VOLCANIC DEPRESSIONS AND LAVA LAKES ON EARTH, MARS, VENUS, IO AND TITAN.

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Introduction: Volcanic depressions are common on the terrestrial planets [e.g., 1]. On Earth, calderas typically form from collapse following: 1) an explosive evacuation of a substantial amount of magma (on the order of cubic kilometers or more) from a storage chamber [e.g., 2]; or 2) repeated injection into and effusive evacuation from a magma chamber of a smaller amount (10^6 – 10^8 km^3) of magma [e.g., 3]. It is not yet certain if either of these mechanisms are responsible for the large volcanic depressions observed on Io and Titan [4]. Furthermore, terrestrial calderas formed by repeated magma injection and eruption may become the home for lava lakes [3], as has been proposed for some volcanic depressions on Io [4]. In this paper, we will compare the morphologies of calderas on Io and Titan with those on Earth and other bodies, discuss possible origin, eruption processes, and global distribution.

Titan, like Io, also appears to have a young surface, as very few impact craters have been found so far [4, also this volume]. In contrast to Io, few calderas have been seen on Titan, and resurfacing seems to be accomplished by a more complex interplay of geological processes [6].

Ionian Paterae: Volcanic depressions are the most common form of volcanic feature on Io [4], and are called "paterae" because they show little (if any) topographic relief, but are characterized by flat-floored, steep-walled depressions that, in some cases, are filled with lava flows [7]. Lopes et al. [4] proposed that patera volcanism, most likely in the form of lava lakes, is the most widespread type of volcanic activity on Io. This has important implications for Io's resurfacing because, if the activity remains confined within calderas for long periods of time, resurfacing is likely being accomplished by processes other than spillage of lava on the surface. Geissler et al. [10] analyzed plume deposits and proposed that they could account for most of Io's resurfacing.

To date, 428 paterae have been identified on Io's surface [7]. Of these, 36 contain bright "islands" of material on their otherwise dark floors. An analyses of this subset of Ionian paterae [8] reveals that most paterae are <2000 km^2, and all but 4 are <6000 km^2. This distribution suggests that either: 1) paterae form through a process that favors small paterae, and these paterae then remain the same size throughout their lifetime; or 2) paterae form small and grow to be large over time. If the latter is true, then paterae size may be directly related to paterae age. By comparing the paterae dimensions to estimated resurfacing rates on Io, we can obtain estimates for paterae life-spans and growth rates. Resurfacing rates [9] indicate that an inactive paterae should be filled in with ash or lava within ~3 million years or less, depending on the initial paterae depth [7]. If all paterae appeared 30 Ma [10] at the size of the smallest paterae yet identified (5 km^2), growth rates of 70 ± 100 m^2/year are obtained. These are reasonable rates for terrestrial effusive calderas; in contrast, terrestrial explosive calderas form in a geologic instant.

Loki Patera is the largest volcanic depression on Io, and is ~200 km^2 across. Its behavior and morphology are unique [8,11], and represents an exceptional style of volcanism that does not have a straightforward terrestrial analog.

Titan: Cassini instruments, the RADAR in particular, have provided evidence of cryovolcanic features on Titan [12]. The Synthetic Aperture (SAR) mode of the RADAR provided images of about 15% of Titan's surface to date. Cryovolcanic features are not ubiquitous on Titan, but SAR images have revealed several caldera-like features, as well as radar-bright flows, a circular volcanic feature named Ganesa Macula, and several flows and craters identified as of possible cryovolcanic origin. The two Titan features that have most confidently been identified as calderas are part of the Ara Fluctus and Rohe Fluctus. Ara Fluctus is a scalloped feature similar in morphology to a feature on the grooved terrain on Ganymede [12] interpreted as a caldera and flow [13]. The Rohe Fluctus feature is a caldera-like feature and associated flow. Rheological modeling on the flow [12] indicate it to be a high-viscosity material, most likely a mixture of ammonia-water or ammonia-water-methanol [12]. The formation of calderas on Titan is not yet understood, but it is unlikely that explosive volcanism played a significant role [12, 14].

Mars and Venus: Both Mars and Venus contain an abundance of volcanic features, and to date, all evidence suggests that the volcanoes on these planets produce mostly basaltic lavas [e.g., 15, 16]. One might infer, therefore, that martian and venusian calderas formed primarily via repeated intrusion into and effusion of fluid magma out of a shallow chamber. Calderas on venusian and martian shield volcanoes are display strikingly similar morphologies to those found on terrestrial basaltic shield volcanoes [1], but the extraterrestrial calderas are 1 – 2 orders of magnitude larger than their terrestrial counterparts. Like Earth, Mars displays calderas that experienced explosive behavior [e.g., 17], but these martian calderas are more morphologically similar to terrestrial effusive calderas.

The available resolution of radar imagery for the venusian surface (~250 m/pixel) is not sufficient to identify whether the venusian calderas contained lava lakes. Recently, Hansen [18] proposed that venusian crustal plateaus are the solidified remains of enormous lava "ponds" that formed from large impact events, and were not related to the formation of a volcanic caldera.

