IDENTIFYING LAVA TUBES AND THEIR PRODUCTS ON OLYMPUS MONS, MARS AND IMPLICATIONS FOR PLANETARY EXPLORATION.

J.E. Bleacher[1], P.W. Richardson[2], W.B. Garry[3], J.R. Zimbelman[3], D.A. Williams[4], and T.R. Orr[5]. [1]Planetary Geodynamics Laboratory, Code 698, NASA GSFC, Greenbelt, MD, 20771, Jacob.E.Bleacher@nasa.gov, [2]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, 02139, [3]Center for Earth and Planetary Studies, Smithsonian Institution, PO Box 37012, National Air and Space Museum MRC 315, Washington, D.C. 20013-7012, [4]School of Earth & Space Exploration, Arizona State University, Tempe, AZ, 85282, [5]Hawaiian Volcano Observatory, USGS, Hawai'i National Park, HI, 96718-0051.

Introduction: Understanding the formation of lava tubes on terrestrial volcanoes was largely driven by the suggestion that lava tube development was responsible for the presence of lunar sinuous rilles [1]. The arrival of *Mariner 9* and the *Viking* orbiters at Mars again led to the suggestion of lava tubes as a possible explanation for ridges on the flanks of large shield volcanoes [2-4]. Higher resolution image data from the post-*Viking*-era orbiters at Mars have revealed several morphologies that are characteristic of lava tubes on terrestrial volcanoes [5]. The presence of lava tubes on a planetary surface involves significant process-related implications for interpreting eruption conditions and hence, the thermal and volcanic evolution of the planet. Lava tubes have also received attention because their final morphology might represent ideal locations for habitation zones, both for possible native life and for future planetary explorers. Therefore, identification of lava tubes on Mars and other planets holds significant value.

Authors Bleacher and Williams are funded to produce a geologic map of Olympus Mons, Mars. Here we present our observations of features across this volcano that we consider to be related to lava tube formation. These observations are coupled with field observations in Hawai'i to support our conclusions.

Approach: Our mapping includes a HRSC mosaic with a spatial resolution of 25 m/pixel that is geometrically rectified to MOLA data as our map base. This mosaic is supplemented primarily by a CTX mosaic with a spatial resolution of 6 m/pixel, and secondarily by MOC, THEMIS, HiRISE images. A primary goal of the project is to determine the areal extent, distribution, and stratigraphic relations of different lava flow morphologies, including tube-fed and channel-fed lava flows, to identify and understand any potential changes in late-stage effusive activity across the volcano [5]. As a result, we have mapped the extent of a large network of lava tubes across Olympus Mons [6]. To support our interpretation of lava tubes we have conducted separately funded analog field research on lava tubes in Hawai'i [7].

Lava Tube Morphologies: We identified four morphologies that we feel are indicative of lava tubes (Figure 1), including 1) raised ridges with primarily smooth surfaces, 2) sinuous chains of rimless pits, 3) deltaic shaped mounds that we call lava fans, and 4) raised rim depressions.

Smooth-Sided, Raised Ridges: Much of the Olympus Mons flank is covered by overlapping, leveed channel-fed flows with channel widths of 100-200 m [8,5]. Smooth-sided, raised ridges protrude from the fields of channels rising up to 100 m above adjacent flows. These features are up to several kilometers wide and often form topographic barriers that influenced the flow direction of younger channels

Sinuous Chains of Rimless Pits: Raised ridges often display chains of sinuously aligned, rimless depressions along their axis. These depressions are typically not circular, and are often interspersed with significantly elongated depressions or trenches. These depressions are generally ~ 100m wide and 10s of meters deep [9,5].

Lava Fans: Fans are positive topographic, delta-like features [5,6]. The apex of a fan marks its highest topographic point and usually consists of a hill or cluster of hills from which flows radiate downslope. Fan dimensions range from a few kilometers wide up to as large as ~20 km wide. The apex of some lava fans are up to 200 m higher than adjacent flows, often standing above local raised ridges.

Raised Rim Depressions: Raised rim depressions are non-circular, flat-floored depressions with slightly raised rims. These features are as large as 200 m across and can serve as a source from which flows emanate from the base. These features have only been identified along the axis of a raised ridge or at the apex of a fan.

Discussion: The features cited here are typically seen in terrestrial shield volcano flow fields in relationship with tubes. In general, the identification of one of these features alone is not indicative of a lava tube, but if two or more are identified together (adjacent or superposed) we feel confident that they reveal the presence of a tube.

Many lava tubes on the flank of Hawai'i form raised ridges with smooth surfaces. Tubes can form by the progressive buildup of channel levees during channel overflow [10]. Overflow events act to build up a ridge around the tube usually composed of smooth pāhoehoe lobes. Raised ridges were originally suggested to represent lava tubes on Olympus Mons

[4]. However, at the ~ 10-20 m/pixel resolution some ridges are seen to display channels along their axis.

Sinuous chains of rimless pits are formed in relation to a tube either as skylights that were open during flow, or as roof collapse after the flow has ceased and the tube drained. If a tube is present the remaining roof forms an overhang above the tube. However, rimless pits with overhangs are also easily formed in volcanic terrains without the existence of a tube. Tectonic subsidence can produce aligned pits with overhanging ledges, as can inflation rise pits [11].

