Factors affecting the lengths of long lava flows: Examples from a flow field southwest of Arsia Mons, Mars

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Abstract. The long length of lava flows (10^6 m) southwest of Arsia Mons, Mars is most likely attributed to high rates of effusion (4.3 x 10^4 m^3/s) and flow beneath an insulating surface crust. Surface ridges along the lengths of lava flows in this field suggest the presence of a coherent crust which may have insulated flow. The viscosity of the Martian lavas (9.7 x 10^5 Pa s - 1.5 x 10^7 Pa s) is most consistent with the upper range of basaltic and basaltic andesite compositions and is not evidence for low viscosity flow. Underlying slopes < 0.5° suggest the long flows are not a result of a steep underlying slope. Comparisons to shorter (10^3 m) terrestrial andesite flows at Sabancaya, Peru reveal a large difference in viscosity and effusion rate. The effusion rate and viscosity of the Sabancaya flows is 5.6 m^3/s and 7.3 x 10^{11} Pa s - 6.0 x 10^{12} Pa s respectively.

1. Introduction

The final length of a lava flow is determined by a number of factors including eruption temperature, effusion rate, viscosity, and local conditions such as topography (Hulme, 1974). Much work has been conducted in the analysis of flow morphology in an attempt to develop empirical models which can estimate rheologic and eruption properties of already emplaced lava flows (Hulme, 1974; Zimbelman, 1985; Keszthelyi et al. 1993; Stasiuk et al. 1993; Pinkerton and Wilson, 1994; Zimbelman, 1998; Gregg and Fink, 2000; Keszthelyi et al. 2000). These models are particularly useful when analyzing remote lava flows on the Moon, Mars, and Venus. For this discussion we will focus on the factors which control the final lengths of lava flows and show how these factors are incorporated into empirical models. Examples from a lava flow field (of unknown composition) southwest of Arsia Mons, Mars and from Sabancaya, Peru (15.47°S, 71.51°W) (andesite flow) will be given (Figure 1).

2. Factors controlling length

2.1 Effusion rate (Q)

Effusion rate is the volumetric rate of erupted lava over time measured in m^3/s. Walker (1973) noted the direct relationship between effusion rate and flow length. He proposed that the large lengths (10^2 km) of some terrestrial lava flows could be solely attributed to rapid extrusion of large volumes of lava. Rapid extrusion would prevent cooling and halting of a flow, allowing it to travel longer lengths than a flow of identical composition erupted at lower rates of effusion. Malin, (1980) challenged this idea indicating that there is a better correlation between flow length and erupted volume. The eruption of large volumes he suggested should be enough to drive a flow down a slope over large distances.

Empirical models have been developed which relate effusion rate to final flow length. The Graetz number (Gz) expression (1) can be used to estimate effusion rate given the flow length (x), thickness (h), and width (w), thermal diffusivity constant (κ), and the assumption that Gz = 300:

$$Gz = Qh / \kappa x w \quad (1)$$

Equation (1) relates the heat loss by diffusion to the heat lost through advection along the length of a lava flow. We can assume Gz = 300 through observation of basaltic lava flows. It was found that basaltic lava flows on Mt. Etna and Hawaii cease to flow when Gz = 300 (Pinkerton and Wilson, 1994). The Graetz number equation illustrates that effusion rate is not the only factor affecting the final length of a flow. Cooling properties of a specific lava composition also affect how long a flow can travel.

To demonstrate use of the Graetz expression in estimating Q we measured the length, width, and flow thickness of Martian lava flows southwest of Arsia Mons (Figure 1).

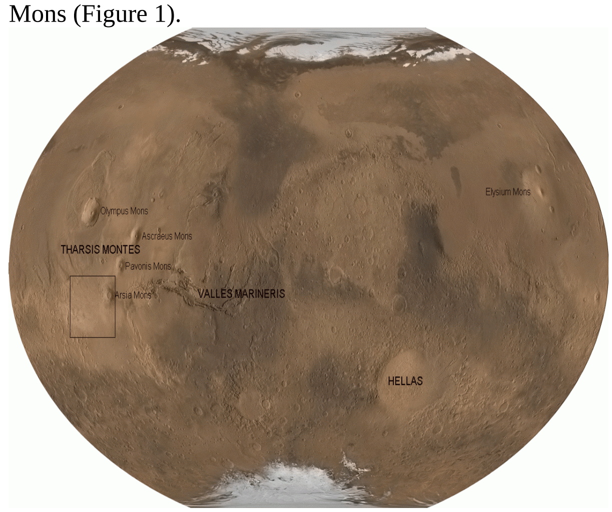

Figure 1. Global map of Mars showing the Tharsis Montes, Elysium and Hellas regions, and the flow field southwest of Arsia Mons (within box). Image is centered at the Martian prime meridian.

