MODELING EMPLACMENT OF TURBULENT CRYOLAVA FLOWS. A. A. Morrison[1,2], A. G. Whittington[2], and K. L. Mitchell[3], [1]University of Missouri, Columbia, MO, [2]University of Texas San Antonio, San Antonio, TX (aaron.morrison@utsa.edu), [3]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 airless, icy bodies.

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, 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 includes the rapid boiling of aqueous species in a low-pressure environment and entrainment of particles in turbulent flow, neither of which are included in Allison and Clifford [1].

Model: A cryolava flow can be divided into similar stages (Figure 1) as outlined in [2]. Stage 1 is initial emplacement of a turbulent cryolava into the low-pressure environment. The cryolava cools to its liquidus dominantly by boiling and 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. 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, acting 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.

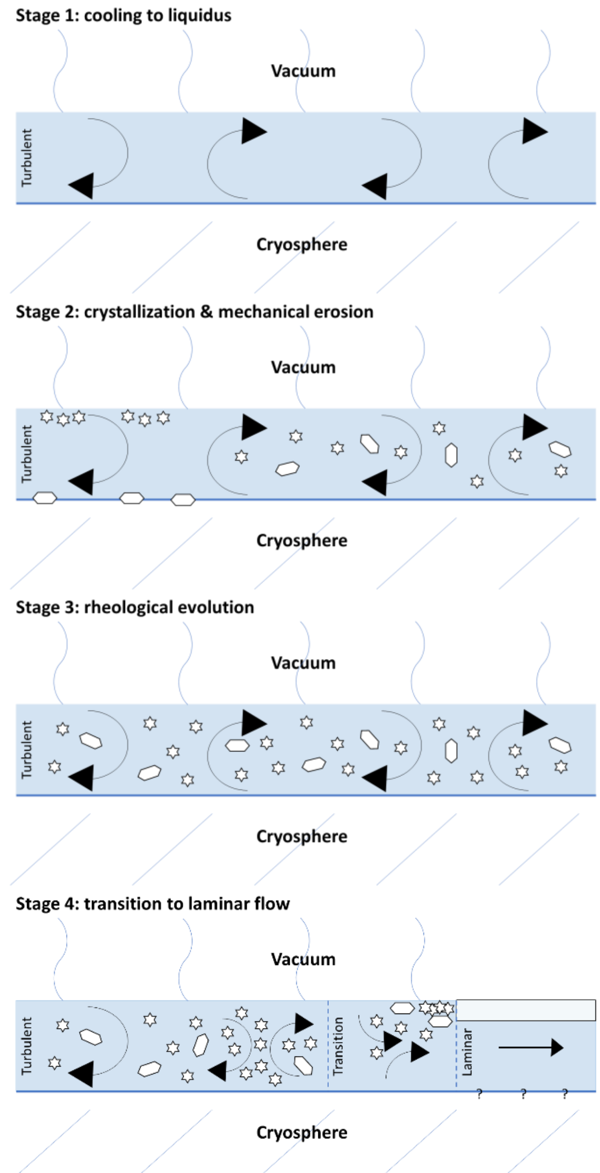

Figure 1. *Conceptual model of the evolution of a hypothetical cryolava flow. Stage 1 is initial emplacement and cooling to liquidus temperature, stage 2 is initiation of crystallization and thermomechanical erosion, stage 3 is increased crystallization that affects the rheology, and stage 4 is the transition 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:

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

where ρ is the flow density, u is velocity, h is flow thickness, and η 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.

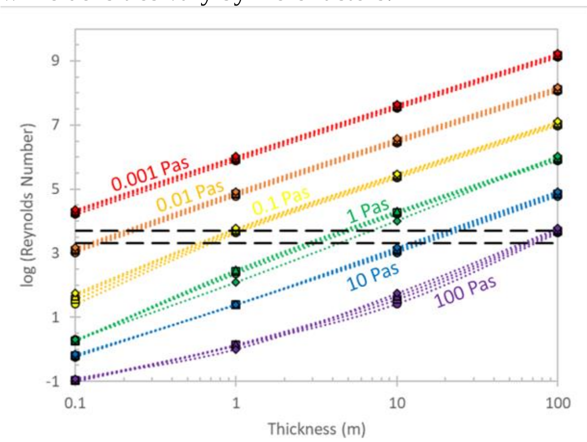

Figure 2. *Reynolds number vs. flow thickness plot. Density is 900 (circles), 1000 (squares), 1100 (triangles), 1200 (diamonds) kgm^{-3}. Viscosity is defined by color 10^{-3} (red), 10^{-2} (orange), 10^{-1} (yellow), 10^{0} (green), 10^{1} (blue), 10^{2} (purple) Pas. Black dashed lines indicate the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

For an especially thick flow (~10 m), the viscosity would have to increase ~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.

Results & Discussion: We modeled different concentrations in the H_2O-NaCl system ranging from 5-23 wt% NaCl. Each concentration was modeled at starting thicknesses of 0.1, 1, 10, and 100 m and for a Europa-like body (e.g., surface pressure, gravity). Initial model results suggested that heat loss from vaporization is the dominant heat flux (orders of magnitude larger in most scenarios). The turbulent to laminar transition occurred over a range of solid fractions between ~40-60% depending on the initial thickness chosen. This suggests that turbulence persists to high solid fractions and thus, the starting material for modeling laminar flow will look much different to that assumed in previous works [1].

The physical state of the flow at the end of stage 3 (turbulent to laminar transition) is the most important output of this model. This output from stage 3 can be used as an input for a secondary model of laminar flow emplacement (stage 4). 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 at the flow front, 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 lobes. This will be further investigated in continued modeling efforts.

This model incorporates physical, chemical, and thermal evolution of a hypothetical cryolava flow. This is an improvement over previous models that tend to focus on tracking certain parameters while others are either ignored or implicit. Knowing the physical conditions of the flow (explicitly) 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.