

RHEOLOGIC INVESTIGATION OF CRYOVOLCANIC SLURRIES: VISCOSITY OF CHLORIDE BRINES. Aaron A. Morrison¹, Alan G. Whittington¹, Fang Zhong², K. L. Mitchell², and E. M. Carey², ¹University of Missouri, Columbia, MO (aamgz8@mizzou.edu), ²Jet Propulsion Laboratory, Pasadena, CA.

Introduction: Cryovolcanic processes have been considered theoretically to explain features on many bodies throughout the outer solar system. Rheological properties of potential cryovolcanic products are fundamental in determining how features are emplaced and the morphologies that result. However, few experimental studies [1,2] have provided supporting data which covers a narrow compositional range. We are addressing this knowledge gap by conducting a rheological investigation of briny crystal-liquid suspensions likely to be erupted on icy bodies. The few previous studies measuring subliquidus viscosity are plotted in Figure 1.

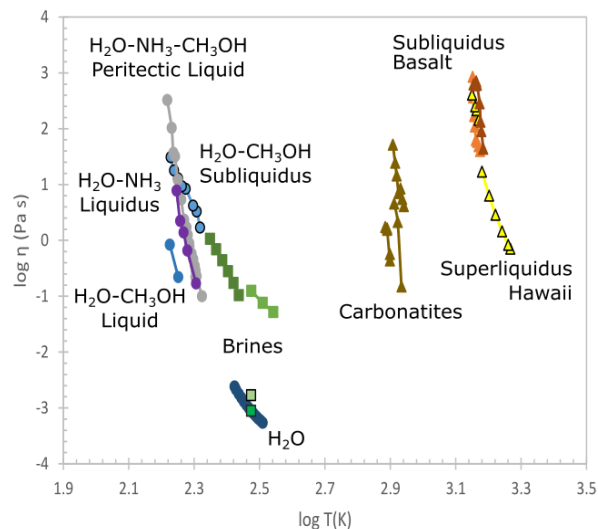


Figure 1. Viscosity data for water [3], brines [4,5], ammonia-water [1], methanol-water [1,2], ammonia-methanol-water [1], East African Rift basalts [6], Hawaiian basalt [7].

Brine compositions can be generated from an ammonia-water/ice source by partial melting, and then modified by crystal fractionation [8,9]. Cryomagmas have been interpreted to form both dome or flow features, and potential cryogenic compositions span a similar viscosity range to that of silicate lavas. Many bodies exhibit flow features/constructs and a defined rheology will allow inferences about possible compositions based on observed morphology. This would be particularly useful on bodies, like Titan, Triton, or Pluto, that have atmospheres or geysers that can cover other features in (methane) frost or ejecta complicating spectral analysis of the feature itself. Understanding

how these materials move, deform, and evolve upon crystallizing will help constrain what morphological features can form by various compositions.

The rheological data will allow comparisons to terrestrial silicates and determinations of how similarly the two kinds of materials behave. If they are, in fact, analogous to silicate systems (in terms of viscosity, flow index, yield strength, etc.), are they formed and emplaced by the same mechanisms and processes? And if not, what factors are contributing to the differences? Determining rheological properties of these cryogenic materials should allow us to answer these questions. Understanding these flows will also provide insight into the past and present evolution of various outer solar system bodies.

Methods: The H₂O-NaCl system was chosen for its simplicity, well characterized nature, and easily achievable temperature ranges. This system may also prove relevant for the cryovolcanism proposed on Ceres [10,11,12]. Solutions of 0, 5, and 15 wt% NaCl were synthesized from reagent grade NaCl powder and doubly-distilled deionized water. An Anton Paar MCR302 rheometer was used to measure viscosity in a rotational parallel plate configuration. Dynamic cooling experiments were conducted at cooling rates of 1 and 0.5 K/min under a constant shear rate of 50 s⁻¹.

Preliminary Results: Figure 2 shows the results of the dynamic cooling experiments. When pure H₂O was cooled at 1 K/min, it was able to undercool 20°C before rapid crystallization. Viscosity increases by a factor of 2 during the cooling segment (from -10°C to -20°C) before freezing. It becomes fully molten again by +7°C and viscosity drops by ~1 mPas (from ~2.4 mPas to 1.4 mPas) over the liquid range during heating. Cooling at 0.5 K/min resulted in crystallization starting at -3°C, representing a lower degree of undercooling than for the 1 K/min experiment.

The 5 wt% solution (liquidus approximately -3°C) also crystallizes near -20°C when cooled at 1 K/min. Again viscosity increased during cooling by a factor of 2. Upon heating, the solution becomes fully molten by +3°C, and its viscosity decreases from 1.4 to 0.7 mPas over the temperature range 3 to 25°C. When cooled at 0.5 K/min, the solution solidifies at -18°C. Viscosity follows a similar trend as the experiment at the faster rate. On heating, the sample becomes fully molten again at +1°C, confirming that we observe true undercooling and not simply thermal inertia.

The 15 wt% solution (liquidus at -12°C) did not fully crystallize at either cooling rate, down to -20°C . For 1 K/min, viscosity increased from 0.4 to 1.4 mPas from 25 to -20°C . At 0.5 K/min, a similar trend is observed but viscosity increased from 0.6 to 2.5 mPas, suggesting some degree of crystallization.