The mean maximum flow length for these flows is 1.3 x 10^6 m. The mean width and thickness is 2.0 x 10^4 m and 67 m respectively. We chose a thermal diffusivity constant of 3.0 x 10^{-7} m^2/s. Assuming Gz = 300, the mean effusion rate for flows southwest of Arsia Mons is 4.3 x 10^4 m^3/s. We also estimated Q for shorter andesite flows off of Sabancaya volcano in Peru for comparison (Figure 2).

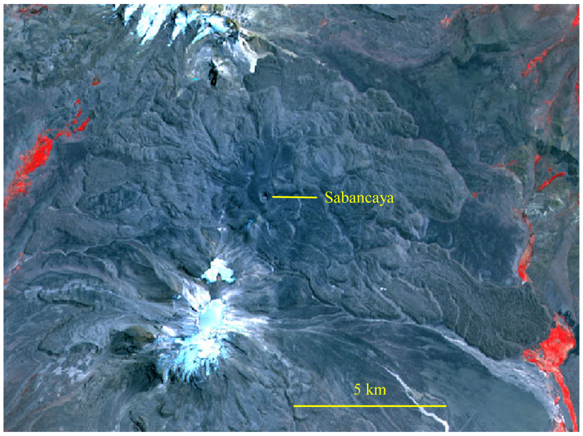

Figure 2. Lava flow field surrounding Sabancaya, Peru. North is to the top of the image.

The mean flow length for these flows is 4.6 x 10^3 m. The mean width and thickness is 1.0 x 10^3 m and 113 m respectively. Using the same value for κ we received a mean effusion rate of 5.6 m^3/s. From equation (1) it would appear that length of the Sabancaya flows is 10^3 lower than for the Martian flows largely due to the 10^3 difference in effusion rate.

Keszthelyi and Pieri, (1993) found that a simple empirical correlation between flow length and effusion rate was not adequate in explaining the large flow lengths of many terrestrial and extra-terrestrial flows. Other factors it would appear strongly influence the final length of lava flows.

2.2. Tube flow, channelized flow, and insulating sheet flow

Lavas erupted at low effusion rates may also travel large distances if they flow beneath an insulating surface crust (Keszthelyi and Pieri, 1993; Zimbelman, 1998). It is common for lavas to form elaborate tube systems allowing later lavas to remain insulated during flow. The long length of the Carrizozo lava flow field in south-central New Mexico has been attributed to insulated tube flow (Keszthelyi and Pieri, 1993). Evidence for tube networks on the Moon and Mars may also explain the extreme lengths of many flows seen there (Zimbelman, 1998).

The channelization of lava flows within pre-existing canyons and valleys also appear to be a mechanism by which flows can travel long distances (Tolan and Beeson, 1984). The longest terrestrial flows on Earth (~1200 km), associated with the Columbia River Basalt group, were emplaced within a canyon system.

We find no evidence for tube or channel emplacement for the long flows southwest of Arsia Mons. Collapsed tubes have not been identified in the region and it appears the majority of the flows were emplaced in sheets. However, the presence of ridged surface texture indicates that a crust may have formed during flow (Figure 3).

