

STEADY-STATE CREEP RESPONSE OF ICE-I/MAGNESIUM SULFATE HYDRATE. C. McCarthy¹, D. L. Goldsby¹, R. F. Cooper¹, S. H. Kirby², and W. B. Durham³, ¹Brown University, Dept. of Geological Sciences Providence, RI 02912 (contact: christine_mccarthy@brown.edu), ²U.S. Geological Survey, 345 Middlefield Rd. Menlo Park, CA, 94025, ³M.I.T., 77 Massachusetts Ave., Cambridge, MA 01239.

Introduction: As our knowledge about the icy moons of the outer solar system improves, ever more questions arise with regards to the nature of active tectonics in the icy shells, and the diversity of their surface expressions. One of the factors that may help explain the morphological diversity is the influence on rheology of the abundant cryominerals that are present in addition to water ice on many of these icy bodies. To date, very little is known about how the presence of secondary minerals affects the physical properties of ice. This work is part of an ongoing experimental investigation into the phase morphology and deformation behavior of several multiphase, ice-rich systems of interest to outer-planet study. In particular, we are examining ice/salt-hydrate binary systems with emphasis on some of the highly hydrated sulfates suggested by Galileo's Near-Infrared Mapping Spectrometer[1] and by laboratory[2] and theoretical studies[3]. Here we present a preliminary flow law for two-phase aggregates of Ice-I and MgSO₄·11H₂O ("MS11") deforming in steady-state that shows the relationship between differential stress σ , strain rate $\dot{\epsilon}$, and temperature T.

Methods: Specimens in this study were prepared via crystallization from a homogeneous binary liquid solution; the protocol is described in detail in Ref. [4]. The approach produces two-phase solids intended to mimic material likely found at the base of the crust, in a crack system if rupture additionally involves upwelling of brine, or in any region experiencing catastrophic melting and subsequent solidification. The eutectic microstructure that results from the solidification reaction of system H₂O-MgSO₄ consists of regular and complex lamellae of MS11 (undecahydrate)[5] and Ice-I (Fig. 1) and can be predicted from the volume fraction of the phase having the highest partial molar entropy of solution and from the magnitude of that entropy[4].

Compressional creep tests were performed at three temperatures (230, 240, and 250K) using both a high-pressure apparatus (N₂ confining medium, P = 50 MPa) and a 1 atm, dead-weight apparatus [6]. In both settings, fully dense cylinders were deformed at constant load in uniaxial compression. The two data sets can be compared by incorporating an activation volume, V*, into the Dorn, or "power-law," model of creep, i.e.:

$$\dot{\epsilon} = A\sigma^n \exp\left[\frac{-(E^* + PV^*)}{RT}\right],$$

where R is the gas constant, n the stress exponent, E^* the activation enthalpy and A a factor associated with aspects of microstructure, chemical potentials and geometry. (For example, where grain size, d , also effects the relationship, the term can be expressed as $A = A'd^{-p}$). In this case, lacking knowledge of the effect of pressure on the effective viscosity of the MS11 phase, we simply used the published activation volume for water ice ($V^* = -13 \text{ cm}^3 \text{ mol}^{-1}$) [7].

Results: The data at various temperatures are plotted as strain-rate vs. stress in Fig. 2. The steady-state creep results show that the eutectic aggregates have an effective viscosity that is at least an order of magnitude greater than that of polycrystalline ice-I at the same conditions.[8] We attribute this increase in strength to the unique microstructure of the eutectic material. The heterophase boundaries are found to be effective barriers to dislocation motion and thus influence the mechanism by which deformation occurs. Three separate creep regimes can be identified in Fig. 2. At the highest stress, and so far only obtainable in the high-pressure apparatus, is flow characterized by a stress exponent of $n = 6 \pm 0.3$. At intermediate stresses, a creep regime is observed that is characterized by $n = 3-4$. The activation enthalpy calculated for this regime is 91.6 kJ mol^{-1} . These two regimes are consistent with the steady-state response of materials exhibiting a lamellar eutectic morphology.[9] In such materials, two parallel mechanisms are believed to be acting in the regions, both dominated by dislocation motion. The high stress regime is associated with dislocation viscous glide and the intermediate stress regime with dislocation climb.[10] Finally, a low stress ($< 2 \text{ MPa}$) regime is identified, with $n = 1-2$ and an activation enthalpy of 52.6 kJ mol^{-1} . Diffusion creep likely dominates such a regime. The ratio of activation enthalpies for the intermediate and low stress regimes is consistent with that predicted for water ice, with one difference: whereas no diffusion creep mechanism has been observed experimentally for water ice, one has been detected here with the eutectic aggregates. Again, the heterophase boundaries likely play a large role in the process. A study of eutectic Sn-Pb by [11] reports a low stress mechanism in which Coble creep is rate

limited not by diffusion of vacancies but by the emission and absorption of dislocations in the heterophase boundaries. Further experimental data is needed for the system $\text{H}_2\text{O}-\text{MgSO}_4$, as well as a detailed microstructural analysis before we can definitively say which mechanisms are acting. Not discussed here are the effects of grain size, or more accurately colony size and lamellar spacing, which effects we plan to explore shortly using a misting and high-temperature annealing process.

