

**MODELING EFFUSIVE CRYOLAVA FLOWS: REEVALUATING FLOW EMPLACEMENT.** A. A. Morrison<sup>1,2</sup>, A. G. Whittington<sup>2</sup>, and K. L. Mitchell<sup>3</sup>, <sup>1</sup>University of Missouri, Columbia, MO, <sup>2</sup>University of Texas San Antonio, San Antonio, TX (aaron.morrison@utsa.edu), <sup>3</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

**Introduction:** Lava flow emplacement has been well studied for silicate lava. However, translating our knowledge of this process to cryogenic regimes in the outer solar system becomes complicated by factors that are not accounted for in (or important for) silicate systems. The cryovolcanic phenomenon is an interdisciplinary topic that lies at the intersection of volcanology and hydrology. By taking existing models from both disciplines, this study aims to present a new model for cryolava flow emplacement on the surface of Europa.

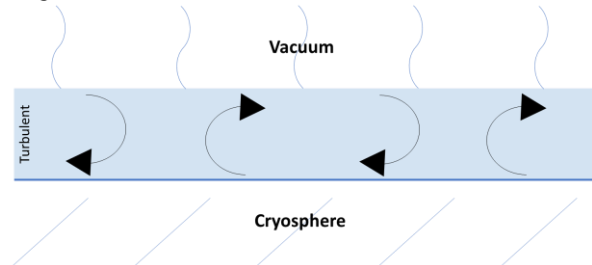
Allison and Clifford [1] modeled ice-covered water volcanism on Ganymede, using the thermal budget to assess flow evolution (i.e. thermal and physical properties, ice cover thickness as a function of time). This work is commonly cited throughout the planetary science literature when discussing the evolution of cryogenic features on various icy bodies. However, they assume (i) instantaneous flow emplacement and (ii) that a thin ice crust exists, which thickens at each temperature step. They suggest this inaccuracy is offset by the simplification of the numerical model.

Instead of making this assumption, we suggest that looking more closely at the flow evolution upon initial emplacement is warranted. Bargery and Wilson [2] modeled large flood events on Mars. The physics of flooding are fundamentally similar to that of an effusive cryolava flow. This hydrologic model provides a useful framework for a volcanic model in the context of an icy body. It also takes into account the rapid boiling in a low-pressure environment and does not rely on the same assumptions as Allison and Clifford [1].

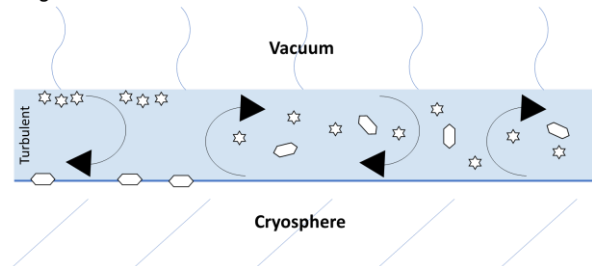
**Model:** A cryolava flow can be divided into the same four stages (Figure 1) as a Martian flood outlined in [2]. Stage 1 is the initial emplacement. The cryolava is turbulent and cools to its liquidus dominantly by boiling in the low-pressure environment. Thermomechanical erosion may take place where energy would be lost to the (partial) melting and assimilation of icy substrate. Stage 2 initiates as the cryolava begins to cool below the liquidus. The turbulence allows cooling to be uniform throughout the flow, and crystals (including eroded substrate fragments) to be entrained, forming a suspension. Stage 3 is initiated by further crystallization which acts to increase the viscosity, decrease the Reynolds number and reduce the turbulence. This is analogous to rivers when washload (i.e. particle transport near the free

surface) becomes bedload (i.e. particle transport near the base) [2]. Stage 4 is the transition to laminar flow, which will be modeled separately. Our model covers stages 1-3.

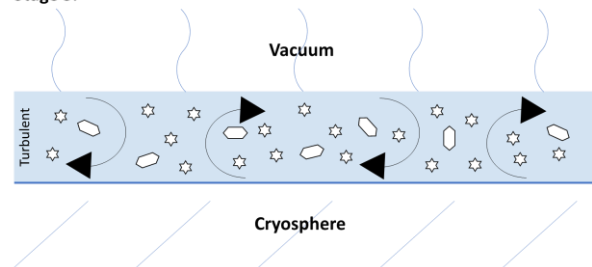
Stage 1:



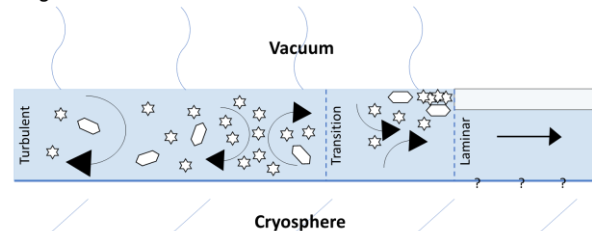
Stage 2:



Stage 3:



Stage 4:

