THE RHEOLOGY AND COMPOSITION OF CRYOVOLCANIC FLOWS ON ICY SATELLITES;

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The rheologic properties of terrestrial lavas have been related to morphologic features of their flows, such as levees, banked surfaces, multilobate structures, and compressional folds. These features also have been used to determine rheologies and constrain the compositions of extraterrestrial flows. However, with rare exceptions, such features are not resolvable in Voyager images of the satellites of outer planets. Often only flow length and edge thickness of cryovolcanic flows can be measured reasonably accurately from Voyager images. The semiempirical lava-flow model presented below is a renewed effort to extract useful information from such measurements.

The model supposes that a flow moves downslope until its chilled crust attains a critical fraction of flow thickness. The solidifying crust is assumed to thicken at a rate proportional to the inverse square root of time, analogous to the solidification of the crust on a lava lake. The model does not explicitly account for fracturing and foundering of crust, for suspension of crystallized solids in the liquid underlying the crust, nor for extrusion of fresh, hot slurry at the leading edges of lava flows. Therefore, this model does not accurately portray the behavior of real lava flows. Despite this simplistic approach, the model successfully relates the Newtonian viscosities of pure phase liquid lavas to actual flow thicknesses and lengths on Earth and the Moon, as shown below. An accurate analytical solution to the problem of the freezing crust (the Stefan problem) was presented by [1]. The time, $\mathbf{t_c}$, for the crust to thicken to the critical fraction of flow thickness defines a flow emplacement time. A characteristic flow speed, **u**, is defined as $\mathbf{u = L/t_c}$, where L is the length of the flow. No unique critical ratio of crust thickness to flow thickness, $\mathbf{T_c/T_f}$, has been defined by actual measurement or by analytical methods. Setting $\mathbf{T_c/T_f = 1/6}$ forces the model of one particularly well documented lava flow, Kilauea's Royal Gardens flow of 1983, to reproduce the observed characteristic flow speeds and the same effective viscosities as given by [2]. Henceforth, it is assumed that this ratio holds for all other flows. The applicability of this assumption to icy flow is supported by laboratory data for ammonia-water slurries [3]. Although the exact physical significance of this ratio is unclear, it might relate to existing concepts of threshold values such as the Bingham yield strength.

An effective viscosity (the 'morphologic viscosity') is estimated by combining the flow speed calculated in the manner just described with the analytical solution presented by [1], relating the viscosity of a fluid flowing down an inclined plane to other parameters, including flow speed:

$$\mu_{morp} = (\rho_l g \sin\alpha \, T_f^4 \rho_c C)/(288 L \lambda^2 k) \qquad (1)$$

where μ_{morph} is morphologic viscosity, ρ_l is the density of liquid, α is surface slope, $\mathbf{T_f}$ is flow thickness, ρ_c is the density of the solidified crust, **C** is the heat capacity of the crust, **L** is the length of the lava flow, **k** is the thermal conductivity of the crust, and λ is a term given by iteration of the transcendental equation (from [1]:

$$e^{-\lambda 2}/\lambda \, erf\lambda = Q\sqrt{\pi}/C(T_m - T_o) \qquad (2)$$

where **Q** is the heat of fusion of the lava, $\mathbf{T_m}$ is its liquidus temperature, and $\mathbf{T_0}$ is the ambient surface temperature. All temperature-dependent material properties of the crust are averages over the temperature interval $\mathbf{T_0}$ to $\mathbf{T_m}$.

Figure 1 shows the morphologic viscosities of 97 flows plotted against measured or estimated viscosities of these lavas at their liquidus temperatures. Morphologic data for these flows and other relevant information were obtained from literature sources [2,4-11]. These flows include a wide range of terrestrial silicate flows, two sulfur flows, one carbonatite flow, and a lunar flow. They range in length from 5 m to 300 km and in thickness from 3.5 cm to 300 m. The least-squares fit has a slope of unity and an intercept of about 10^5. The modeled morphologic viscosity correctly tracks the actual liquidus viscosity (Fig. 1) even though the mechanics of real lava flows are far more complex than modeled. The dispersion of data about the correlation line indicates a 1σ uncertainty of 1.25 log units in the liquidus viscosity thus determined. A great deal of important physics probably accounts for the dispersion, but for present purposes these effects may probably be ignored.

