera depth are comparable to earlier Viking-era measurements of caldera dimensions [6], with the following exceptions. Our measurements of the average caldera depth reveal that Elysium Mons has a shallower caldera than previously believed (0.381 km vs. 1 km), as do Jovis Tholus (0.606 km vs. 2 km), Pavonis Mons (3.603 km vs. 5 km), Tharsis Tholus (1.587 km vs. 2.4 km), and Uranius Patera (1.269 km vs. 2.2 km). In all cases, the values reported here are lower than the estimates of Crumpler et al. [6] that were determined from shadow length measurements. In part, this difference is believed to be due to the bias towards reporting the maximum rim heights using the shadow length method, rather than the average heights around the entire caldera rim that are described here. Because volcano summits are often asymmetric, we favor our interpretation of caldera depth over these earlier single-point shadow length estimates because they include all points on both the rim and the floor.

It is also evident that not all calderas are located at the highest point on the volcano. The extreme case is Tharsis Tholus, where the caldera rim is 2.662 km below the summit of the volcano. This volcano has previously been recognized as the prime candidate for a "sector collapse" volcano on Mars [8] and so may be atypical for Martian volcanoes in general. Alba Patera (667 m), Ceraunius Tholus (205 m), Olympus Mons (240 m) Pavonis Mons (130 m) and Uranius Patera (124 m) also have a significant height off-set between the highest point of the volcano and the highest point on the caldera rim. Such a height offset is quite common on terrestrial volcanoes (e.g., Kilauea and Mauna Loa volcanoes, Hawaii; [9]), and is interpreted to be due to multiple episodes of cone growth and subsequent collapse. During the evolution of the volcano, the magma chamber may not stay at the same physical location, and so successive collapse events may be localized at different positions [10, 11].

A comparison between the average volcano height and the average depth of the caldera also reveals some interesting relationships. For almost all terrestrial basaltic volcanoes, the caldera floor is above the level of the surrounding surface upon which the volcano is constructed [1]; i.e., the ratio of caldera depth to volcano height is <1.0. In contrast, the Martian volcanoes Albor Tholus and Ulysses Patera have caldera floors below the level of the surrounding plain! The caldera depth-to-height ratio for these volcanoes is 1.33 and 1.13, respectively, and indicate significant burial of their lower flanks by lava flows from other volcanoes [12]. Most volcanoes measured here have caldera depth/volcano height ratios that are <0.5, but Biblis Patera (0.77), and Jovis Tholus (0.61) are also exceptions. At the other end of the spectrum, Elysium Mons (0.03), Alba Patera (0.05), Hecates Tholus (0.05), Olympus Mons (0.05), and Arsia Mons (0.08) all have very shallow calderas compared to the height of the parent volcano. We note, however, that these are average caldera values which are affected by the topographic variability of the floor. In some cases, such as Tharsis Tholus and Ascraeus Mons, 1 standard deviation (1 S.D.) in floor topography can be as great as 1,200 m and 1,149 m, respectively. Other volcanoes, such as Olympus Mons, have multiple collapse craters, some of which are more than 1 km deep, but the floor variability statistics are dominated by the much larger, shallower, segment of the caldera.

References: [1] Pike, R. J. (1978) *Proc. Lunar Planet Sci. Conf. 9th*, 3239 - 3273. [2] Wu, S. S. C. et al. (1984) *Nature 309*, 432 - 435. [3] Mouginis-Mark, P. J. & M. S. Robinson (1992) *Bull. Volcanol. 54*, 347 - 360. [4] Zuber, M. T. & P. J. Mouginis-Mark (1992) *J. Geophys. Res*. *97*, 18295 - 18307. [5] Thornhill, G. D. et al. (1993) *J. Geophys. Res*. *98*, 23,581 - 23,587. [6] Crumpler, L. S. et al. (1996) In: *Volcano Instability on Earth & Other Planets*, Geological Society of London, pp. 307-348. [7] Mouginis-Mark, P. J. (1981) *Proc. Lunar Planet Sci. Conf 12B*, 1431-1447. [8] Robinson, M. S. & S. K. Rowland (1994) In: *Conf. Volcano Instability on Earth and Other Planets*, Geol. Soc. London, p. 44. [9] Walker, G. P. L. (1988) *J. Geophys. Res. 93*, 14,773 - 14,784. [10] Knight, M. D. & G. P. L. Walker (1988) *J. Geophys. Res. 93*, 4301 - 4319. [11] Wilson, L. (2001) *J. Geophys. Res. 106*, 1423 - 1433. [12] Whitford-Stark, J. L. (1982) *J. Geophys. Res. 87*, 9829 – 9838.