VISCOSITY AND FLOW RATE CONSTRAINTS FOR TUBE-FED PLANETARY LAVA FLOWS. S. E. H. Sakimoto[1], S. Baloga[2], and J. Crisp[3], [1]Geodynamics Branch, Code 921, NASA's Goddard Space Flight Center, Greenbelt, MD 20771, sakimoto@denali.gsfc.nasa.gov, [2]Proxemy Research Inc., 20528 Farcroft Lane, Laytonsville. MD 20882, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

Eruption rates and lava flow emplacement times are important factors in understanding planetary volcanism, and tube-fed lava flows are a significant part of the volcanic geologic record on the Earth, Mars, and possibly Venus and Io. In this work, we develop a basic fluid dynamic model for planetary lava tube flows that considers the relative roles of pressure and gravity as driving forces. This allows us to explore the relative importance of pressure and gravity and to use inferred lava tube dimensions to provide some new constraints on the viscosity and flow rate eruption conditions that produced particular lava tube flows. We demonstrate this for a variety of tube flows and slopes on Olympus Mons and Alba Patera volcanoes. The results also are presented in a general form for use on other planetary basaltic provinces.

Pressure-driven flows have been suggested since many of the longest known lava tubes are on slopes <1°. These include the 160 km Undara flow and nearby flows in Queensland, Australia [1, 2], the 75 km Carrizozo flow field in New Mexico [3], and the 200 to 300 km long tube flows of Alba Patera, Mars [e.g. 4]. Pressure features, such as tumuli and dome-shaped flow sections, have been documented in some of these low-slope flows [3, 5]. These observations prompt questions of the possible role of pressure as a dominating force influencing flow length and flow morphology.

We explore potential ranges and limitations on the distribution of pressurization within lava tubes, such as those observed at Alba Patera and Olympus Mons. The model we develop features a relationship between the pressure field and flow parameters such as the effusion rate, viscosity, lava tube diameter, and slope. We assume that the flow is isothermal and incompressible with a constant viscosity, and that it is steady, laminar, fully developed, and flowing in a full, straight, constant radius, circular tube with smooth walls. We examine three regimes of tube-flow: pressure-driven, gravity-driven, and combined pressure- and gravity-driven flow and consider both Newtonian and power law rheologies.

When no slope is present, the flow is what we call "pressure-driven" from the tube entrance, with a pressure drop vs. distance along the tube that is a function of the flow rate, tube radius, and viscosity. Since the roof and surrounding wall rock is of limited tensile strength, the maximum length of such a flat tube segment can be constrained assuming typical values of strength for a jointed rock mass. This is done for a range of tube sizes, flow rates, and tube diameters estimated from images of the collapse pits.

The addition of an underlying slope allows two additional types of flow models. The simplest is what we call "gravity-driven" tube flow, where the fluid pressure is hydrostatic at all points along the path of the flow and gravity supplies the only driving force. This situation can be caused by flow over steep topographic slopes that makes the pressure gradient in the Navier-Stokes equation negligible compared to the external gravitational force. In "combined flow", both the pressure gradient and gravitational forces are significant and must be considered simultaneously.

On the flanks of Mars' Tharsis shield volcanoes, Viking images clearly show lava flows with evidence for tubes [5]. Low ridge-shaped flows with central collapse pits indicative of tube-fed flow can be traced for distances of 20-30 km. Alba Patera images reveal much larger lava tube flows on its NW and SE flanks [4, 6, 7]. These long tube flows have been studied carefully by several authors [6, 7, 8]. In many cases, chains of collapse pits along these flows can be easily identified typically for tens or hundreds of kilometers. The lava tube flows in Alba Patera flow over slopes estimated to be less than half a degree, while the Olympus Mons tube flows considered here are on slopes of 5° to 34°. In both cases, the lengths of the tubes are inferred from the extent of the chains of central collapse pits where the tube roof has collapsed. These collapse depressions are typically 1 to 5 pixels (70 to 500 m) across. Even with allowance for a collapse pit width that is greater than the underlying tube, the data presently available suggest tube radii of at least many tens of meters.

As an upper limit to the internal tube roof pressure, we assume a roof strength of 0.1 to 2.5 MPa (2-4 meters of jointed basalt [9]). For an lower effusion rate limit, we assume average travel times of either ≤ 100 days, or ≤ 1000 days, since preliminary cooling calculations indicate that this allows only a few degrees of cooling—consistent with the constant viscosity assumption.

At Alba Patera, we have examined the available Viking Images, and selected representative tube lengths of 200 and 50 km. Figure 1 shows a 40 km long segment of one the flows, with the collapse pits indicated by arrows. From examinations of the collapse depression sizes, we consider tens of meters to a hundred meters to be representative dimensions, so we assumed tube diameters of 50 and 100 m.

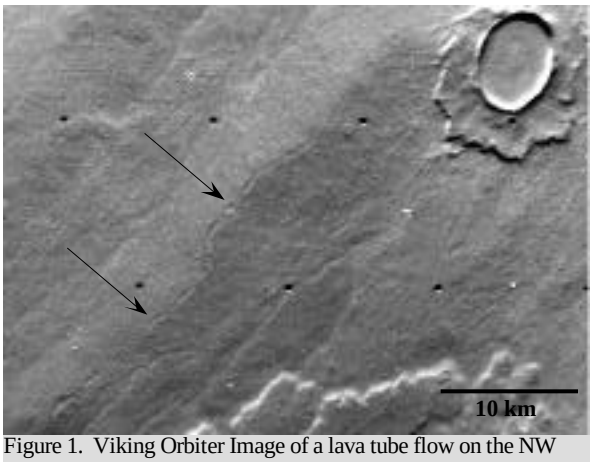

Figure 1. Viking Orbiter Image of a lava tube flow on the NW flanks of Alba Patera, Mars. Arrows point to tube collapse pits. Resolution is 94 m/pixel and location is 47.5 °N , 118°W.

