RHEOLOGICAL PROPERTIES OF LATE-STAGE LAVA FLOWS ON ASCRAEUS MONS: NEW EVIDENCE FROM HRSC.

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Introduction: The Tharsis Montes, Arsia Mons, Pavonis Mons, and Ascraeus Mons, are large volcanic constructs that are part of the Tharsis rise. The Tharsis rise is commonly interpreted to be the result of a long-lasting large mantle upwelling that constructed the rise through a combination of uplift and magmatism (plutonism and volcanism) [e.g., *1-7*]. Of particular interest is the construction of the huge individual edifices, their ages, duration, episodicity [8], and rheology. Here we report on estimates of the rheological properties of late-stage lava flows on the eastern flank of Ascraeus Mons, Mars.

Data: Our estimates are based on new images obtained by the High Resolution Stereo Camera (HRSC) on board ESA's Mars Express spacecraft. The HRSC camera is a linescan camera with 9 CCD lines (blue green, red, IR, 3 stereo channels, 2 photometric channels) oriented perpendicular to the flight direction. The HRSC camera acquires images at spatial resolutions of about 10 m/pixel and is complemented by a Super Resolution Channel (SRC) with a 1024 x 1032 pixel frame CCD, which obtains images of about 2.3 m/pixel from an altitude of 250 km at periapsis. We used HRSC data from orbit 16 to investigate lava flows on Ascraeus Mons, one of the three Tharsis Montes. Compared to earlier studies, the high spatial resolution of the HRSC data allowed us to map 25 late-stage lava flows and to measure their dimensions, as well as their morphological characteristics in greater detail. Values for the slope α, flow length l, flow width w, flow height h, total levee width w_l, and the width of the leveed flow channel w_c can be determined directly either from MOLA data or from the imaging data. Length and width of these lava flows can be readily measured on HRSC images, but the height of these flows is currently below the vertical resolution of digital elevation models (DEM) that can be confidently calculated from the HRSC data at this time. Such height measurements will be possible in the near future when more experience has been gained in producing high-resolution DEMs. Here we used shadow measurements along the lava flows and the flow fronts.

Morphology and Dimensions: In the HRSC images we observe several lava flows with well-defined leveed channels, some of which are truncated by the collapse of the calderas and extend for tens of kilometers downslope. We measured the length of each flow and performed about 184 measurements of the flow width, 224 measurements of the flow height, and 80 measurements for the levee and channel widths. We find the average flow length to be ~19 km, ranging from ~4.1 to ~38.3 km. The average width is ~1.3 km, with a minimum of ~570 m and a maximum of ~2030 m. We find the average leveed flow width to be on the order of ~990 m, ranging from ~590 m to ~2270 m. The average levee width varies between ~450 m and ~1740 m. with an average of ~710 m. The average channel width is about 280 m, with a minimum of ~140 m and a maximum of ~530 m. We performed 224 individual shadow measurements along the 25 investigated flows. We find that these flows are on average 39 m thick, varying from ~25 to ~90 m. These results are in good agreement with measurements of 25-220 m [9], 5-65 m [10], ~30 m [11], 65 ± 20 m [12], 13-33 m [13], and ~20 m [14] and greater than reported from Olympus Mons (4-26m) [28]. The average slopes of the studied flows range from ~1.5° to ~6.7°, with most flows being emplaced on slopes of ~3.5°.

On the basis of morphologic similarities between terrains on Ascraeus Mons and terrestrial shield volcanoes, *Zimbelman and McAllister* [15] proposed that individual prominent flows on Ascraeus Mons are a'a flows and the planar areas adjacent to the flows are pahoehoe flows. *Wilson et al.* [16] reported that if no other factors intervene, thermal constraints will be the limiting factor for the maximum length of a flow fed by a given volume or mass effusion rate. They classified lava flows into several categories, including (1) cooling-limited flows, (2) volume-limited flows, (3) accidentally-breached flows, (4) break-out flows, (5) captured flows, (6) tube-fed flows. We find that our flow N shares numerous characteristics of a volume-limited flow such as short length, a drained channel, and no break-out flows. However the majority of flows appear to be more akin to cooling-limited flows or break-out flows. Flows E1 - E3 might have formed as accidentally-breached flows or break-out flows. We did not find evidence for captured flows and evidence for tube-fed flows remains at best ambiguous.

