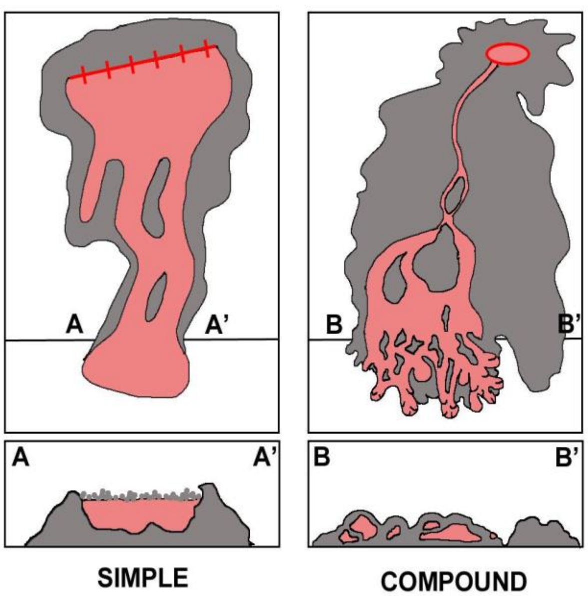
PROGRESS TOWARD A POROUS FLOW MODEL FOR THE EMPLACEMENT OF PAHOEHOE FLOW FIELDS. L. P. Keszthelyi[1] and M. E. Rumpf[1], [1]USGS Astrogeology, Flagstaff AZ 86001 (laz@usgs.gov)

Introduction: The emplacement of compound pāhoehoe flow fields involves the extrusion of thousands of individual meter-scale lobes, each governed by local heterogeneities in the topography and previously emplaced lava. Despite this, the overall advance of the flow field, and the formation of preferred lava pathways within it, appear to be governed by larger-scale properties of the environment and eruption (Fig. 1). There has been some success in modeling this behavior through the mathematics of a biased random walk [1]. Here we examine a moderately different technique to predict large-scale behavior when the small-scale processes are chaotic, building upon methods used to model flow through porous media.

Figure 1. Stereotypical geometry of simple and compound (i.e., pāhoehoe) lava flow fields [2]. Vents are shown in red, actively flowing lavas in pink, and stagnant or frozen lava in grey. Planview on top, cross sections underneath. The more straightforward nature of simple flows has made them more amenable to modeling.



The Hypothesis: The central idea we are examining is that the tortuous flow of a fluid through a porous material is similar to the convoluted path lava takes through a network of pāhoehoe lobes. To simulate the development of more distinct lava pathways (i.e., sheets and tubes), we call upon a flux-dependent permeability. By having permeability locally increase where there is sustained flow, as in water flowing through a matrix containing salt, distinct internal pathways can develop [3]. This type of model has proven useful in modeling the flow of magma through a crystal-liquid mush [3,4]. While this conceptual model does not attempt to replicate the complexity of the advance and evolution of a pāhoehoe flow field, it may provide a simple tool to describe the larger-scale development of such lavas. If successful, it could provide a tool for hazard forecasting on Earth, better understanding ancient eruptions (especially flood lavas), and provide new ways to investigate eruptions on the Moon, Venus, Mars, and Io.

The porous flow model can be expressed in a form analogous to Darcy's Law. In one dimension, it can be written as

$$Q = A\, K_{eff}\, (dP/dx), \qquad \text{(Eq. 1)}$$

where Q is the volumetric flux of lava across a given area, A is the cross-sectional area of the flow, K_{eff} is the "effective" permeability (i.e. the material permeability (m^2) multiplied by porosity and divided by the dynamic viscosity (Pa•s)), and dP/dx is the driving pressure gradient (Pa/m). We will test the idea that the model can be confined to two planimetric dimensions with the saturation of pores as a stand-in for the flow thickness. In particular, we will be looking to see if a 2D model is able to reproduce the effect of lava flow inflation, which is a key aspect of pāhoehoe flow fields.

The main challenge is to determine if the small-scale complexity of pāhoehoe lava flows can really be captured in a single parameter, K_{eff}. It is clear that K_{eff} cannot have a single constant value. Instead, the hypothesis is that having K_{eff} be a function of the local flux. This makes the problem fully recursive, which is challenging to solve even numerically. It may also be important to add an effect for the topographic roughness of the substrate at the decameter- to meter scale.

The Test: We are using COMSOL, a large commercial finite-element package widely used in many engineering and science applications [5]. As of writing this abstract, we are starting with simple geometries to see if the general behavior of pāhoehoe can be replicated (Fig. 2).

We are using the Richardson Equation option within the Porous Flow module of COMSOL since this is designed for partially saturated porous flow. As of the writing of this proposal, we have made important preliminary progress. The use of effective saturation as a substitute for lava flow thickness appears to work. We have also confirmed that there are values of permeability that allow reasonable rates of lava advance while using realistic slopes and fluid properties (density and dynamic viscosity) appropriate for basaltic lava (Fig. 2). Fine-tuning of the mesh, numerical solvers, and formulation of initial and boundary conditions to allow stable solutions has been completed.

We continue to work the problem of implementing a flow rate dependent permeability. One option is to halt the simulation at intervals and calculate permeability that is then held constant for the next interval. This can work if permeability varies very slowly. An alternative is to use a (fictional) intermediary parameter to allow COMSOL's multi-physics capabilities to be applied. It is expected that, once this complexity is added, additional tuning of the model will be required to have the runs complete successfully over regions tens to hundreds of kilometers in size while utilizing reasonable amounts of computational resources.

Future Work: Once we have identified the range of parameter space that produces results on roughly the correct spatial and temporal scales, we will attempt to more closely reproduce the behavior observed in active eruptions in Hawaiʻi and Io. We will test our hypothesis by comparing numerical model results to observations from the 1983-2018 Pu`u `Ō`ō – Kupainaha flow field. The rates of advance of the flow front and the timescale for the development of preferred pathways is documented for a large number of separate flows [6-8]. The slope and roughness of the terrain the lava crossed is also known. The effusion rate and vent location are also well-constrained [9,10]. The data for Io is less complete, but applying it to an airless low-gravity body will test how general the model is.

References: [1] Baloga S. M. and Glaze L. S. (2003) *JGR*, *108*, doi:10.1029/2001JB001739. [2] Walker G. P. L. (1971) *Bull. Volc.*, *35*, 579-590. [3] Kelemen P. B. et al. (1995) *JGR*, *100*, 475-496. [4] Aharonov E. et al. (1997) *JGR*, *102*, 14821-14833. [5] comsol.com. [6] Heliker C. and Wright T. L. (1991) *Eos*, *72*, 47. [7] Heliker C. et al. (2003) *USGS Prof. Pap. 1676*, 1-28. [8] Rumpf M. E. et al. (2017) AGU Fall Meeting, V41B-07. [9] Kauahikaua J. P. et al. (1998) *JGR*, *103*, 27303-27324. [10] Kauahikaua J. P. et al. (2003) *USGS Prof. Pap. 1676*, 137-148.

Figure 2. Examples of output from COMSOL during preliminary testing. **Left:** detail of an 9 m x 8 m portion of the mesh near the vent showing how the density of nodes is incrementally reduced away from the vent. The detailed region is extended in the down-flow direction. **Right:** An example showing the advance of the lava to a distance of 15 m over 23 minutes. This is slightly slower than typical of real pahoehoe flows but is appropriate when considering that the vent pressure in the model is brought up gradually to avoid numerical instabilities The value that is plotted (effective saturation) is being used as a substitute for flow thickness in these 2D model runs.