Table 1 shows the summary of all of the Alba Patera tube flow results. In general, the pressure term in the driving force dominates for very small slopes, but the gravity term eclipses the pressure term as the slope increases. We have combined the analyses so that the effusion rates encompass the ranges predicted for pressure-driven, gravity-driven, and combined flows. The lower viscosity lavas (10^2 Pa s) produce turbulent flow for all gravity-driven cases considered, but only a few of the pressure-driven cases. Table 1 does not include the turbulent flow cases, only the laminar pressure-driven ones. The effusion rates and viscosities span a large range for all of the Alba Patera tubes considered (2 to 10^5 m^3/s, and 10^2 to 10^6 Pa s). Selecting a particular tube size and maximum travel time narrows the ranges by one or two orders of magnitude. Generally, though, the viscosity ranges in Table 1 center on values of approximately 10^3 Pa s, and effusion rate ranges center on values of around a few hundred to a few thousand m^3/s, with variations for individual tube geometries. This is consistent with the basaltic compositions suggested for Alba Patera [6, 7], although the effusion rates are generally lower than the 10^5 to 10^6 m^3/s suggested by Cattermole [4]. These lower effusion rate estimates and higher viscosity estimates are compatible with eruptions that are closer in style to terrestrial basaltic eruptions than those suggested by Cattermole, although the flows are still considerably larger in scale than the familiar Hawaii tube flows.

Olympus Mons, the highest volcano on Mars, rises 23 kmabove the surrounding plains, with a diameter over 500 km, mean slopes of 4°, and a steep basal scarp up to 6 km high [e.g. 6, 10]. The volcano flanks have a radial fabric of narrow flows interpreted to be leveed, channel, and lava tube flows, with some draped over the steep basal scarp [6]. We examined several flows draped over the NE scarp (e.g. Figure 2), with apparent slopes along the flows ranging from 5° to 34°. For these flows, this model predicts that the steeper slopes would have caused the internal tube pressure to quickly exceed the roof strength if the tubes were full. We conclude that either the tubes were normally partially full, and were never full over their entire length at once, or that the proposed tube flows were probably not the classic type of tube-fed flow with a continuous roof. Also possible, although less likely, is that the material was stronger than the assumed terrestrial jointed basalt. In either case, this model would be inappropriate for effusion rate estimations.

In conclusion, we find that very low lava viscosities are not essential for Alba Patera lava tubes, and that tube formation may be a better indicator of the steadiness of the eruption and the presence of low slopes than it is of low viscosities (e.g. 10^2 Pa s) . In addition, this analysis suggests that the tube systems on the steep flanks of Olympus Mons are fundamentally different from those at Alba Patera. The Olympus Mons flows could not have roofed over, been continuously full, or maintained a continuous lava tube transport system in the assumed full, steady, and fully developed conditions.

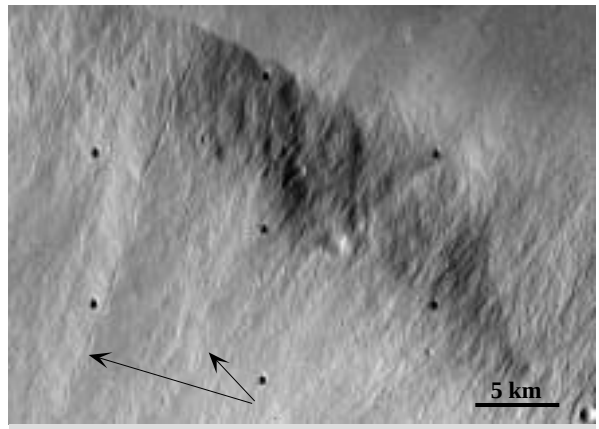

Figure 2. Viking Orbiter Image of two possible lava tube flows over the NE scarp of Olympus Mons, Mars. Arrows point to collapse pits over the tube. Resolution is 85 m/pixel and image location is approximately 21.5 °N , 130.5°W.

References:
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Table 1.: Summary effusion rate ranges for pressure-driven, gravity-driven and combined laminar lava tube flow for several viscosities, tube lengths, and tube sizes typical of Alba Patera tube flow for slopes of ≥ 0.01 °, and driving pressures ≥ 0.01 MPa.

Tube Length [km]	Viscosity [Pa s]	Tube diameter [m]	Effusion Rate Range [m^3/s] for average lava travel times ≤ 1000 days	Effusion Rate Range [m^3/s] for average lava travel times ≤ 100 days
200	10^2	100	1000–5000	1000–5000
	10^3		100–3x10^4	200–3x10^4
	10^4		20–3000	200–3000
200	10^2	50	80–3000	80–3000
	10^3		8–2000	40–2000
	10^4		4–200	40–200
50	10^2	100	—	—
	10^3		600–1x10^5	600–1x10^5
	10^4		30–1x10^4	40–1x10^4
50	10^2	50	200–2000	200–2000
	10^3		20–8000	20–8000
	10^4		2–700	10–700