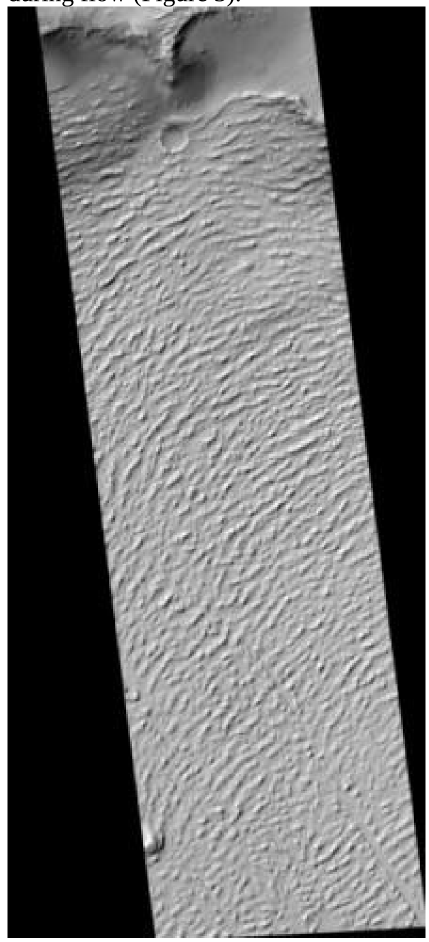

Figure 3. MOC image M0200101. This image shows the ridged surface texture common on the flows southwest of Arsia Mons. The image width is 2.85 km. North is to the top of the image.

This crust would have allowed later lavas to be insulated during flow. Along with the high rates of effusion measured using equation (1), we believe insulation may have allowed the flows southwest of Arsia Mons to travel large distances.

2.3. Viscosity (η)

Low viscosity lavas (such as ultramafic and basaltic lavas) tend to flow further than high viscosity lavas (Hulme, 1974; Keszthelyi and Pieri, 1993; Cashman et al. 1998; Zimbelman, 1998). Viscosity alone, however, is affected by a number of factors. High eruption temperatures, an abundance of dissolved water, and high Ti-Alkali contents decrease a lavas viscosity. Increasing the amount of crystals or vesicles will conversely increase a lavas viscosity (Gregg and Fink, 1996). A basaltic flow, for example, may travel half the length of another basaltic flow due to the differences in crystal content. Likewise, an andesite flow with an abundance of dissolved volatiles may flow further than a basaltic flow with a large percentage of crystals or vesicles. This demonstrates the difficulty in determining the composition of remote lavas simply from viscosity data.

The long flows southwest of Arsia Mons appear to have lengths most similar to terrestrial flood basalts (Cashman et al. 1998); however, it is possible that these are more evolved flows erupted at high temperature or with a large percentage of dissolved volatiles. We estimated viscosity for the flows of southwest Arsia Mons using models developed by Fink and Fletcher (1978) and Fink and Griffiths (1990) in an attempt to determine if the long lengths of the lavas can be attributed to a low viscosity. The Fink and Fletcher (1978) model (2):

$$R = \eta_o / \eta_I \qquad (2a)$$

$$\ln R > 28A / d \qquad (2b)$$

$$\varepsilon\eta_i > \rho g A / 0.08\, R \ln R \qquad (2c)$$

uses surface ridge morphology to estimate viscosity. The wavelength (d) and amplitude (A) (Figure 4) of the ridges is dependent upon the ratio, R, between the interior viscosity (η_i) and exterior viscosity (η_o) of the flow as well as the surface crust thickness. Fink and Fletcher (1978) found that the natural log of the ratio R should be greater than about thirty times the ridge amplitude divided over the ridge wavelength. The viscosity ratio (R) can therefore be calculated by measuring the fold morphologies. Equation (2c) can be used to estimate the interior viscosity (η_i) given R, fold amplitude, gravitational acceleration (g), lava density (ρ), and compressive strain rate (ε). For the Martian ridged lavas (Figure 2) we calculated a mean viscosity of 9.7×10^5 Pa s.

The Fink and Griffiths (1990) model incorporates effusion rate (Q) and flow thickness (h) in estimating viscosity (3):

$$h = (Q\eta / \Delta\rho g)^{1/4} \qquad (3)$$

Using this model the mean viscosity of the Martian lavas is 1.5×10^7 Pa s. It appears the long lengths of the Martian lavas cannot be attributed to a low viscosity. Our estimated viscosity values fall within the upper range of typical basaltic viscosities and lower range for typical andesites (Wilson and Head, 1994).

For comparison, using the same models, the viscosity of the Sabancaya lavas is 7.3×10^{11} Pa s (using Fink and Fletcher, 1978) and 6.0×10^{12} Pa s (using Fink and Griffiths, 1990). The lower lengths of the Sabancaya lavas, therefore, can also be attributed to a higher viscosity.