Calculated viscosities of three flows on Triton and one on Ariel are listed in Table 1. Both viscosities calculated for the flow on Ariel are several orders of magnitude less than calculated by [12]. The liquidus viscosities of Triton's and Ariel's flows are in the range exhibited by multi-component ammonia-water liquids [3,13]. The liquidus viscosities are also much greater than the viscosities of water (10^{-3} Pa-s) and brines (10^{-3} to 10^{-1} Pa-s), and they are much less than the viscosity of ice (warm ice viscosity ~10^{3} Pa-s). These viscosity comparisons do not necessarily imply that flows on Ariel and Triton are composed of ammonia-water liquids, but such a composition is cosmochemically reasonable.

References. [1] Turcotte, D.L. and G. Schubert, 1982, *Geodynamics*, John Wiley & Sons, New York, 450 pp. [2] Fink, J.H. and J.R. Zimbelman, 1986, *Bull. Volcanol.* **48**, 87-96. [3] Kargel, J.S., S.K. Croft, J.I. Lunine, and J.S. Lewis, 1991, *Icarus*, **89**, 93-112. [4] Moore, H.J. and G.G. Schaber, 1975, *Proc. Lunar Sci. Conf.*, *6th*, 101-118. [5] Swanson, D.A., T.L. Wright, and R.T. Helz, 1975, *Amer. J. Sci.*, **275**, 877-905. [6] Tazieff, H., 1977, *Bull. Volcanol.*, **40-3**, 189-200. [7] Frazzetta, G. and R. Romano, 1984, *Bull. Volcanol.*, **47-4**, 1079-1096. [8] Murase, T., A.R. McBirney, and W.G. Melson, 1985, *J. Volcanol. Geotherm. Res.*, **24**, 193-204. [9] Duffield, W.A. and G.B. Dalrymple, 1990, *Bull. Volcanol.*, **52**, 475-487. [10] Wadge, G. and R.M.C. Lopes, 1991, *Bull. Volcanol.*, **54**, 10-24. [11] Gadmundsson, A., et al., 1992, *Bull. Volcanol.*, **54**, 238-246. [12] Jankowski, D.G. and S.W. Squyres, 1988, *Science*, **241**, 1322-1325. [13] Kargel, J.S. 1993, *Icarus* (in press).

TABLE 1. Calculated flow viscosities.

Flow name	Satellite	Morphologic viscosity	Liquidus viscosity (Pa-s)	Possible lava compositions (Pa-s)	Unlikely lava compositions
Crater dome flow lat 14N long 39	Triton	1.7 x 10^{10}	1.7 x 10^{5}	H2O-NH3-GKWE*	Pure water, brine, pure ammonia-water, or pure ice
Lobate flow lat 9S long 57	Triton	3.1 x 10^{8}	3.1 x 10^{3}	H2O-NH3-GKWE*	Pure water, brine, pure ammonia-water, or pure ice
Lake spill flow lat 20N long 20	Triton	1.8 x 10^{7}	1.8 x 10^{2}	H2O-NH3 or H2O-NH3-GKWE*	Pure water, brine, or pure ice
Kewpie-Brownie flow**	Ariel	2.3 x 10^{9}	2.4 x 10^{4}	H_2O-NH_3-GKWE*	Pure water, brine, or pure ice
		or 4.6 x 10^{6}	49	H_2O-NH_3 or H_2O-NH_3-GKWE*	

* GKWE = God-Knows-What-Else. Might include methanol, ammonium sulfide, sodium chloride, or other substances providing substantial added freezing-point depression and increased viscosity [3, 4].

**First entry based on assumption of axial eruption; second entry, on assumption of longitudinal flow.

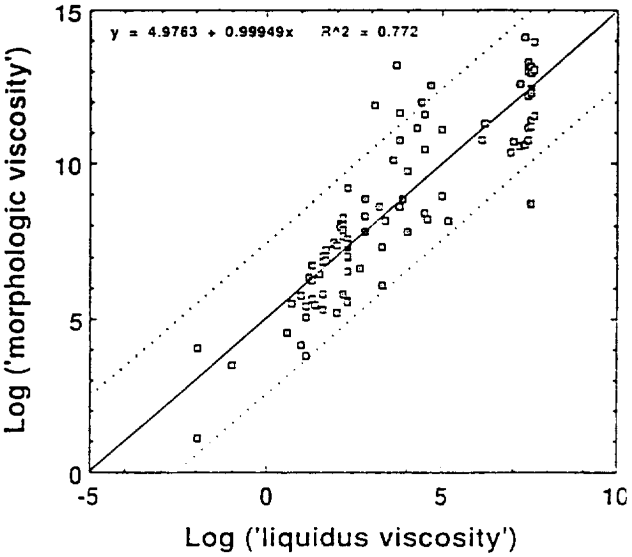

Figure 1. Calculated morphologic viscosities and estimated liquidus viscosities of 97 lava flows.