ESTIMATING ERUPTION RATES OF PLANETARY LAVA FLOWS

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A new method of estimating eruption rates of planetary lava flows has been developed, which is based on a two-component thermal model for the emplacement of lava flows. This model features a crustal thermal boundary layer and a hotter well-mixed core that is partially exposed at the top surface, where it loses heat by radiation. The motivation for such a model is the common observation of bright hot material on the surface of active lava flows in cracks, shear margins, wavelike surface deformations, overspills, and surges. Solutions were derived for a crust that increases thickness linearly with time and for a constant thickness crust. Another solution for core-crust interaction involves conduction from core to the crust in addition to radiation at the top surface.

Previously, three approaches have been used to estimate eruption rates of lava flows. Hulme [1] used an isothermal Bingham fluid flow model to derive eruption rate as a function of viscosity, slope, and levee and channel geometry. Another approach to modeling lava flows involves the comparison to heat loss from a fluid flowing in a cooler pipe and a critical Graetz number, $Gz_c = Q\ h\ /\ [\kappa\ L\ w]$, where $Gz_c \approx 300$ for some basaltic lava flows [2,3,4]. Pieri and Baloga [5] found that thermal mixing and radiation cannot satisfactorily explain the observed relationships between Q and A, even for carefully pre-selected lava flows from Hawaii. However, the observed correlations were indexed by an empirical "effective radiation temperature" that, in essence, made the flow lose the right amount of heat. The new model of this study has a finite crust thickness and no longer depends on an empirical radiation temperature, and therefore supersedes this third approach.

In our new model, f is the fraction of core that is continuously exposed at the surface. The assumption that the core is well-mixed requires the temperature of the inner core to decrease after it has been exposed at the surface. The general solution is obtained by setting up a heat balance for a core control volume, requiring that the initial temperature at the vent be a constant, and prescribing a constant core temperature for the case of $f = 0$.

Despite considerable uncertainties in our present ability to estimate f for actual lava flows from visual observations, the predicted values of the model (Fig.1) correspond well with estimates for Hawaiian flows of $f = 0.001$ to 0.1. The results of the model also show that the core temperature is particularly sensitive to f and flow thickness, but is not sensitive to the way in which the upper thermal boundary layer thickens with time.

One of the main objectives for all heat loss models of lava flows has been to determine the relationship between the length or planimetric area of a flow and the eruption rate at the source of the flow. Our new two-component model gives

$$Q/A = 3\ E\ \sigma\ f\ T_o^3\ /\ \{\ \rho C_p\ (1 - \delta/h)\ [\ (T_o/T_{cf})^3 - 1\ ]\ \} \qquad (1)$$

for the case of a boundary layer with constant thickness, where E = emissivity, σ = Stefan-Boltzmann constant, T_o is the initial temperature of the core at the vent, ρ = density, C_p = heat capacity, $\delta = \delta(t)$ = boundary layer thickness, h = flow thickness, and T_{cf} is the final temperature of the core. The Q/A relationship predicted by the above equation is fairly insensitive to $\delta(t)$ and extremely sensitive to the parameters f and T_{cf}, which presently have significant uncertainties.

The most comprehensive and appropriate data set available for testing the relationship is that of the 1983-4 Puu Oo eruptions [6]. Yet even for this data set, there is considerable scatter in a plot of Q versus A, despite similar temperatures, flow thicknesses, and magma compositions for several single-lobed flows. The slope of the Q versus A relationship is 30 $\pm$ 25 $m^3\ s^{-1}\ km^{-2}$ ($\pm$ 2-sigma). Only 13% of the variation in Q is explained by the linear regression of Q on A. This poor correlation is expected from Eq.(1).

This new model indicates that the results of the Hulme and Graetz methods are plausible but there are a lot of sensitivities that are not accounted for by these other two methods. The new model gives eruption rate estimates that are similar to the results for the Graetz number method applied to Ascraeus flows [7] if f $\approx$ 0.001 and for the Hulme method applied to leveed Alba flows [8] if f $\approx$ 0.01-0.1. For the Alba flows measured by Cattermole [8], assuming that the average fraction of exposed core was between 0.001 and 0.1, the predicted range of eruption rates is 50 - 5000 $m^3\ s^{-1}$ for the smaller $\approx$ 100 km^2 flows and 5000 - 500,000 $m^3\ s^{-1}$ for the largest $\approx 10^4\ km^2$ flows.

At present, this new model does not provide a tight constraint on eruption rates for planetary flows. However, it does provide us with more understanding of the factors f, h, T_o, and T_{cf} can influence eruption rates.

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Fig.1. Area fraction of exposed core versus dimensionless emplacement time. The time scale $\Gamma = \rho C_p h/E\sigma T_o^3$ is typically 0.5-5 days. ΔT ratios are for degrees K. Solid curves are for a constant boundary layer thickness δ = 0.2h. Dashed curves are for a boundary layer that thickens linearly from zero at vent to 0.2h at the flow front. Vertical dotted lines indicate the t/Γ for a few 1983-4 Puu Oo single-lobed flows, an Etna flow, and a Mauna Loa flow.