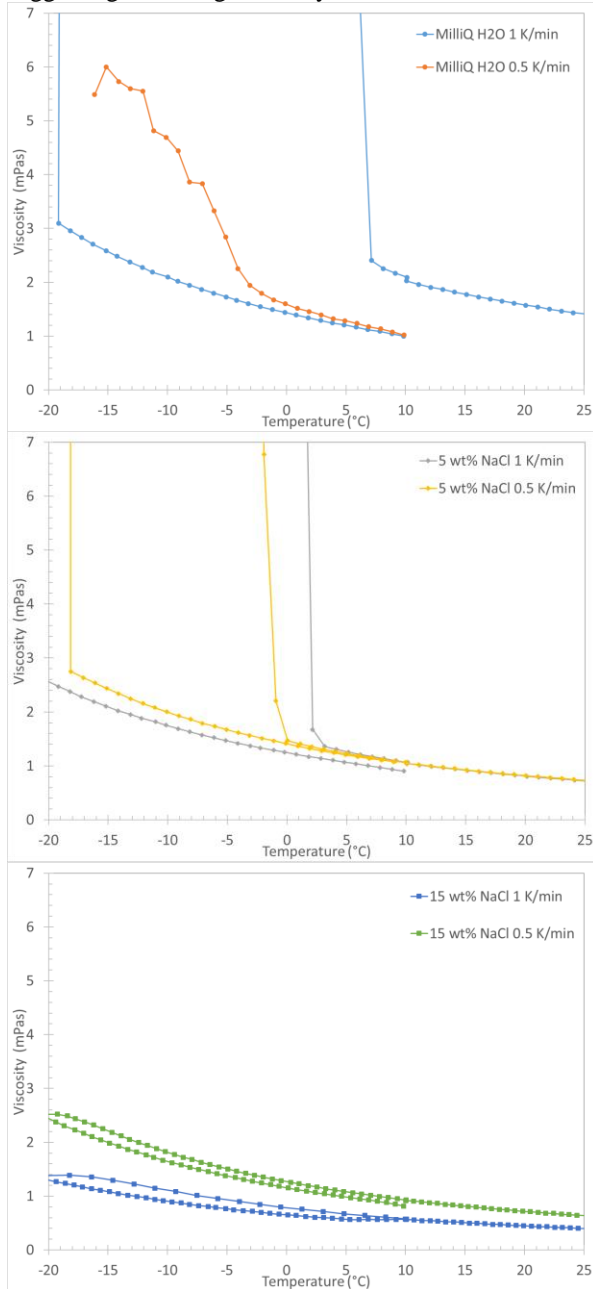


Figure 2. Viscosity data (in mPas) from dynamic cooling experiments at 1 and 0.5 K/min. 0, 5, and 15 wt% NaCl solutions were cooled from 10°C to -20°C and back up to 25°C .

Implications: Understanding how these materials move, deform, and evolve upon crystallizing will help

constrain what morphological features can form by various compositions. The rheological data will allow comparisons to terrestrial silicates and determinations of how similar the two materials behave. If they are, in fact, analogous to silicate systems (in terms of viscosity, flow index, yield strength, etc.), are they formed and emplaced by the same mechanisms and processes further strengthening their link? And if not, what factors are contributing to the difference? Determining rheologies of these cryogenic materials should allow us to answer these questions. Understanding these flows will also provide insight into how various bodies have evolved (or are evolving).

Future Work: Dynamic cooling experiments mainly provide information about the kinetics of crystallization, and the effect of temperature on viscosity. In contrast, isothermal experiments can provide more information on the effect of crystals and strain rate on viscosity. These types of experiments will also be conducted at several temperature steps to provide a more robust evaluation on how viscosity evolves during crystallization. These will also allow us to vary the strain rate at each temperature step to investigate how the viscosity is affected.

The compositional range of experiments will also be expanded. Liquid viscosities will be measured for a series of binary and ternary compositions including other aqueous chlorides (Na,K,NH₄), sulfates (Mg,K,NH₄), and carbonates (Ca,Mg,Fe). The chloride and sulfate binaries are fairly well studied above 0°C but very few data exist at lower temperatures relevant to outer solar system conditions. Rheological data will also be obtained in the subliquidus range of temperatures to investigate both the dependence of crystallization (size and shape distributions) and strain rate on viscosity.

References: [1] J. S. Kargel et al. (1991) *Icarus* 89, 93–112. [2] F. Zhong et al. (2009) *Icarus* 202, 607–619. [3] J. Kestin et al. (1978) *J. Phys. Chem. Ref. Data* 7, 941–948. [4] H. Ozbek et al. (1977) *Am. Chem. Soc. 29th Southeast Reg. Meet.* [5] H. L. Zhang et al. (1997) *J. Chem. Eng. Data* 42, 526–530. [6] A. Morrison (2016) Master's Thesis, Univ. Missouri 74. [7] A. Sehlke et al. (2014) *Bull. Volc.* 76, 876. [8] J. S. Kargel (1991) *Icarus* 94, 368–390. [9] J. S. Kargel (1995) *Earth, Moon, and Planets* 67, 101–113. [10] O. Ruesch et al. (2016) *Science* 353. [11] O. Ruesch et al. (2018) *Icarus* in press. [12] L. C. Quick et al. (2018) *Icarus* in press.

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