LAVA FLOW DYNAMICS DRIVEN BY TEMPERATURE-DEPENDENT VISCOSITY VARIATIONS.

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Introduction

Pahoehoe lava flows dominate terrestrial basaltic lavas throughout subaerial and submarine environments [1] on the Earth and other planetary bodies [2]. Initially flowing as a sheet with a uniformly distributed liquid lava core, thermally and mechanically preferred pathways develop -- forming lava channels and tube systems [3,4]. These allow for more efficient delivery of lava from the source vent to the flow front [5], but greatly complicate efforts to estimate flow duration, lava rheology, and overall flow evolution from surface morphology.

It is important to understand how these channels and tubes initialize as that yields the starting measurements for many lava flow evolution models and would affect the interpretation of early lava flow morphology. It has generally been hypothesized that channel and tube formation are controlled primarily by topography and flow-depth [e.g., 4]. However, laboratory experiments with lava have shown that viscosity contrasts (10^2-10^4: as shown in Figure 1) can arise from small differences in temperature and (related) crystallization or volatile content and large viscosity-contrasts have been observed in the lab to drive the formation of preferred pathways [3, 6]. Other studies have used this type of dynamic instability to explain temporal [7] and spatial [8] oscillation within fissure flows.

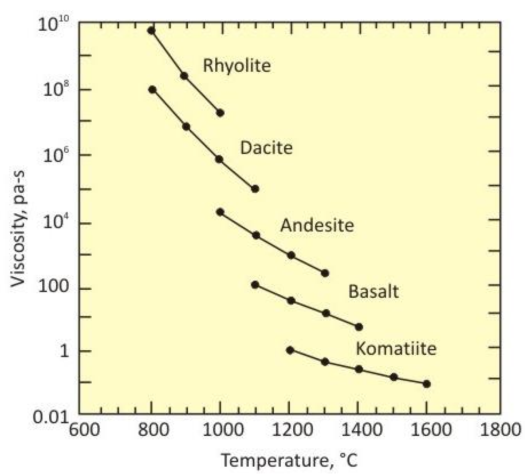

Figure 1. The exponential temperature-dependence of viscosity of several lava types, determined from laboratory experiments. Plot is taken from [9].

Study Objective

We investigate the likelihood that this viscosity-driven dynamic instability plays a significant role in creating lava tubes and channels within an initially uniform lava sheetflow. If shown to be influential, then consideration of this general dynamic model will improve interpretation of lava flow and eruption characteristics from flow morphology. It will also make it easier to compare flows in different sites, or on different planets, as it does not require locally-specific information such as pre-flow topography.

Model Structure

We assume Newtonian laminar and incompressible flow with a depth-averaged two-dimensional system, and thus we use standard fluid equations with a few modifications:

(1) due to assumed flow geometry (flow depth << width or length or a Hele-Shaw cell type geometry), we use a Darcy model for the momentum equation instead of viscous flow;

(2) the fluid viscosity depends exponentially on the temperature, where $\mu \sim \exp(\beta T)$.

Additionally, we assume that heat is lost through a surface crust (at a rate δ) and side walls are kept at a constant cold temperature.

The two parameters: $\boldsymbol{\beta}$ and $\boldsymbol{\delta}$, are the main two unknowns in the system and the two primary controls on the dynamics. Their physical values depend on lava rheology, eruption parameters, and eruption duration.

Results and Comparison with Terrestrial Flows

Through numerical simulations (example results given in Figure 2) and analysis of the model equations, we have determined that:

(1) With even small temperature differences, **when β is sufficiently large the instability will grow and fingers will form** (i.e., when $\beta > 3$, or a viscosity contrast factor of > 20, over a 100°C temperature difference). Laboratory experiments with basaltic lavas yield β values of 1-2 until the temperature drops below the liquidus (<1200°C, generally down to ~1100-1150°C) as crystallization increases viscosity non-smoothly. **Eruption temperatures in Hawaii are generally within this range (and all basaltic flows will eventually cool to those temperatures), so β is likely > 3 for basaltic flows.** This perhaps explains the ubiquitious nature of channels and tubes within basaltic flows.