Rootless shields are seen to form in Hawai'i over active tubes when they become over-pressurized, erupting lava to the surface, and have repeatedly formed during the last 10 years by the ongoing Pu'u 'Ō'ō eruption. Pre-existing tubes also can be reoccupied by younger flows, sometimes leading to the eruption of lava through skylights or collapsed roof sections. All of these processes produce a morphology similar to lava fans on Olympus Mons. Furthermore, the rootless outpouring of lava from a tube can also build a rim around a collapsed section of roof as seen at the Pōhue Bay flow, HI [12, 7], if the flow of lava to the surface is not continuous enough to build a fan. Likewise, shatter ring development, the repeated upheaval of tube roof above an overpressurized section of the flow, can produce a raised rim pit [13]. However, vents that are fed from depth or through rift zones and are emplaced onto the flanks of shield volcanoes can also produce fan-like morphologies and rimmed depressions as the process, eruption of lava from a subsurface source, is the same.

Conclusions: The identification of shield volcanoes on Mars led to the suggestion that some features on their flanks were the products of lava tube formation. Our mapping of Olympus Mons has led us to support those findings and an updated list of morphologies that together indicate the presence of a lava tube, including raised ridges, sinuous chains of rimless pits, lava fans, and raised rim depressions. Using these criteria we have developed a map of the locations of likely lava tubes on the flank of and at the base of Olympus Mons.

Developing a series of criteria for identifying lava tubes on other planets is critical for the planetary community as these features are discussed as possible protected habitation zones for native life and future human explorers. However, we urge caution when interpreting any single morphology presented in this abstract as evidence of a tube as volcanic ridges, rimless pits with overhanging ledges that are aligned in chains, local outpourings of lava, and raised rim depressions can all be formed in volcanic terrains independent of lava tubes.

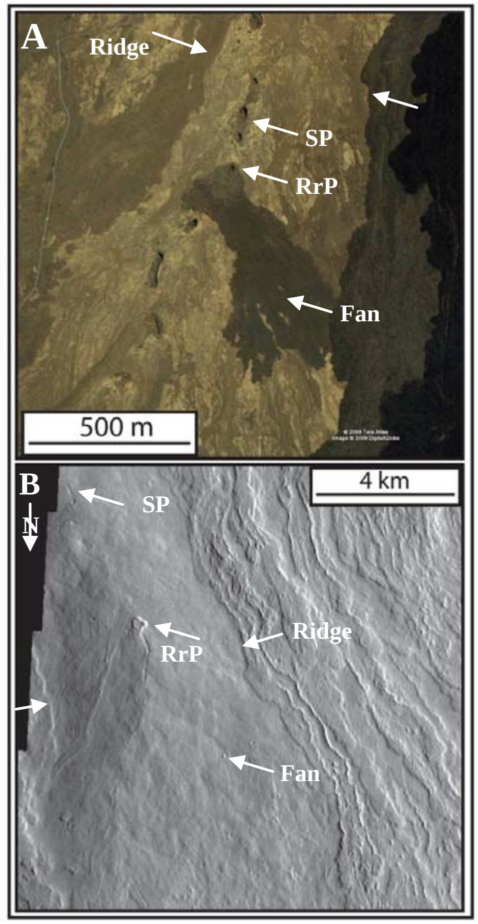

Figure 1. A) Landsat image (credit Google) showing the Pōhue Bay lava flow with several rimless depressions that are sinuously aligned (SP) along the axis of a raised ridge (Ridge). Some pits also display raised rims (RrP), with one as the source for a ~750 m 'a'ā flow (Fan). B) Themis VIS image showing an Olympus Mons lava tube with several rimless depressions that are sinuously aligned (SP) along the axis of a raised ridge (Ridge). A raised rim pit (RrP) also is located at the apex of a lava fan (Fan).

Acknowledgements: Funding for this work was provided through NASA's MDAP and MMAMA programs.

References: [1] Oberbeck et al. (1969) *Modern Geology*, **1**, 75. [2] Carr, M. (1973) *JGR*, **78**, 4049. [3] Greeley, R. (1973) *Geology*, **1**, 175. [4] Carr et al. (1977) *JGR*, **82**, 3985. [5] Bleacher et al. (2007) *JGRE*, doi:10.1029/2006JE002826. [6] Richardson et al. (2009) *LPSC*, #1527. [7] Bleacher et al. (2009) *LPSC*, #1980. [8] Morris and Tanaka (1994) *USGS Misc. Inv. Series Map I2327*. [9] Pupysheva, et al. (2006) *44th Vernadsky-Brown Microsymposium*. [10] Greeley, R. (1987) *U.S. Geol. Surv. Prof. Pap.*, **1350**, 1589. [11] Walker, G.P.L. (2009) *IAVCEI Sp. Pub.*, **2**, 17. [12] Jurado-Chichay & Rowland (1995) Bul. Vol. doi:10.1007/s004450050083. [13] Orr, T.R. (2010) Bull. Vol. doi:10.1007/s00445-010-0414-3.