

NUMERICAL MODELING OF LAVA FLOW BEHAVIOR ON EARTH AND MARS: A MULTI-LAYER RHEOLOGICAL APPROACH. M. M. Sori¹, C. W. Hamilton¹, E. Lev², and S. Scheidt¹. ¹Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA (sori@lpl.arizona.edu). ²Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA

Introduction: Volcanism is a ubiquitous planetary process [1], with evidence for basaltic flows observed on every terrestrial planet in the Solar System. However, active eruptions have only been observed on Earth and Io, and thus studies of extraterrestrial lava flows are in large part constrained by the final geometry of those flows. Final geometry is a complex result of many factors, including, but not limited to, lava composition and rheology, temperature, cooling rate, effusion rate, crystal abundance, volatile content, and underlying topography [2]. Typically, few of these parameters are well known for any particular flow, and therefore lava flow modeling must make simplifying assumptions, such as utilizing an idealized rheology.

Many studies have successfully used simplified models to characterize flow evolution [2], especially for cases of purely molten lava without a brittle or viscoelastic crust that can be approximated by a Bingham fluid [e.g., 3–5]. Here, we use the finite element method (FEM) to study flow rates of sheet-like basaltic lavas after crustal formation. We explore a wide parameter space with the goal of learning about the similarities and differences between lava flow evolution on Earth and Mars. For Earth, our parameter space is inspired by observations of the McCartys lava flow in New Mexico [6, 7]. For Mars, our parameter space comes from observations of flows within the northeastern Cerberus Fossae 2 unit [8, 9].

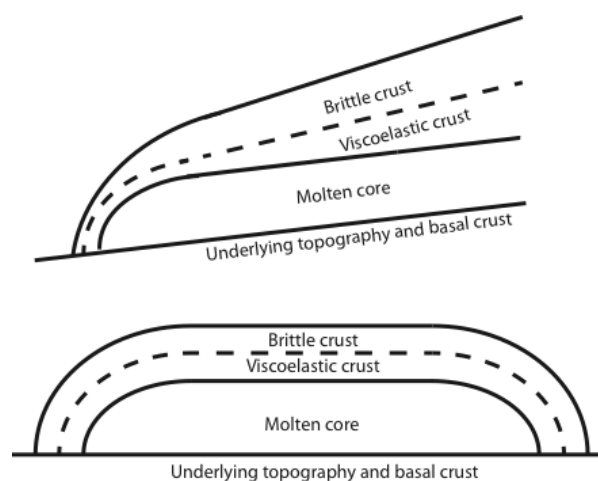


Figure 1. Schematic of our modeled lava flow showing an example cross-section of the flow structure down-slope (top) and cross-slope (bottom).

Methodology: We use the multi-physics FEM software Elmer to solve the Navier-Stokes equations

and map the stresses and velocities of lava flows. We model flows with three layers as described by [10]: an exterior brittle crust, an underlying viscoelastic layer, and an interior molten core. The brittle crust that does not flow and has temperature $<800^{\circ}\text{C}$. The underlying viscoelastic crust has temperature $800\text{--}1070^{\circ}\text{C}$. The interior molten core behaves as a Bingham fluid with temperature $>1070^{\circ}\text{C}$; however, it can become a purely Newtonian fluid at sufficiently high temperatures. Below these flow layers is the underlying topography, which may be a plane or have a more complex form. The basal boundary layer found in natural lava flows is taken to be part of this substrate base. An example schematic of our flow model is shown in Figure 1.

The McCartys lava flow is part of the Zuni-Bandera volcanic field and is composed of porphyritic basalt [6]. Geological mapping of inflated pāhoehoe lobes [7] has yielded valuable datasets from which to derive parameters for flow modeling. The study also makes several observations that our modeling can elucidate. For example, fractures up to 15 m in depth were observed on the steep slopes of the flow fronts, which constrains the brittle crust thickness to at least 15 m; our models can map the state of stress under such geometry.

High Resolution Imaging Science Experiment (HiRISE) [11] observations of volcanic provinces on Mars [8] represent the most detailed imagery of lava flows outside the Earth-Moon system. Of particular interest here is the northeastern region of Elysium Planitia, the Tartarus Colles lava flow [9]. As with the case of the McCartys flow, observations of the geometry of this Martian flow yield parameters and constraints for our modeling. An analysis of HiRISE and MOLA data for the distal margins of the Tartarus Colles flow reveals that it includes two terraces, which are interpreted to be inflated lava-rise plateaus. The outer terrace typically has a thickness of 20–25 m and the inner terrace generally has a thicknesses of 55–60 m. These layers are generally thicker than what is observed for terrestrial flows, and thus we allow for larger thicknesses of our modeled Martian flows than for our terrestrial ones.

Viscosity of the viscoelastic component of the crust is poorly constrained, although there are some experiments suggesting that its viscosity is several order of magnitudes higher than the molten core [12]. Given the uncertainty in the appropriate viscosity value, we consider it as a free parameter in our model. Rheology for the molten core layer is better known, but still a matter of debate. It is often described as a Bingham

fluid, but can also be approximated by a power law rheology [13]; we adopt values measured from field observations [14] that have shown to be consistent with controlled experiments [15]. The relative thickness of each layer is dependent upon the time since emplacement, as sheet-like basaltic flows undergo crustal thickening over time [10]. We vary density between 2000–3000 kg/m³. Lower gravity of Mars will decrease flow magnitude relative to Earth for any rheology. We assume laminar flow, based on observed low Reynolds numbers of basaltic flows [15].

