RHEOLOGIC INVESTIGATION OF CRYOVOLCANIC SLURRIES: VISCOSITY OF CHLORIDE AND SULFATE BRINES. Aaron A. Morrison[1], Alan G. Whittington[1], Fang Zhong[2], K. L. Mitchell[2], and E. M. Carey[2], [1]The University of Texas at San Antonio, San Antonio, TX (aaron.morrison@utsa.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Introduction: Cryovolcanism has been implicated on many icy bodies in the outer solar system to explain many of the observable surface features. Rheological properties of potential cryovolcanic products are fundamental in determining how features are emplaced and the morphologies that result. The few experimental studies [1,2] that have been conducted provide supporting data for only a narrow range of compositions. We conduct rheological experiments of briny crystal-liquid suspensions to expand the compositional range where experimental data exist to be more relevant to the variety of material that may be erupted on icy bodies. The few previous studies measuring subliquidus viscosity are plotted in Figure 1.

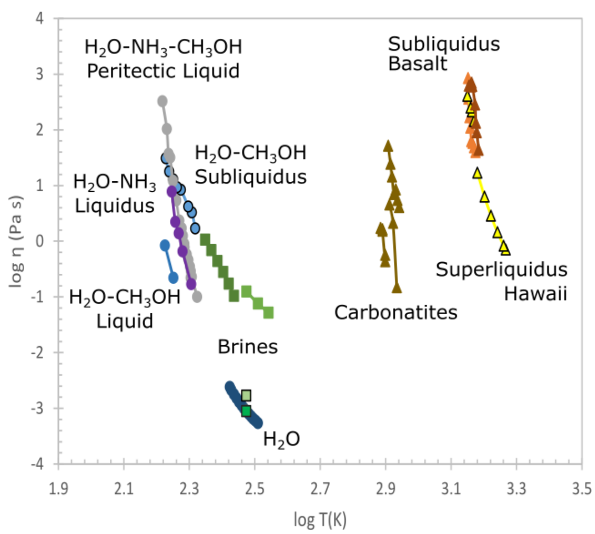


Figure 1. *Viscosity data for water [3], brines [4,5], ammonia-water [1], methanol-water [1,2], ammonia-methanol-water [1], East African Rift basalts [6], Hawaiian basalt [7].*

Generation of briny compositions can result from hydrothermal alteration in the interior or by partial melting of an ammonia-water/ice source, modified by crystal fractionation [8,9]. Figure 1 shows that cryogenic compositions span a similar viscosity range as silicate lavas allowing a range of morphologies to occur (e.g. domes or flows). Many icy bodies exhibit flow features/constructs and having a defined rheology allows inferences about possible compositions based on the observed morphology. This would be particularly useful on bodies, like Titan, Triton, or Pluto, that have atmospheres or erupted deposits that may cover or otherwise obscure other features in (e.g. 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.

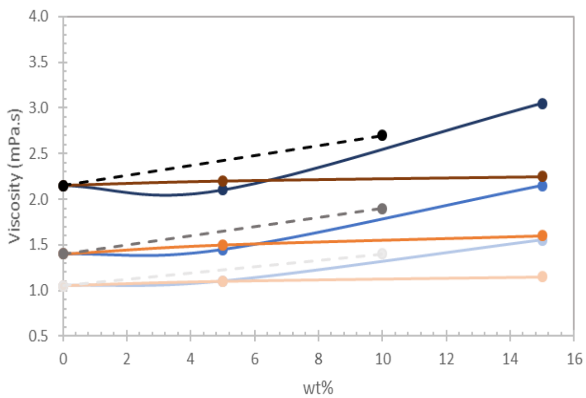
The rheological data will allow comparisons to terrestrial silicates and determinations of how similarly the two kinds of materials behave. If they are, in fact, analogous to silicate systems (in terms of viscosity, flow index, yield strength, etc.), are they formed and emplaced by the same mechanisms 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 H_2O-XCl (X = Na,K) and H_2O-YSO_4 (Y = K_2,Mg) binary systems were chosen for their simplicity, well characterized nature, and easily achievable temperature ranges. These systems may also prove relevant for the cryovolcanism proposed on Ceres and Europa [10,11,12]. Solutions of two different concentrations were synthesized from reagent grade powders and deionized water for each composition (5 and 15 wt% for XCl; 2 and 5 wt% K_2SO_4; 5 and 10 wt% $MgSO_4$). To investigate the effects of mixed cations and mixed anions, two ternary compositions were synthesized: 80-5-5 wt% H_2O-NaCl-KCl and 80-5-5 wt% H_2O-KCl-K_2SO_4. An Anton Paar MCR302 rheometer was used to measure viscosity in rotational parallel plate and cone-and-plate configurations, utilizing a Peltier plate temperature control system. Cooling experiments were conducted at rates of 2, 1, and 0.5 K/min under a constant shear rate of 50 s^{-1}. Isothermal measurements were made at intervals between room temperature and the freezing point. This represents the equilibrium case or effectively the 0 K/min cooling experiment.

