ON THE FORMATION OF LUNAR SINUOUS RILLES: INSIGHTS FROM MULTIPHYSICS MODELING TECHNIQUES.

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Introduction: Lunar sinuous rilles are defined as troughs, typically with U-shaped topographic cross-sections, with lengths ranging from 2 to 566 km; widths from 0.16 to 4.3 km; and depths ranging from 5 to 530 m [1]. The lack of water on and in the Moon [2] requires that lunar sinuous rilles formed from flowing lava, although there is not yet a consensus as to precisely how lava shaped these rilles. Different models of formation have meaningful and distinct implications for magma generation, storage, and eventual rise to the surface. We are using COMSOL multiphysics® [3] software to constrain the behavior of lunar lavas and therefore the formation of sinuous rilles.

Background: There are many models for the formation of lunar sinuous rilles, but they can be simplified into a continuum: 1) rilles are formed through thermal and mechanical erosion [e.g., 4, 5]; or 2) through construction of lava tubes or channels [e.g., 6, 7]. Formation via thermomechanical erosion interprets the rilles as erosional channels, similar to dry river channels on Earth. Erosional mechanisms require high effusion rates, possible low viscosity lava compositions, and turbulently flowing lava to efficiently transfer lava heat into the ground [e.g., 8]. Formation via construction interprets lunar rills as drained lava channels or collapsed lava tubes, and requires steady, long-lived (weeks or months) lava flow [e.g., 9]; see Fig. 1 for how these flow regimes differ.

An erosional origin for lunar rilles therefore implies high magma supply rates to the surface, and high flow velocities throughout the eruption duration. In contrast, a constructional origin requires a lower, but steady, magma supply rate to the surface, and lower, but steady, flow velocities with few (if any) pauses in

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<th>Erosional Formation</th>
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<td>Channel Flow</td>
<td>Tube Flow</td>
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Figure 1. Computational regimes for lunar rille formation. Open channel flow in the turbulent flow regime (left) with thermal or mechanical erosion; internal (tube) flow primarily in the laminar regime (left).

Methods: We use COMSOL multiphysics® software with the computational fluid dynamics (CFD), subsurface, and heat-flow modules to calculate velocity fields and wall shear stresses as well as calculate thermal effects for Newtonian and non-Newtonian lava rheologies. Figure 2 shows a short section of Rima Marius, a 312-km-long rille averaging 600 m wide and 100 m deep [1]. Recent work [9] strongly suggests a lava tube formation, and Figure 3 shows one of several computational approaches used to model flow within the rille. Here it is shown modeled as an elliptical tube with semi-major axis of 630 m and semi-minor axis or 106 m. Boundary conditions here are no-slip walls, and periodic boundary conditions for the two cross sectional flow faces to maintain along-axis steady developed flow.

Figure 2. Section of the >300-km-long Rima Marius at 16.15°N, 213.19°W in Oceanic Procellarum. LROC image from https://quickmap.lroc.asu.edu.

Figure 3. Elliptical tube computational flow model geometry for lava tube formation model of Rima Marius.
To model rilles as erosional features, we use a 3-D channel approach (e.g. Figure 4) with no-slip walls, periodic cross-sectional area boundary conditions, and a no-shear-stress channel surface. We consider the shear stress on the channel walls for mechanical erosion capabilities, and the time-dependent propagation of heat into the substrate for thermal erosion.

**Preliminary Results and Discussion:** For tubes of the size and shape shown in Fig. 3, flow is usually laminar on low lunar slopes (<1°), although the CFD model can handle turbulence if necessary.

Figure 4 shows results for laminar channel flow simulations for four common lava rheologies: Newtonian, power-law thinning, power-law thickening, and power-law thinning plus a yield stress. All non-Newtonian rheologies inhibit the onset of turbulence, because viscosity contrasts reduce the effective hydraulic channel diameter and discourage turbulent eddy formation.

Cooling silicate lavas are not pure Newtonian fluids, so considering non-Newtonian effects on wall shear stress is appropriate. For gravity-driven channel flow at a given flow depth, transition to turbulence reduces the maximum down-flow velocity and volume flow-rate in the channel, as a portion of the flow energy is dedicated to the turbulent energy, so the turbulent flow depth would need to be deeper than the laminar one for a given volume flow rate. The local shear stress on the wall depends on the normal gradient of the tangential wall velocity. As the flow regime changes from laminar to transitional to turbulent, the effective thickness of the boundary layer from "no flow" to the highest flow velocity is significantly thinner in the turbulent flows, and thus the wall shear stress and potential for mechanical erosion is increased.

However, thermal losses from the top of an open-channel flow are large compared to the conductive losses to the walls, so open-channel flows cool significantly faster than corresponding tube-fed flows, and therefore cannot maintain a Newtonian rheology unless they are erupted at temperatures significantly above their liquidus (which is rare for terrestrial lavas). As flows scale up in size, thermal losses reflect the surface-area-to-volume ratio as well as the fraction of the flow that is crusted over or insulated. Thus, bigger tubes cool more slowly per unit length than smaller tubes of flow networks, and the cooling of channels per unit length depends on their depth-to-width ratio.

Results from modeling to date therefore suggest that rille formation from tube flow is more likely than open channel flow.