ESTIMATING THE RHEOLOGY OF BASALTIC LAVA FLOWS. B. Ellis, L. Wilson and H. Pinkerton, Environmental Science Dept., Lancaster University, Lancaster LA1 4YQ, UK. (b.ellis1@lancaster.ac.uk).

Summary: We use detailed information on the advance of Hawaiian lava flows to deduce down-flow trends of viscosity, yield strength and cooling.

Introduction: Many aspects of the advance of planetary lava flows have been the subject of theoretical treatment [1 - 12]. One obvious drawback to validating and calibrating these models is the lack of real-time data on active flows on other planets (the Galileo coverage of the flows on Io is not sufficiently detailed as regards spatial or temporal resolution to be used for this purpose). Indeed, adequate observations on active flows on Earth are quite rare due to access and safety problems. We have used field measurements made by the USGS on Hawaiian flows for which there are detailed records of flow morphology and motion. We analyze these in terms of a simple rheological and thermal model to see how well it can explain the flow behaviour.

Data: Values of the width, W, thickness, D, travel distance, X, flow front advance speed, U, and sin (substrate slope), S, are available as a function of time for various flow units of the 1983-onward Pu'u 'O'o flows on Kilauea volcano [13] and the 1984 flows on Mauna Loa volcano [14]. These values were compiled as a data base in Excel.

Analysis: It is widely realised that as a lava flow loses heat it develops a complex internal thermal structure. At first sight this argues against trying to use simple rheological models to characterize flows. However, it is also clear that neither the scarcely cooled material in the deep interior of a flow nor the extensively cooled material at the surface of a flow can be the key elements controlling its motion. For flows that stop their advance due to cooling (rather than the cessation of supply from the vent, which we ignore here), it has been observed [6] that they do so when the dimensionless Grätz number, Gz, decreases from an initially high value to a value of about 300. The Grätz number is defined as

$$Gz = (U D_e^2) / (\kappa X), \qquad (1)$$

where κ is the thermal diffusivity of the lava (~7 x 10^{-7} m^2 s^{-1}) and D_e is the equivalent diameter of the flow, defined as 4 times the cross-sectional area of the flow divided by its wetted perimeter. For all of the flows considered here, which are much wider than they are thick, D_e = 4 D. If a flow front advances at constant speed, we can put X = (U t), where t is the time since the material at the flow front left the vent. The Grätz number is thus equal to (16 D^2) / (κ t), and if the flow motion is laminar, the depth, λ, into the flow to which a wave of cooling will have penetrated is ~$(\kappa t)^{1/2}$, so that Gz = 16 $(D / \lambda)^2$. The observation that flows stop moving when Gz = ~300 thus implies that they do so when D / λ = 4.33, i.e. λ / D = 0.23. Thus cooling has penetrated only about half way from the upper and lower margins to the center of such a flow, and it must be the properties of lava at the flow front that has been subjected to some intermediate level of cooling, causing it to develop some finite effective strength, that causes the flow to halt. Similarly the fact that flows are commonly observed to thicken and widen when flowing at constant flux down a constant gradient implies that it is some effective viscosity, rather than the viscosity of the uncooled flow core, that controls the motion.

We have therefore chosen to characterize flows by an effective yield strength, Y, determined from the typical flow thickness, and an apparent viscosity, η, determined from a Jeffreys-type relationship. We thus regard the lava as locally being a Bingham plastic [15], but we do not assume that the rheological properties are constant along the flow. Instead, both Y and η are allowed to vary with position. They are given by

$$Y = \rho g D S \qquad (2)$$

and

$$\eta = (\rho g D^2 S) / (3 U), \qquad (3)$$

where g is the acceleration due to gravity, 9.8 m s^{-2}, and ρ is the lava density, taken as 2000 kg m^{-3}.

Since we have field measurements of D, S and U we can find Y and η at a series of points along the flow. At each of these points we can then evaluate the lava volume flux F where

$$F = U D W, \qquad (4)$$

and the Grätz number of the flow front from (1) with D_e = 4 D.