Results: Based on McCarty's observations, we model a cross-slope cross-section pāhoehoe sheet flow on Earth with total thickness 20 m, flow side width 40 m, and flow side shape as a quarter sine wave. Resultant cross-slope flow velocities are shown in Figure 2. The rock density is 2500 kg/m³ and the underlying topography is flat. Crustal thickness is half the total thickness, which is divided equally into an upper brittle crust and a viscoelastic layer. Crusts have been observed to form on sheet flows relatively quickly, so this model corresponds to a moment after the initial period of rapid inflation by molten core thickening and cooling-induced crustal growth [10]. The maximum flow velocity for this model is ~10 m/s. The viscosity of the viscoelastic crust is 4 orders of magnitude greater than the molten core, which results in flow velocities on the order of mm/min to cm/min in this layer.

Most basaltic sheet flows in the modern geologic record on Earth are not as thick as those observed in the McCarty's flow. We also ran a simulation with the same shape described above but with a thickness of only 5 m, and found maximum flow velocities of ~5 m/s. These velocities are lower than those observed for Etna flows (for example, the 4.5-m-thick Etna 1983 flow had observed velocities as high as ~30 m/s [15]). This discrepancy may be due to steeper underlying topography for the Etna flows (Fig. 2 shows cross-slope velocity, rather than down-slope) and fluid pressurization in the molten core caused by the influx of lava into the lava pathway system.

Figure 3 shows cross-slope flow velocities for a pāhoehoe-like sheet flow on Mars. The parameters are the same as those of Figure 2, except that the flow thickness is 40 m and the flow side width is 80 m, and the gravitational acceleration is the Martian value of 3.71 m/s². The maximum flow velocity for this model is ~8 m/s.

Discussion: Free parameters we are exploring for their effects on flow behavior include flow thickness, underlying topographic slope, rheology of the molten core, rheology of the viscoelastic crust, pressurization of the molten core, and curvature of the flow front. Two competing effects between the terrestrial and Martian cases are the higher gravitational acceleration

of Earth and the greater flow thicknesses of Martian flows. We generally find that these effects are of the same in order of magnitude, and that the flow velocities of Martian flows tend to be close to those found in terrestrial flows (Figures 2 and 3).

Other parameters have trends in the expected direction; for example, more viscous rheology leads to lower flow velocities. A parameter with a less obvious effect is curvature of the flow front and flow sides. We ran models with the same parameters as those shown in Figure 2 and 3, but varied the curvature of the flow sides. We find that a linear flow front yields smaller flow velocities than convex or concave ones. This is likely the result of steeper local slopes in curved fronts. Different curvatures have been observed to be associated with different types of fracturing at the McCarty's flow [7], and our mapping of flow velocities and stresses will be useful in understanding their formation. Our ongoing work will further explore the space in the free parameters described above, calculate down-slope flow velocities, and consider the roles of fluid pressurization in the molten core and a crust that breaks up as lobes inflate.

References: [1] Basaltic Volcanism Study Project (1981), Pergamon Press Inc., New York, USA. [2] Dragoni, M. (1993) in C.R.J. Kilburn and G. Luongo, *Active Lavas*, UCL Press, London, UK. [3] Robson, G.R. (1968), *Nature* 216, 251–252. [4] Shaw, H.R. et al. (1968), *Am. J. Sci.* 266, 225–234. [5] Dragoni, M. et al. (1986), *J. Volcan. and Geotherm. Res.* 30, 302–325. [6] Nichols, R.L. (1946). *GSA Bull.* 57, 1049–1086. [7] Scheidt, S.P. et al. (2014), *LPSC* 45, 1491. [8] Keszthelyi, L. et al. (2008), *J. Geophys. Res.: Planets* 113, E04005. [9] Hamilton, C.W. et al. (2011), *J. Geophys. Res.* 116, E03004. [10] Hon et al. (1994), *GSA Bull.* 106, 351–370. [11] McEwen, A.S. et al. (2007), *J. Geophys. Res.* 112, E05S02. [12] James, M.R. et al. (2003), *J. Volcan. and Geotherm. Res.* 132, 99–113. [13] Hardee, H.C. and Dunn, J.C. (1981), *J. Volcan. and Geotherm.* 10, 195–207. [14] Shaw, H.R. (1972), *Am. J. Sci.* 272, 870–893. [15] Lev, E. et al. (2012), *J. Volcan. and Geotherm. Res.* 247–248, 62–73.

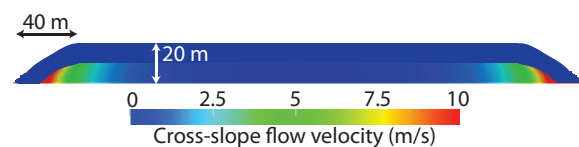


Figure 2. Cross-slope flow velocities for a cross-slope cross-section of a 2D modeled lava flow on Earth. See text for model parameters. Lava is flowing outward.

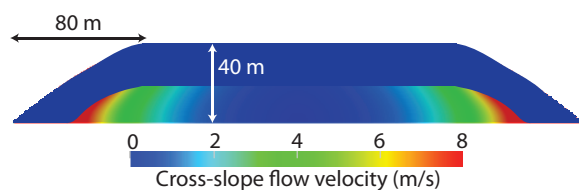


Figure 3. Cross-slope flow velocities for a cross-slope cross-section of a 2D modeled lava flow on Mars. Note that the spatial scale of the figure is the same as in Figure 2. See text for model parameters. Lava is flowing outward.