Conclusions: The mechanical behavior of the ice-I/MS11 aggregate shows a rheology distinctly different from single-phase ice. The flow laws here offer additional parameters to be considered in the tectonic modeling of Europa and other icy moons.

References: [1] McCord, T. B. et al. (1998) *Science*, 280, 1242-1244. [2] Dalton, J. B. et al. (2005) *Icarus*, 177, 472-490. [3] Kargel, J. S. (1991) *Icarus*, 94, 368-390. [4] McCarthy, C. et al. (2007) *American Mineralogist*, in press. [5] Peterson R. C. and Wang, R. (2006) *Geology*, 34:11, 957-960. [6] Goldsby D. L. and Kohlstedt, D. L. (2001) *JGR*, 106:B6, 11,017-11,030. [7] Durham, W. B. et al. (1997) *JGR*, 102:E7, 16,293-16,302. [8] McCarthy, C. et al. (2007) *LPSC XXXVIII*, #2429. [9] Bang, W. H. et al. (2005) *J. Elec. Mat.*, 34:10, 1287-1300. [10] Darveaux, R. (1992) *IEEE Trans.* 15:6, 1013-1024. [11] Schneibel, J. H. and Hazzledine, P. M. (1983) *J. Mat. Sci.* 18, 562-570.

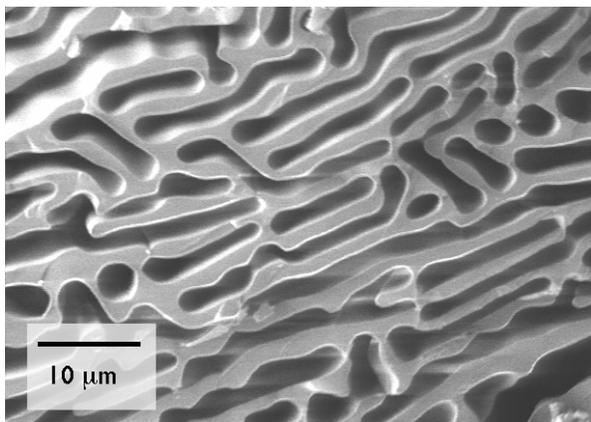


Figure 1: CSEM secondary electron image of fresh fracture surface of system $\text{H}_2\text{O}-\text{MgSO}_4$. Although the composition here slightly off eutectic (19.5wt% vs. $C_E = 17.3\text{wt}\%$), the observed microstructure shows the lamellar and complex morphology that is representative of this system. In the image, the hydrate phase stands in relief while the ice phase is recessed due to sublimation.

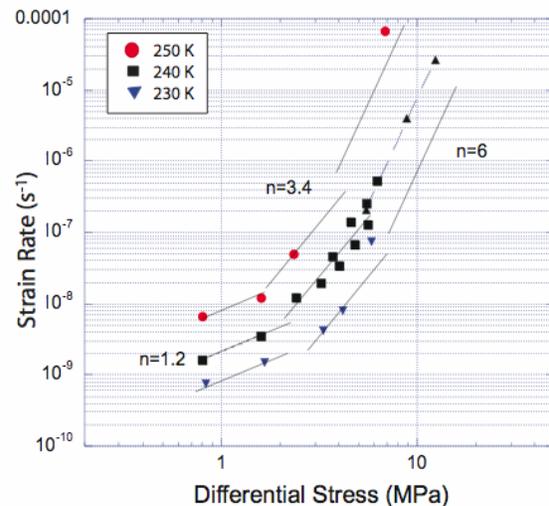


Figure 2: Log-log plot of strain-rate versus stress for eutectic ice-I/MS11 aggregates at various temperatures. The triangles and one high stress point for 250 K are high pressure data that have been normalized from a confining pressure of 50 MPa to atmospheric pressure using an activation volume of $-13 \text{ cm}^3/\text{mol}$. Stress exponent values have been obtained from the 240 K data and transcribed to the 230 K and 250 K data.