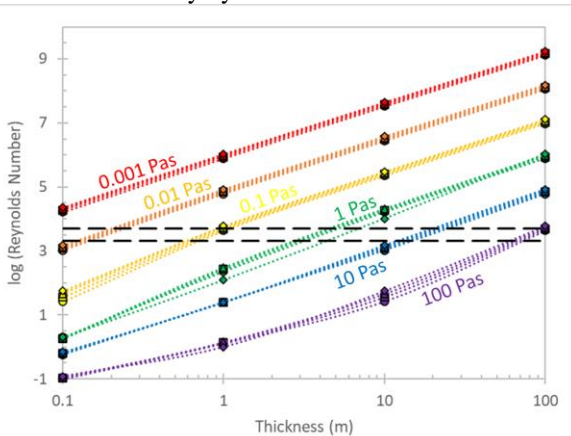


**Figure 1.** Evolution of potential cryolava flow. Stage 1 is initial emplacement and cooling to liquidus temperature, stage 2 is initiation of crystallization and thermomechanical erosion, stage 3 is increased crystallization that affects the rheology, and stage 4 is the transition to laminar flow.

One of the most important variables to track is the dimensionless Reynolds number ( $Re$ ), which defines whether a flow is turbulent (high  $Re$ ) or laminar (low  $Re$ ). The Reynolds number is defined as follows:

$$Re = \frac{4\rho uh}{\eta} \quad (1)$$

where  $\rho$  is the flow density,  $u$  is velocity,  $h$  is flow thickness, and  $\eta$  is viscosity. Figure 2 shows the Reynolds number as a function of density (symbol shape) and viscosity (color) for various flow thicknesses. The figure demonstrates that the viscosity of aqueous solutions is much more important than the density for determining the Reynolds number and flow regime, since viscosity can vary by orders of magnitude while densities vary by mere factors.



**Figure 2.** Reynolds number vs. flow thickness plot. Density is 900 (circles), 1000 (squares), 1100 (triangles), 1200 (diamonds)  $\text{kgm}^{-3}$ . Viscosity is defined by color  $10^{-3}$  (red),  $10^{-2}$  (orange),  $10^{-1}$  (yellow),  $10^0$  (green),  $10^1$  (blue),  $10^2$  (purple) Pas. Black dashed lines indicate the turbulent to laminar transition.

For an especially thick flow ( $\sim 10$  m), the viscosity would have to increase  $\sim 4$  orders of magnitude to become laminar. This would require a substantial amount of crystallization to occur, resulting in a suspension of the crystals in the initially turbulent fluid. This results in a slurry rather than a liquid flowing beneath an ever-thickening ice cover.

**Discussion:** The physical state of the flow at the end of stage 3 is the most important output of this model. The model output from stage 3 can be used as an input for a secondary model of laminar flow emplacement. How much crystallization occurs will drastically affect what happens in the laminar regime. If enough crystallization occurs that a framework (i.e. yield strength) develops, then the flow may cease and freeze in place. Or, the laminar flow regime may be punctuated by bursts of flow when pressure builds up behind the flow from continued mass flux until the yield strength is overcome resulting in short advance. Or, perhaps the

liquid is able to drain through the crystal framework forming ponds, moats around the flow front, or even secondary breakout flows akin to pahoehoe. Alternatively, the crystal content at the turbulent to laminar transition may be minor allowing efficient Stokes separation where ice rafts may develop over the flow eventually creating an insulating cover or even cryolava tube.

This is the focus of concurrent work to investigate whether cryolava tubes are feasible emplacement mechanisms. While stated casually in the literature [3,4,5], there has been no quantitative study of whether tubes can form in analogous manner to silicate lava tubes. Tube formation only occurs in the laminar flow regime since turbulence tends to disrupt the roof or crust that is required to form the tube. Therefore, understanding how the flow evolves in the turbulent flow regime and the state of the flow at the onset of the laminar regime is the first step in modeling cryolava tube formation.

Understanding the rheology of the materials used in this model will be important due to the strong control of viscosity on the state of the system. Concurrent work is being presented in another abstract on progress toward experimental determination of rheology for cooling and crystallizing aqueous solutions. Such experimental data will better constrain the microphysics involved in aqueous solution evolution. Having better constrained physical properties (e.g. viscosity as a function of crystal fraction) will provide better input data/parameters for modeling the macrophysics (e.g. flow emplacement).

What this model allows us to do is predict what the morphology of the flow will look like. Knowing the physical conditions of the flow for a given time, temperature, or distance from the vent will allow us to infer what the flow texture, albedo, and/or geometry might be. This would aid in photogeology and interpretations of features observed during upcoming missions to ocean worlds.

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**References:** [1] Allison M. L. & Clifford S. M. (1987) *JGR*, 92, 7865–7876. [2] Bargery A. S. & Wilson L. (2011) *Icarus*, 212, 520–540. [3] Carroll M. R. (2019) *Ice Worlds of the Solar System*, 69–93. [4] Furfaro R. (2010) *Plan. & Space Sci.*, 58, 761–779. [5] Kargel J. S. (2019) *Comparative Planetology with an Earth Perspective*, 101–116.