Preliminary Results: Figure 2 shows the results of the cooling experiments. The non-linear evolution of viscosity as a function of temperature and concentration are clearly seen. The chlorides have a clear difference in behavior as the slope of the viscosity increases at higher NaCl concentrations, whereas, concentration seems to have little influence on the viscosity of KCl solutions. The viscosity of the mixed-salt-solution had a higher viscosity than either single solute solution. This suggests a mixed cation effect may exist, but more data is required to draw conclusions.

The differences between the sulfates are, however, less clear. Viscosities are similar up to 2 wt% where the $MgSO_4$ continues to increase while the K_2SO_4 begins to plateau. The eutectic of the K_2SO_4 system is very close to the pure water endmember and thus high concentrations will result in precipitation of the solute out of solution rather than ice crystals. The mixed anion effect between KCl and K_2SO_4 is similarly undetermined. This is exacerbated by the fact that concentration does not dramatically influence the viscosity at these dilute compositions.

The empirical model of Laliberté (2007) works well at predicting the viscosity of these and many other solute bearing solutions. However, the model has trouble extrapolating viscosity down to supercooled temperatures.



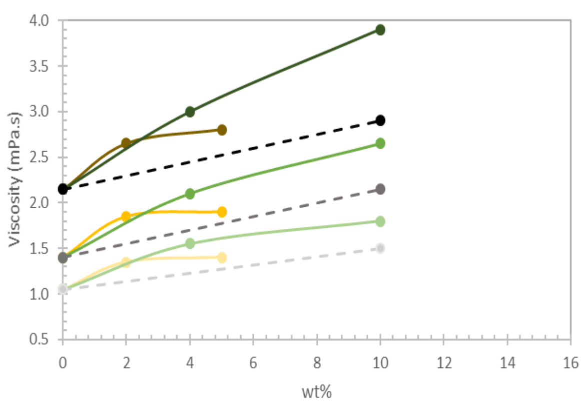


Figure 2. *Viscosity data (in mPas) from isothermal experiments at different concentrations of solutions. (top) NaCl in blue and KCl in orange. Dashed lines are viscosities of a solution with 5 wt% NaCl and 5 wt% KCl. (bottom) $MgSO_4$ in green and K_2SO_4 in yellow. Dashed lines are viscosities of a solution with 5 wt% $MgSO_4$ and 5 wt% K_2SO_4. Data is shown for 10°C (dark), 0°C (medium), and -10°C (light).*

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 (with similar rheological parameters), this may suggest they were formed and emplaced by similar processes and mechanisms. Determining rheologies of these cryogenic materials should allow fewer assumptions to be made when modeling potential flows on icy bodies. Understanding such flows will also provide insight into how the surfaces of icy bodies have evolved (or are evolving).

Future Work: 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.

The compositional range of experiments will be expanded. Liquid viscosities will be measured for varying concentrations of a series of binary and ternary compositions including: H_2O-NH_3-CH_3OH, other aqueous chlorides (Na,K,NH_4), sulfates (K,Mg,NH_4), 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.

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