(2) **The system settles into a steady-state where $T \sim \exp(-\delta/u^* x)$**, where u^* is the average velocity within the finger (and is dependent on the amount

of flow-focusing; i.e., related to β). Using expected β values, we find **natural characteristic lengthscales of ~1-10m for basalt and ~1000m for silicic flows.** Both of these values are consistent with observations: channels tend to form quickly and near the vent within basaltic flows [3-5], while lava channels are infrequently found within silicic flows and, when found within particularly long flows, have surface expression of channelization starting ~1km from the vent [10].

(3) Assuming mass conservation (i.e., no breakouts), then the final u* value will control the total finger-width. Work is ongoing to better define the across-flow characteristic lengthscale.

Conclusions and Future Work

Measurements of finger characteristics have so far been consistent with predictions from simulations (of threshold β and along-flow lengthscales) across several types of lava rheologies and eruption sites. This suggests that this general dynamic does play an important role in lava tube and channel formation. More field and laboratory measurements, though, are needed to continue refinement of the model and to constrain the growth and evolution of finger systems. In particular, we will continue investigation of the influence of initial temperature perturbation on the final flow configuration (e.g., number and location of fingers) and how scaling changes between planets.

Acknowledgements
SD was supported by an appointment to the NASA Postdoctoral Program, administered by Oak Ridge Associated Universities, at Caltech/JPL under a contract with NASA.

References
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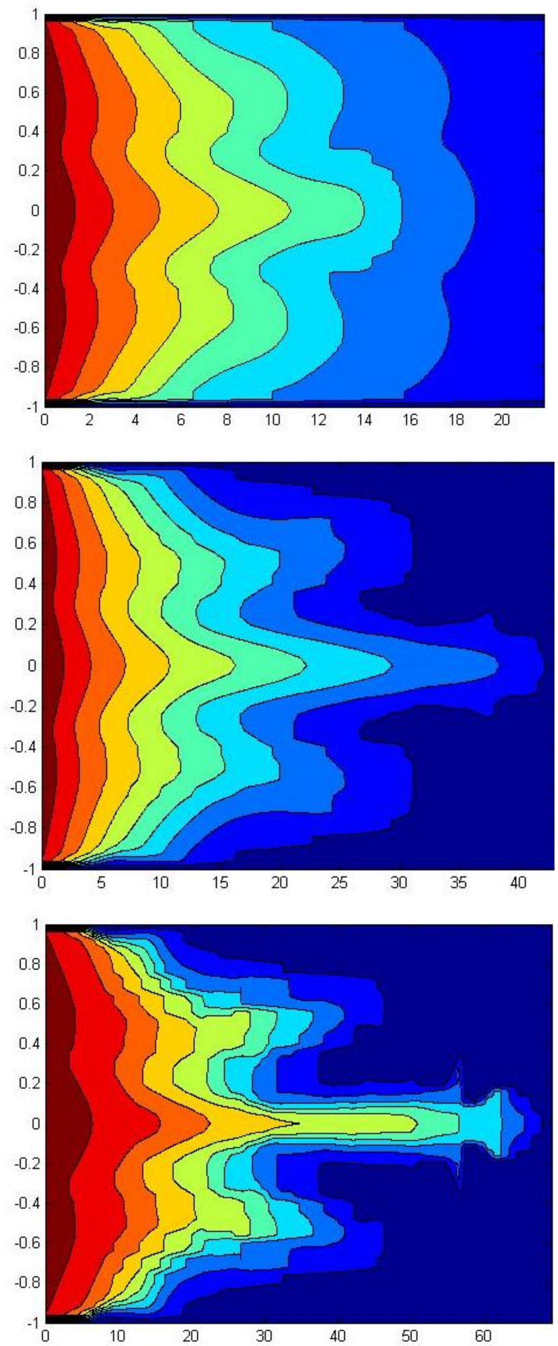

Figure 2. Example numerical simulation showing finger formation within the flow (planform view; time increases downward). Color indicates temperature: red is hot and blue is cold (with maximum temperature difference of 100°C). The influx boundary is along the left (flow is from left to right): initialized with uniform velocity and temperature perturbations of a few degrees – all other temperature and velocity changes are due to the initial small viscosity contrast. All distances are in meters and time increases moving downwards. B~5 and δ~0.1 *in this example.*