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Numerical simulation of the effect of solidifying crusts on lava propagation and arrest

Janine Birnbaum[1,2], Einat Lev[2], Marc Spiegelman[2,3], Jackie Kendrick[1], and Yan Lavallée[1]
[1]Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität München, Munich, Germany (j.birnbaum@lmu.de)
[2]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA
[3]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA

Silicate melts have highly temperature-dependent viscosity and at low temperatures, crystalize and/ or vitrify. The development of a solid rind or carapace results in a transition in deformation mechanism from dominantly viscous to elastic or plastic. This transition has a significant impact on the rate and style of emplacement of lava flows and domes, including on the construction of channelized flows, over-steepened margins, and advance due to lava flow breakouts. These processes are especially important in subaqueous, subglacial, and extraterrestrial environments in which cooling is accelerated, resulting in a current lack of models specifically calibrated for these environments.

We develop a numerical model, Viscous-Elastic Numerically Unified Solver for Solidifying flows (VENUSS), for cooling and solidifying free surface flows. The model couples a viscous fluid interior with an elastic shell whose thickness grows in response to cooling. We use a numerically unified approach that solves for the velocity field in the viscous and elastic fields together. Interface tracking is provided using the level set method combined with an extended finite element (XFEM) approach to avoid costly remeshing. Simulations are performed in two-dimensional planar or axisymmetric conditions which allows for modeling natural geometries such as lava flows and lava domes. This approach presents an improvement upon existing models of lava flow and dome evolution that either neglect or greatly simplify the mechanical effects of a crust.

As a validation/test of our model, we simulate the advance of meter-scale experimental lava flows from the Syracuse Lava Project. We find the flow propagation is highly sensitive to the boundary conditions applied at the flow base. Under no-slip conditions, the simulated flow arrests more quickly than the experiments. No-stress conditions at the flow base produce plug-like flow that propagates too quickly. Adding an imposed ruptured condition (no solidification and viscosity appropriate to the flow interior) in a thin layer at the flow base produces a lobate morphology that qualitatively resembles observations of natural and experimental flows.

In our models, flows are slowed and stopped by the development of a coherent crust at the flow front, whereas natural flows would continue to propagate via rupture of the skin or crust, highlighting the importance of including these mechanisms in models. However, crust

development and rupture are usually omitted from lava flow models, in which propagation and arrest are usually controlled by an increase in viscosity through the entire flow thickness. Our new model allows for investigation into the development and arrest of lava flows that depends on geometry, the competition between flow advance and cooling, and the mechanical properties of a solidified skin or crust. Such insight can be embedded into flow field scale models and allow for physics-based, complex flow fields impacted by breakouts, ooze-outs, channelization, and other critical crust-dominated processes.