STUDIES OF FLUID INSTABILITIES IN FLOWS OF LAVA AND DEBRIS

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Introduction

Estimating the rheology of lava flows is an essential tool for the remote determination of flow compositions on other planets and is also a component in the evaluation of many volcanic hazards. For flows whose emplacement is not observed, indirect methods must be used to assess such physical parameters as viscosity, yield strength, density, and volatile content. Most studies of this type have assumed that the geometry of large scale morphological features on the flow surface reflects the bulk rheology of the active lava. One class of lava surface structures that is particularly well-suited to this sort of interpretation includes those periodic features that result from fluid instabilities.

At least two instabilities have been identified and utilized in lava flow studies: surface folding and gravity instability. Both lead to the development of regularly spaced structures on the surfaces of lava flows. The geometry of surface folds, first analyzed by Fink and Fletcher (1978), has been used by Fink (1980a), Fink et al. (1983), Zimbelman (1985), Head and Wilson (1986), and others to estimate the rheology of lava flows on other planets. Fink and Fletcher's (1978) analysis assumed that lava flows have a temperature-dependent newtonian rheology, and that the lava's viscosity decreased exponentially inward from the upper flow surface.

The presence of a gravity or Taylor instability was proposed by Fink (1980b) to explain certain regularly spaced domal outcrops of low density pumice on the surfaces of silicic lava flows. Subsequent investigations (Fink, 1983; Fink and Manley, 1986; Manley and Fink, submitted) have attempted to relate the density inversion to the distribution and migration of volatiles within actively advancing flows. Such studies provide possible criteria for the identification of silicic lava flows on high resolution images of other planets, since diapirism results in flow surfaces with very high albedo contrasts, and the associated concentrations of volatiles may lead to formation of large craters and other explosive features on the surface of a silicic flow. These models are also important for hazards studies since the presence of volatiles in silicic magmas is considered a major factor in the inception of explosive volcanism.

Analyses of surface folding

Surface folding (Biot, 1960; Fink and Fletcher, 1978) produces regularly spaced ridges that range from cm-scale ropes on pahoehoe basalt flows to 100-m-scale lava ogives seen on rhyolite flows. Analysis shows that ridge spacings depend on the thickness of the cooling crust, magnitude of the compressive stress, and weight of the lava. Ridges can only form when the ratio between surface and interior lava viscosities lies in a restricted range: if the crust is too stiff (cool), the surface deforms by fracture rather than flow; if too soft (hot), ridges form but are not retained.

The application of this model to extra-terrestrial lava flows has been attempted by numerous investigators. One of the main drawbacks of the model has been that it requires estimating the thickness of a flow's thermal boundary layer (crust). Previous planetary applications have required assumptions about the strain rates and times of formation associated with large ridges (formation times have been assumed to be between 1 day and one week), and about how the crustal thickness relates to the amplitude of the ridges (crust thickness was generally assumed equal to ridge amplitude).

A lower bound on strain rates was obtained from observations of the active 1984 Mauna Loa basalt flow. During this eruption, surface ridges with wavelengths ranging from 10-30 m and amplitudes of 1-2 meters were seen to form relatively abruptly at positions that migrated upstream as part of an overall change in aa surface characteristics described by Lipman, Banks, and Rhodes (1986). Ridges were seen to form behind flow constrictions over a period of less than a day. The observed wavelengths and amplitudes correspond to strains of between about 0.003 and 0.080. If these occurred over periods of less than a day, the minimum strain rates would be between 10^{-7} and 10^{-8} sec^{-1}, which are considerably less than those used in earlier calculations. Lower strain rate estimates in turn lead to higher calculated viscosity values.

Analyses of Taylor instability in lava flows

Recent drilling investigations in rhyolite flows (Eichelberger et al., 1985; Goff et al., 1986) have provided new information about their volatile distributions, and now allow more accurate specification of boundary conditions for the gravity instability model. Fink's original linear analysis (1980b) assumed newtonian rheology, an absence of slope-induced shear stresses, a rigid upper flow surface, and a two-dimensional perturbation of the unstable interface. The new drill data have motivated a more rigorous and generalized analysis of the Taylor instability in lava flows.

The new formulation allows for three dimensional disturbances, the effect of a mean shear flow on the instability, and a deformable free upper surface. This analysis allows determination of whether transverse ridge formation is favored over other possible orientations, assessment of the deformation of the free surface relative to that of the unstable internal interface, and use of the viscosity ratio to help determine the state of volatiles within the buoyant layer.

Results of the new analyses (Baum et al., in review) include calculations of preferred wavelength and growth rates as functions of buoyant and dense layer thicknesses and viscosities. In general, diapir spacing increases in proportion to the thickness of the buoyant layer and to the viscosity of the dense layer. The measured thicknesses of buoyant and dense layers in three different drill cores and in two well-dissected rhyolite flows in Arizona allow the relative viscosities of the layers to be determined. It was found that the presence of regularly spaced, dark, pumiceous diapirs on the surface of terrestrial silicic flows reflects a local concentration of volatiles of from 3 to 6 times the average values. Recognition of such diapiric structures in conjunction with unusually large surface ridges on martian or venusian flows would suggest more evolved lavas than have previously been identified. Such features are currently being sought in high resolution Viking images.

Surface folding on debris flows

Not all terrestrial flows that preserve regularly spaced ridges are lavas. Debris flows, landslides, mudflows, and other sorts of mass movements may all develop surface folds in response to flow parallel compression. As part of a study of the Chaos Jumbles debris avalanche deposit at Lassen National Park, an analysis of surface folding instabilities on plastic materials was conducted (Eppler, Fink and Fletcher, 1987). The main differences between the rheological model used for debris avalanches and for lava flows were (1) the debris was assumed to have an isothermal, power-law rheology with a finite yield strength, rather than a temperature-dependent newtonian rheology; and (2) the debris was assumed to move primarily by slip over a frictionless basal surface rather than by continuous flowage.

A surprising result of the analysis was that the spacing of ridges was proportional to the total thickness of the flow, rather than to the crustal thickness alone. The ratio of ridge spacing to flow thickness ranged from 1.4 to 2.8 for all reasonable rheologic values. These two endmembers correspond to relatively low and high values of debris strength. Hence, by measuring the spacing of ridges on a debris flow, it may be possible to estimate its thickness (and volume) to within a factor of two. For the case of Chaos Jumbles, volume estimates based on ridge spacing were consistent with volume estimates based on the size of the collapse scar left behind by the falling debris. Application of this model to the interpretation of landslide deposits on Mars is currently in progress.

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