Given the morphologic similarities between martian and terrestrial calderas, it seems likely that at least some of the martian calderas hosted lava lakes at some time. The available images for Mars have ever-increasing resolution and topographic data. A solidified lava lake can be identified with high-resolution topographic data (<20 m/pixel vertical resolution) by seeking a lava flow surface within a caldera that has reached an equipotential surface. Comprehensive high-resolution (<10 m/pixel) imagery could help to constrain the difference between lava flows and a lava lake on a caldera floor, by revealing individual flow margins, or the pseudo-polygonal cracking that forms on the surface of solidifying basaltic lava lakes on Earth.

Comparisons: Large volcanic depressions on Earth appear to be formed from either explosive or repeated effusive volcanic eruptions. The morphologies of calderas on Mars and Venus are consistent with formation via repeated effusive eruptions. The Ionian paterae, however, appear unique in comparison (Figure 1) suggesting that their formation and evolution cannot be directly analogous to what is observed for caldera formation on Earth. The calderas on Titan are more morphologically similar to those on Earth, Mars and Venus than to those on Io, suggesting potential similarities in formation.

References: [1] Mouginis-Mark, P. and S.K. Rowland, 2001, *Geomorphology 37(3-4):*201-223. [2] Lipman, P,W., 2000, Calderas in *Encyclopedia of Volcanoes,* Academic Press, pp. 643-662. [3] Walker, G.P.L., 2000, Basaltic volcanoes and volcanic systems, in *Enclyclopedia of Volcanoes*, Academic Press, pp. 283-290. [4] Lopes, R.M. et al., 2004, *Icarus 169(1)*:140-174. [6] Lopes, R.M. et al., 2007, *Icarus 186*:395-412. [7] Radebaugh, J. et al., 2001, *J. Geophys. Res. 106(12):*33,005. [8] Black, S.M., 2006, M.S. Thesis, University at Buffalo, 79 pp. [9] Geissler, P. et al., 2004, *Icarus 169(1):*29-64. [10] Matson, D.L., and others, 2001, *LPSC XXXII,* #1938. [11] Lougen, J.L., 2006, M.S. Thesis, University at Buffalo, 118 pp. [12] Lopes, R.M. et al., 2007, I*carus 186*:395-412. [13] Prockter, L., 2004, in *Volcanic Worlds,* Praxis Press, pp. 145-178. [14] Lorenz R., 1996, Planet. Space Sci. 44(9):1021-1028. [15] Bandfield, J., 2002, *J. Geophys. Res. 107(6)*, doi:10.1029/2001JE001510. [16] Crumpler et al., 1997, in *Venus II*, University of Arizona Press, pp. 697-756. [17] Greeley, R. and D.A. Crown, 1990, *J. Geophys. Res. 95(5):*7133-7149. [18] Hansen, V.L., 2006, *J. Geophys. Res. 111(E11010)* doi:10.1029/2006JE002714.

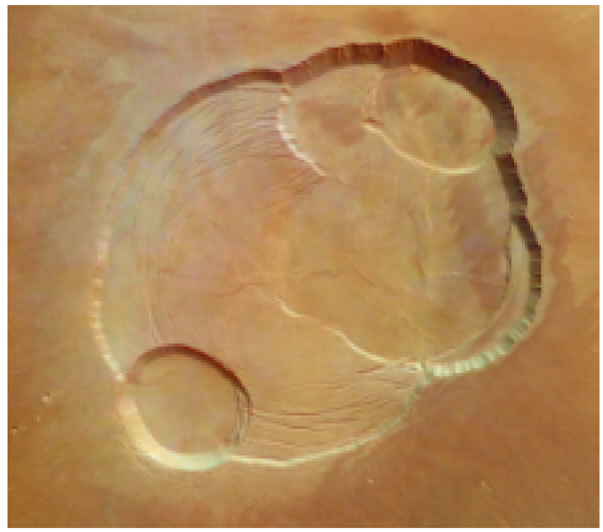

Figure 1A. Caldera of Olympus Mons, Mars. Image width is ~100 km. (Image courtesy of ESA/DLR/FU.)

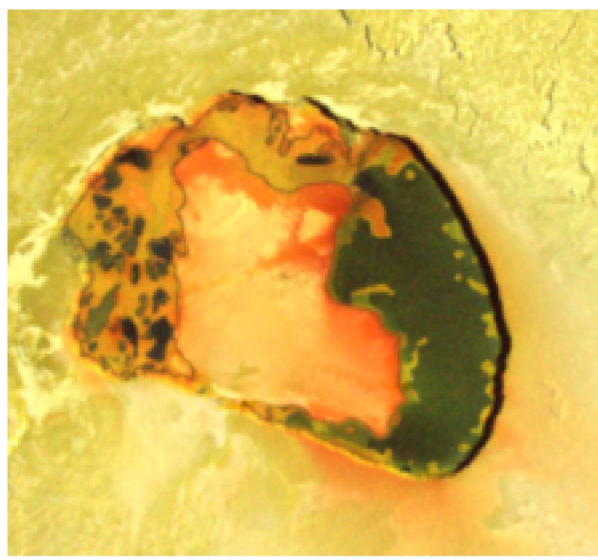

Figure 1B. Tupan caldera, Io. Caldera is ~75 km across. (Image courtesy of NASA/PIRL/LPL/UA.)