2.4. Underlying slope (θ)

Gregg and Fink (2000) analyzed the effects of slope on flow morphology. In their analysis they used polyethylene glycol (PEG) to model lava flows. In general it was found that length increased with increasing slope angle. Increasing the slope onto which the PEG was erupted had a similar effect to increasing the effusion rate. Surface morphologies such as pillows, rafts, and folds could be formed in their experiments simply by changing the slope angle.

Mars Orbiter Laser Altimeter (MOLA) data for the region southwest of Arsia Mons reveals slopes on average < 0.5°. These slopes are sustained over several hundred kilometers away from the Arsia Mons shield. The long lengths of the Martian flows therefore cannot be attributed to a steep underlying slope. In comparison, the slopes at Sabancaya are ~4° and the flow lengths are 10^3 lower than at Arsia Mons. Our results from equation (1) indicate the flows of Sabancaya were erupted at significantly lower effusion rates. Also, our viscosity data indicate the Sabancaya lavas have much higher viscosities than the Martian lavas. We therefore cannot attribute the difference in length of these two flow fields to the differences in their underlying slope.

3. Conclusion

It is probably more correct to say that a multiple of factors combine to influence the final lengths of lava flows. We have analyzed how only a few (effusion rate, insulated and channelized flow, viscosity, underlying slope) factors affect the length of a lava flow field southwest of Arsia Mons. It would appear that the Martian flow field reaches extensive lengths (10^6 m) due to high rates of effusion and by insulated sheet flow. Our viscosity data is not consistent with an unusually low viscosity flow and MOLA data suggests a low underlying slope. Comparisons with a terrestrial andesite flow at Sabancaya, Peru indicate that the differences in length between the two flow fields is largely attributed to a difference in viscosity and effusion rate.

References

Cashman, K., Pinkerton, H., Stephenson, J., Introduction to special section: Long lava flows, *Journal of Geophysical Research, 103,* 27281-27289, 1998.

Gregg, T. K. P., Fink, J. H., Quantification of extraterrestrial lava flow effusion rates through laboratory simulations, *Journal of Geophysical Research, 101*, 16891-16900, 1996.

Gregg, T. K. P., Fink, J. H., A laboratory investigation into the effects of slope on lava flow morphology, *Journal of Volcanology and Geothermal Research*, 96, 145-159, 2000.

Hulme, G., The interpretation of lava flow morphology, Journal of Geophysical Research, Astronomical Society, *39*, 361-383, 1974.

Keszthelyi, L. P., McEwen, A. S., Thordarson, T., Terrestrial analogs and thermal models for Martian flood lavas, *Journal of Geophysical Research*, 105, 15027-15049, 2000.

Keszthelyi, L. P., Pieri, D. C., Emplacement of the 75-km-long Carrizozo lava flow field, south-central New Mexico, *Journal of Volcanology and Geothermal Research, 59,* 59-75, 1993.

Malin, M. C., Lengths of Hawaiian lava flows, *Geology, 8,* 306-308, 1980.

Pinkerton, H., Wilson, L., Factors controlling the lengths of channel-fed lava flows, *Bulletin of Volcanology*, 56, 108-120, 1994.

Stasiuk, M. V., Jaupart, C., Sparks, R. S., Influence of cooling on lava flow dynamics, *Geology*, 21, 335-338, 1993.

Tolan, T. L., Beeson, M. H., Intracanyon flows of the Columbia River Basalt Group in the lower Columbia River Gorge and their relationship to the Troutdale Formation, *Geological Society of America Bulletin*, 95, 463-477, 1984.

Walker,G. P. L., Lengths of Lava Flows, *R. Soc. London Philos. Trans*., A274, 107-118, 1973

Wilson, L., Head, J. W., Mars: Review and analysis of volcanic eruption theory and relationships to observed landforms, *Reviews of Geophysics*, 32, 221-263, 1994.

Zimbelman, J. R., Estimates of rheologic properties for flows on the Martian volcano Ascraeus Mons, *Journal of Geophysical Research, 90,* D157-D162, 1985.

Zimbelman, J. R., Emplacement of long lava flows on planetary surfaces, *Journal of Geophysical Research, 103,* 27503-27516, 1998.

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