Yield strength: Lava flows are often modeled as a Bingham plastic controlled by two parameters, the yield strength and the plastic viscosity [e.g., *17*]. The yield strength τ of lava flows can be related to the flow dimensions by following equations

$$\tau = \rho\, g \sin\alpha\, h$$

$$\tau = \rho\, g\, h^2/w$$

$$\tau = \rho\, g \sin^2\alpha\; 2w_l$$

$$\tau = \rho\, g \sin^2\alpha\; (w-w_c)$$

Gravity g is known as 3.7278 ms^{-2} and density ρ was chosen to be 2,500 kgm^{-3}. Other input parameters, e.g., the flow height and width, channel and levee width, and the slope angle, were derived from HRSC or MOLA data. Depending on the equation used, we find a minimum yield strength of ~5.1×10^3 and a maximum yield strength of ~1.2×10^5 Pa. Calculating the average of all derived yield strengths, we find a value of ~2.7×10^4 Pa; a yield strength very similar to that published by *Zimbelman* [11], i.e., ~2.1×10^4 Pa. These values are comparable to estimates for terrestrial basaltic lava flows, and are in good agreement with estimates of *Zimbelman* [11] derived for a small number of lava flows on Ascraeus Mons.

Effusion rate: The effusion rate Q is given as

$$Q = G_z\, \kappa\, x\, w/h$$

where G_z is the dimensionless Graetz number, κ is the thermal diffusivity (m^2s^{-1}), x is the flow length (m), and w and h is defined as above. In analogy to terrestrial lava flows we assumed a Graetz number of 300 and a thermal diffusivity of 3×10^{-7} m^2s^{-1}. As a result we find that effusion rates range from ~7 to ~210 m^3s^{-1}, averaging about 70 m^3s^{-1}. Such effusion rates for the Ascraeus flows studied are similar to effusion rates of 18-60 m^3s^{-1}, with an average of 35 m^3s^{-1} [11].

Emplacement time: On the basis of our estimates of the effusion rates and the measured dimensions of the flows, we calculated that the time necessary to emplace the flows is on average on the order of tens to hundreds of days.

Viscosity: For the determination of the viscosities η we made use of the following equation [e.g., 12, 18]

$$h = (Q\, \eta/\rho\, g)^{1/4}$$

This equation assumes a Newtonian flow behavior and is therefore in conflict with the assumption that lava flows have a Bingham rheology [e.g., 19-20].

Jeffrey's equation also relates the viscosity of a flow to its effusion rate and its dimensions [e.g., 21-22].

$$\eta = (\rho\, g\, h^3\, w \sin\alpha)/\, nQ$$

In this equation n is a constant equal to 3 for broad flows and 4 for narrow flows. *Gregg and Fink* [22] pointed out that although Jeffrey's equation has been widely used to derive lava flow characteristics, it requires the questionable assumption that lava behaves as a Newtonian fluid.

Wilson and Head [17] and *Zimbelman* [11] presented another method to calculate viscosities

$$r = w_c/(w-w_c)$$

$$\eta = (w_c^{\,3}\, \tau \sin^2\alpha)/(24Q) \qquad \text{for } r<1$$

$$\eta = (w_c^{\,11/4}\, \tau^{5/4} \sin^{6/4}\alpha)/(24Q\, g^{1/4} \rho^{1/4}) \qquad \text{for } r\geq 1$$

As a result we calculated average viscosities of ~5×10^5 to ~6×10^6 Pa-s. Minimum viscosities are on the order of 3×10^4 Pa-s, maximum viscosities are about 4×10^7 Pa-s. Using Jeffrey's equation yields significantly higher average viscosities of 6.2×10^8 Pa-s, ranging from 1.7×10^7 to 4.2×10^9 Pa-s. The values based on Jeffrey's equation appear to be unrealistically high compared to basalt/andesite flows on Earth and other planetary bodies. Our results are in excellent agreement with previously published viscosities, which range from 9.7×10^5 to 6.9×10^6 Pa-s [e.g., 11, 12, 20, 23]. In addition, our results are consistent with viscosities of terrestrial basalts and andesites, which are on the order of 1.4×10^2 to 1×10^7 Pa-s [e.g., 20, 24-27].

For the future we plan to include older lava flows on Ascraeus Mons in order to investigate possible changes in the rheologic properties with time [e.g., 11]

Conclusions: In summary, the new data allow us to estimate more precisely the areas and volumes of lava flows, the duration and rates of their emplacement, their petrologic evolution, their relation to the geologic history of Mars and their influence on the atmosphere and the environment. On the basis of our investigation we conclude that the lava flows investigated are likely to be basaltic to andesitic in composition. A comparison to terrestrial flows indicates that the investigated flows share several characteristics with terrestrial a'a flows.

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