VISCOSITY OF LIQUID FERRIC SULFATE SOLUTIONS AND APPLICATION TO THE FORMATION OF GULLIES ON MARS. V.F. Chevrier[1], R. Ulrich[1,2], T.S. Altheide[1], [1]Arkansas Center for Space and Planetary Science, [2]Department of Chemical Engineering, University of Arkansas, Fayetteville, AR 72701, USA; vchevrie@uark.edu.

Introduction: Almost all flow models for martian gullies to date have assumed liquids that exhibit viscosities on the order of 1 cP (10^{-3} Pa.s) such as pure water [1,2] and liquid carbon dioxide [3]. Alternatively, salt solutions have been suggested based on thermodynamic and kinetic arguments as a way to stabilize liquid water in present day martian conditions [4,5].

We have recently proposed that concentrated aqueous solutions of ferric sulfate $Fe_2(SO_4)_3$ might be a liquid under martian conditions because it has amongst the lowest eutectic temperature (205 K) of common ionic materials [6]. This paper reports on experimental measurements of the visocity of ferric sulfate solutions as a function of temperature and concentration [7]. We then use this information in a numerical flow model of a standard gully as a bridge between the composition and temperature of the brine and the fluid dynamics, to identify geomorphological characteristics that might be observed on Mars [8,9]. Specifically, in this study we estimate the flow velocity and the drag forces on boulders within the gullies for these highly viscous fluids.

Methods: Viscosity of various concentrations of $Fe_2(SO_4)_3$ brines was measured using EZ/Zahn (ASTM) Dip Viscosity Cups (#1 – 5). These cups were filled with ferric sulfate brines and the time for the solution to drain through a calibrated hole in the bottom was measured. Empirical equations produced by the manufacturer were used to determine the viscosity from the drain time.

Results: The viscosity of ionic solutions increases with higher concentrations and lower temperatures (Fig. 1). Values range from 7.0 10^{-3} Pa.s for 38.8 wt% at 285 K to 4.6 Pa.s for 58.2 wt% at 260 K. The total error on the final dynamic viscosity was estimated to be approximately 10%.

To determine the dependency of viscosity on concentration and temperature, we used an extended version of the usual Arrhenius-type law. Fitting the dependency of our data, we obtain the following semi-empirical equation:

$$\mu = \exp\left[aC^{b}\right]\exp\left[\frac{\Delta E}{R}\left(\frac{1}{273.15}-\frac{1}{T}\right)\right] \qquad (1)$$

where μ is the viscosity in Pa.s, C the concentration in kg kg^{-1}, T the temperature of the fluid in K, ΔE the activation energy in J, R the ideal gas constant (8.314), and a and b are empirical constants (Fig. 1B). This equation is used to model the behaviour of fluids under martian conditions (Fig. 1).

Modeling: The gully modeled is V-shaped with a 60° bottom angle, a 15° slope, and an average roughness of 0.1 m (Fig. 2A,B). The independent variables are kinematic viscosity (10^{-6} to 10^{-2} m^2/s, corresponding to water densities of 1 to 10,000 cP) and depth of liquid in the gully (1 to 5 m). Gravity is 3.73 m/s^2 and the flow is uniform and steady.

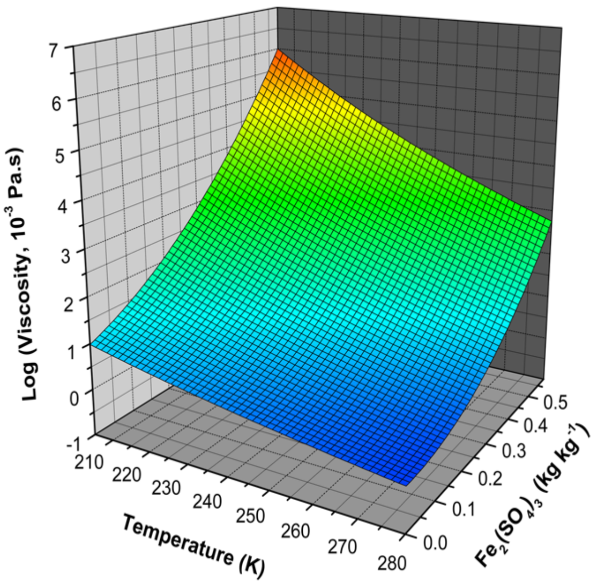

Figure 1. 3D view of viscosity data of $Fe_2(SO_4)_3$ as a function of concentration and temperature, calculated using eq. (1). This equation was determined from experimental data. Ferric sulfate solutions exhibit viscosities up to 6 orders of magnitude higher than pure water at 273 K.

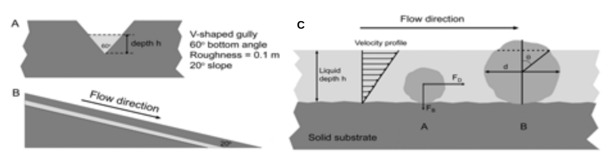

Figure 2. Schemes of the gully model used in this study. **A**. Front view. **B**. Side view. **C**. Boulder displacement with the two cases where the boulder is below or above the surface of the liquid.

We used a general Bernoulli energy balance relating potential energy supplied by the 15° slope to energy dissipated by friction against the wetted perimeter. Three regimes are observed: at low temperature, laminar flow dominates, and the velocity is strongly dependent on the viscosity, at higher temperature, turbulent flow is observed, with constant velocity around 8.5 m s^{-1} (Fig. 3). The transition regime shows a strong increase of velocity, up to 14 m s^{-1}. In regions of turbulence, at high T and low viscosity, the flowrate is a very weak function of viscosity. Indeed, at high Reynolds number, above 10^5, faster flow only amplifies the random eddy motion without changing its scale.