Results: Figures 1 to 3 show the down-flow variations of η , Y and Gz for three Pu'u 'O'o flows and one Mauna Loa flow. The Mauna Loa flow data were analyzed in a piece-wise fashion whereas smooth curves were fitted to the Pu'u 'O'o flow depth and travel distance data. The smooth curves did not fit the data exactly at the distal ends of the flows which is part of the reason for the decreases in the

values of η and Y near the flow termini; this problem does not affect the values of Gz, however, which were calculated from unsmoothed data. It is possible that some flow units (especially Pu'u 'O'o flow unit P3) did not reach their cooling limited lengths, and as a result partial drainage of the main channel took place; this may have influenced the distal values of Gz. The distal behavior of flow P4 is particularly anomalous. We intend to investigate these issues in detail in future work.

Conclusions: The main findings of the present phase of this work, illustrated in Figures 1 to 3, are that (1) basaltic Hawaiian flows appear to stop when their apparent viscosity rises to ~10^7 Pa s; (2) it does not appear that a unique effective yield strength is involved in halting flows; (3) the flows cease moving when the Grätz number approaches a limiting value of about 300, as found in earlier work [6].

References: [1] Walker, G.P.L. (1973) *Phil. Trans. Roy. Soc. Lond.*, *A274*, 107. [2] Sparks, R.S.J. & Pinkerton, H. (1978) Nature, 276, 385. [3] Baloga, S. M. & Pieri, D. (1986) *JGR*, *91*, 9543. [4] Baloga, S.M. (1987) *JGR*, *92*, 9271. [5] Crisp, J. & Baloga, S.M. (1994) *JGR*, *99*, 11,819. [6] Pinkerton, H. & Wilson, L. (1994) *Bull. Volc.*, *56*, 108. [7] Baloga, S. M. et al. (1995) *JGR*, *100*, 24,503. [8] Zimbelman, J.R. (1998) *JGR*, *103*, 27,503. [9] Baloga, S. M. et al. (1998) *JGR*, *103*, 5133. [10] Glaze, L.S. and Baloga, S.M. (1998) *JGR*, *103*, 13,659. [11] Baloga, S. M. et al. (2001) *JGR*, *106*, 13,395. [12] Baloga, S. M. et al. (2003) *JGR*, *108*, 5066, doi: 10.1029 /2002JE001981. [13] Neal et al. (1988) USGS Prof. Pap. 1463. [14] Lipman, P.W. & Banks, N.G. (1987) USGS Prof. Pap. 1350, 1527. [15] Hulme, G. (1974) Geophys. J. Roy. Astr. Soc., 39, 361.

Figure 1. Down-flow viscosity variations.

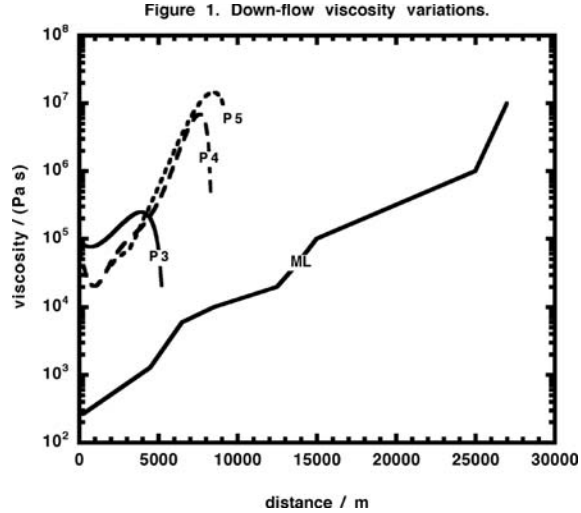

Figure 2. Down-flow yield strength variations.

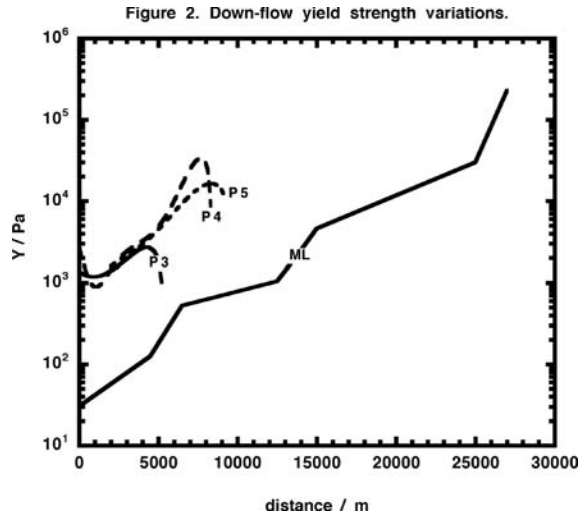

Figure 3. Down-flow Gratz number variations.