TIME-DEPENDENT LEVEE GROWTH FOR MARS LAVA FLOWS. S. M. Baloga[1] and L. S. Glaze[1], [1]Proxemy Research (20528 Farcroft Lane, Laytonsville, MD 20882, steve@proxemy.com).

Introduction: On the plains of Mars, there are many large channelized lava flows with thicknesses in excess of 50-60 m and lengths beyond 100-200 km. Often these flows have relatively constant channel widths and levee dimensions, and show relatively little thickening with distance. The lack of cross-sectional changes and morphologic similarity with distance along the flow suggests steady state emplacement conditions, except toward the flow front. At present, there are no satisfying quantitative models of rheologic or emplacement characteristics for such flows.

There has been a fundamental problem with inferences about channelized lava flows on Mars that has persisted for decades. Previous theoretical models have attempted to obtain rheologic inferences from the dimensions of the channels, levees, the density, and the pre-existing slope [e.g., 1-7]. If the model is based on some form of the Navier-Stokes equations, all one can obtain is a constraint between the lava flow rate and the viscosity, each of which could vary by 5 or 6 orders of magnitude. Further, the inherent constraint between flow rate and viscosity precludes refining the emplacement time to better than several orders of magnitude. Thermal dynamics is of little help in narrowing the constraints because most large leveed lava flows on Mars show little or no thickening due to a cooling-induced viscosity change.

A new model is presented here that overcomes this fundamental shortcoming and dramatically narrows the constraints between viscosity, flow rate, and emplacement time. The stationary margins or "levees" on Mars flows could be the result of two possibilities, either remnants from the passage of the front or channel overspills. Here we focus on the first possibility.

The Model: We divide the lava flow into two zones. Upstream flow conditions are considered steady and there is no growth of the stationary collateral margins. In the distal zone (of fixed length L), flow conditions are time-dependent and lava is transferred from the active to the stationary component to construct the embanking levees. The model develops inferences by asymptotically matching conditions in these two zones. It is assumed that the slope is constant and the flow advances at a more or less constant rate. Within the upstream channel there is undoubtedly a vertical velocity profile. This makes the upper layer of the flow, whether it is deformable or not, advance faster than the average. Our model takes this excess flow rate and asserts that it is continually consumed by the levee building process in the frontal zone, regardless of the detailed time-dependent processes of construction.

With this model, the lava flow consists of an inner deformable, molten core of depth h_c. The core is overlaid by a layer of crust or otherwise non-deformable lava so that the total depth of the flow is h_l. The overall flow advances at the average flow velocity of the interior core in the steady state upstream zone. The central idea is that the levees are constructed by the difference in the flow rate for all material traveling faster than the average flow velocity. In the steady state, the average velocity of the core is

$$\overline{u}_c = \frac{\rho g \sin\theta h_c^2}{3\mu} \qquad (1)$$

and the upper surface of the core advances as

$$u_c(h_c) = \frac{\rho g \sin\theta h_c^2}{2\mu} = \frac{3}{2}\overline{u}_c \qquad (2)$$

Thus some fraction of the deformable zone always travels faster than the average flow velocity. At least part of this fraction must be able to cool sufficiently in the levee building zone to form a stationary component of the flow. Once the dimensions of the levees and levee building zone are known, a relation between the cooling time constant and a time constant for levee building can be determined.

For different thicknesses of the non-deformable layer, the "excess" flowrate that must go into levee building can be computed from (1) and (2). Once in the levee building zone, everything above the height in the deformable zone where the velocity equals the mean velocity must get converted into a stationary margin. The height at which the velocity in the deformable layer is equal to the mean value is given by:

$$z^* = h_c\left(1-\sqrt{1/3}\right) = 0.42 h_c \qquad (3)$$

All laminae above this height within the flow travel faster than the average velocity of the flow. The non-deformable excess velocity is

$$\Delta u_{nd} = u_c(h_c) - \overline{u} = \frac{g \sin\theta h_c^2}{6\nu} \qquad (4)$$

This excess flow rate is contained in a channel of width w. Thus, the steady state excess flow rate for the nondeformable upper layer is given by

$$Q_{ex:nd} = \Delta u_{nd} w (h_l - h_c) \qquad (5)$$

The excess contribution from the deformable zone between z^* and h_c can also be found to be:

$$Q_{ex:d} = \frac{g \sin\theta}{3\nu}\left(h_c^3 - \frac{3}{2}h_c z^{*2} + \frac{z^{*3}}{2}\right) w \qquad (6)$$

Combining (5) and (6) gives the total excess flowrate,

Q_{ex}. Half of Q_{ex} goes into the construction of the levee on one side. Assuming a triangular levee yields the relationship

$$w_l = Q_{ex} / (\overline{u}_c h_l) \qquad (7)$$

This is the critical link between the growth and dimensions of the levees in the frontal zone and the steady dynamics in the upstream channel.