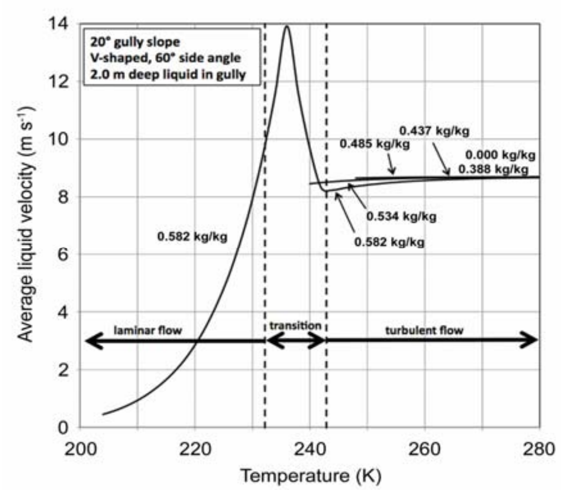

Figure 3. Results of numerical modeling of flow velocity as a function of temperature and concentration in the typical gully described by our model.

Drag Forces on Boulders: Viscous flows tend to remove smaller-sized rocks because of their high surface area to volume ratio. Drag force depends on surface area and weight on volume. Our flow model is used to estimate the force that these flows would impart on a boulder. To a first order, if neglecting the friction forces between the boulder and the gully floor, the limit of boulder displacement may be defined as the equilibrium between the weight force F_B and the drag force F_D (if $F_D > F_B$, then the boulder moves). This amounts to a rolling resistance, F_B/F_D, of one. The two forces are:

$$F_B = \left(\frac{\pi}{6}d^3\right)(\rho_b - \rho_f)g \quad \text{and} \quad F_D = \frac{1}{2}\rho_f C_D\left(\frac{\pi}{4}d^2\right)V^2$$

The boulder density (ρ_b) is 3000 kg m^{-3}. The dependency of the solution density (ρ_f) with concentration was empirically determined from experimental measurements as correlated with the ARrhenius-type equation. The drag coefficient (C_D) is a function of the boulder's Reynolds number. Then the two forces are set equal and numerically solved for the diameter *d*.

Results show that most of the flow occurs in turbulent conditions (green), where the boulder limit size is constant at 3 m (Fig. 3). The transition zone appears at low temperature and high concentrations (around 230 K and 0.45-0.5 kg kg^{-1}) in red, where high velocities move boulders up to 4 m (Fig. 3). The laminar regime occurs only at very low temperatures, close to the eutectic (red to green to blue), and is characterized by overall much lower boulder sizes (down to ~0.5 m).

Conclusions: MRO-HiRISE observations have shown that boulders with sizes ranging from 0.5 to 3 m are more abundant in gullies than in the surrounding terrains [10], suggesting that smaller size objects have been removed. The results of our model are consistent with this observation, since our size limit is 3 m for the greatest part of the flow space in the turbulent regime. The fact that abundant boulders of lower size are found in gullies suggest that low-velocity laminar flows are also occurring, which is once again supported by other observations [9]. Ferric sulfate solutions provide an excellent analogue for brines and visous fluids in general, due to the large range of viscosities covered. Yet, the very reduced field of temperature and concentration to reach very high viscosities suggests that the liquid phase probably contain a large amount of debris.

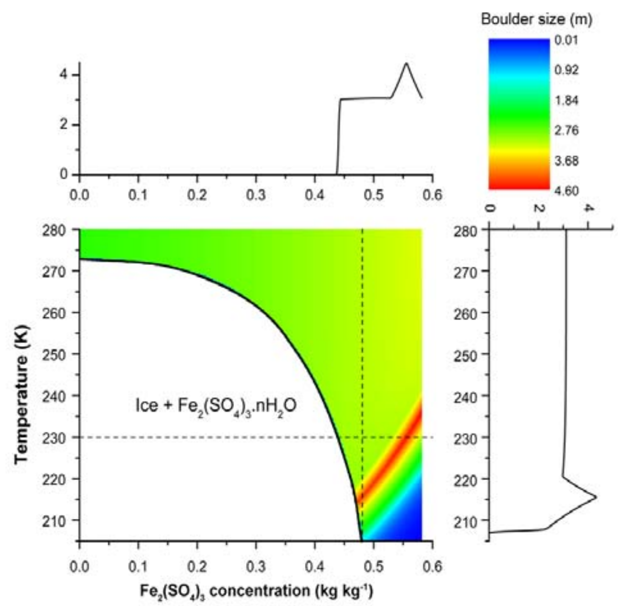

Figure 4. Results of numerical model determining the boulder size threshold for flow-induced displacement. The legend for the colour map is in the top right corner. In the white area, ferric sulfate brine is frozen. The thick black line is the liquidus line: from 273.15 K for pure water (*C* = 0) to ~205 K for saturated ferric sulfate solution (*C* = 0.48 kg kg^{-1}).

References: [1] Costard F. et al. (2002) *Science* 295, 110–113. [2] Heldmann J. L., M. T. Mellon (2004) *Icarus* 168, 285-304. [3] Musselwhite D. S. et al. (2001) *Geophys. Res. Lett.* 28, 1283-1285. [4] Brass G. W. (1980) *Icarus* 42, 20-28. [5] Sears D. W. G., J. D. Chittenden (2005) *Geophys. Res. Lett.* 32. [6] Chevrier V., T. S. Altheide (2008) *Geophys. Res. Lett.* 35. [7] Chevrier V. et al. (2009) *J. Geophys. Res.* In press. [8] Coleman K. A. et al. (2008) *Planet. Space Sci.* In press. [9] Mangold N. et al. (2003) *J. Geophys. Res.* 108, #5027. [10] McEwen A. S. et al. (2007) *Science* 317, 1706-1709.