Mars Reference Example: The channel and levee dimensions in this example are from studies [6, 7] of a 200 km long flow north of Pavonis Mons. The flow is approximately 50 m thick with a channel width of 5 km and a total width of about 25 km. Figure 1 shows the thickness of the inner deformable core in the steady state zone necessary to build time-dependent levees in the front zone of the Pavonis flow. It is remarkable that such a large nondeforming layer is required, probably more than half the total flow depth in the channel. Given the actual dimensions of the levees, the viscosity is capped at the upper end slightly above 10^6 Pa-s. It seems physically implausible that such a thick flow could glide continuously for 200 km over a deformable basal layer only a meter or two thick, thus suggesting a viscosity greater than 10^4 Pa-s. Figure 2 also highlights a feedback of the model in that both the total emplacement time and the levee building times are highly constrained to a few years and a couple months respectively, in spite of the wide viscosity range in the deformable layer.

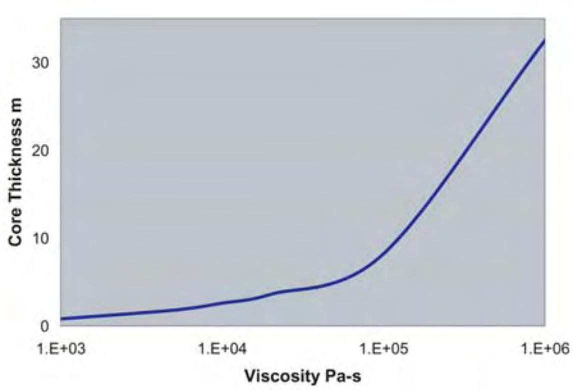

Figure 1. Core Thickness

An even tighter set of constraints is obtained by considering the cooling that must occur in the distal zone to form stationary margins. The excess deformable flow in the upstream steady zone must cool continuously and sufficiently in the distal zone. For a viscosity of 10^6 Pa-s, a depth equivalent of at least 19 m of deformable lava must cool to near solidus in a levee-building time of 39 days. This would require a continuously exposed fraction of inner core in the distal zone of >10%, which is beyond the norm of terrestrial experience [4]. However results with a viscosity of 10^5 Pa-s satisfy this constraint comfortably. Thus, it appears that the viscosity of this flow must reside between 10^4 and 10^5 Pa-s to manufacture distal levees and advance over a plausible basal layer for 200 km. We have investigated detailed models for the time-dependent growth in the levee zone. Such details imply only secord-order refinements to the constraints above.

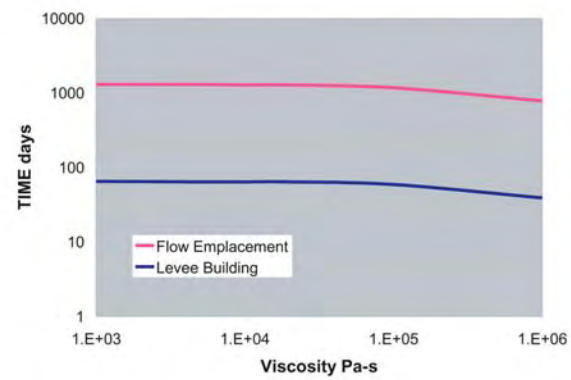

Figure 2. Total emplacement and levee building times.

Conclusions: Time-dependent levee building confined to a distal zone of an advancing lava flow provides a powerful new constraint on the rheology and emplacement times for the large channelized lava flows on the Mars plains. For the Pavonis flow studied here, the viscosity is limited to about 3 orders of magnitude by the levee building mechanics and only about 2 orders of magnitude, or less, when the thermal dynamics of levee emplacement are considered. The admissible viscosity range is at the high range of experience for large terrestrial basalt flows. Even with this range of viscosities, the emplacement times are constrained to 2-3 yrs and the levee building occurs in the distal zone in about one to two months. Because such large channelized lava flows are found in numerous volcanic provinces on Mars, this is a significant refinement of the rheologic and emplacement constraints that were previously available. For many such flows, however, a significant contribution to the stationary margins results from channel clogging and stagnation that causes overspills and breakouts. It remains to be determined how these processes affect the new constraints on viscosity and emplacement time.

References: [1] Hulme G. (1974) *Geophys J R. astr. Soc.*, *39*, 361. [2] Zimbelman J.(1985) *JGR*, *90*, D157-D162. [3] Baloga S. (1987) *JGR*, *92 (B9)*, 9271-9279. [4] Crisp J. A. and Baloga S. M. (1990) *JGR*, *95 (2)*, 1255-1270. [5] Baloga S., Glaze L. S., Crisp J. A., and Stockman S.A. (1998) *JGR*, *103 (B3),* 5133-5142. [6] Baloga S. M., Mouginis-Mark P. J. and Glaze L. S. (2003) *JGR*, *108 (E7)*. [7] Glaze L. S. and Baloga S. M. (2006) *JGR*, *111* (E09006).