ICE/HYDRATE EUTECTICS: THE IMPLICATIONS OF MICROSTRUCTURE AND RHEOLOGY ON A MULTI-PHASE EUROPAN CRUST.  C. McCarthy1, R. F. Cooper1, S. H. Kirby2 and W. B. Durham3, 1Brown University Geological Sciences, Box 1846, Providence, RI 02912, christine_mccarthy@brown.edu, 2U.S. Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025, 3U.C. Lawrence Livermore National Laboratory, Livermore, CA 94450

Introduction: Galileo’s Near-Infrared Mapping Spectrometer observed distorted and asymmetric water absorption bands suggestive of H2O in a physical state other than crystalline ice on the surface of Europa.[1,2] The microstructure and related mechanical response of the crust, then, is dependent not on just pure ice, but more likely on a polyphase aggregate of ice and (a) non-ice phase(s). Laboratory spectroscopy studies and thermochemical models based on chondritic abundances point to several possible candidates for the non-ice component [1,2,3,4]. We present part of our ongoing investigation into the phase morphology and deformation behavior on two binary ice-salt hydrate systems that are likely volumetrically important on Europa: H2O-Na2SO4 and H2O-MgSO4. In both cases, the aggregates are characterized by a eutectic solidification/melting reaction.

Methods: The samples in this study were solidified from a homogeneous liquid solution. Compositions corresponding to a system’s stable or metastable eutectic (Fig. 1) were immersed in a cryobath that was calibrated so as to monitor heat release upon crystallization; the method allowed quantification of phase growth rate during solidification. Temperature cycling about the eutectic was implemented to promote growth of stable phases [5]. Microstructural analysis was performed using images obtained from Cryogenic Scanning Electron Microscopy (CSEM). Compressional creep tests (240 ≤ T(K) ≤ 250; 2.7 ≤ σ(MPa) ≤ 12.7) were carried out in an apparatus employing gaseous N2 (P = 50MPa) as the confining medium; specimens (fully-dense cylinders 25-mm dia., 66-mm long) were jacketed in In (250-μm thick) to separate them from the pressurized gas. Two samples in the system H2O-Na2SO4 and three in the system H2O-MgSO4 were tested.

Eutectic microstructure: All samples grown from solution exhibited classical eutectic microstructures, that is, the solids consist of “colonies” of a fine, ordered intergrowth of two phases; colonies impinge upon one another as they grow, forming colony boundaries. We found that the pattern, or morphology, the intergrowth takes within a colony is unique to each ice/sulfate system, regardless of its bulk composition. As nominally identical structures have been long identified in metallurgy, we borrow their terminology[6] in stating that (i) the H2O-Na2SO4 system forms a “broken lamellar” structure and (ii) H2O-MgSO4 system forms a “complex regular lamellar” structure. The broken lamellar morphology is characterized by uniform blade-like mirabilite (Na2SO4•10H2O) arranged in roughly parallel columns within a water ice matrix (Fig. 2a). The complex regular structure seen in the system H2O-MgSO4 involves an interconnected maze-like structure with dispersed regions of aligned plates, or lamellae (Fig. 2b); both the stable eutectic phase, MgSO4•12H2O (“MS12”) and the metastable eutectic phase MgSO4•7H2O (“MS7”; epsomite) exhibited this microstructure, differing only in scale.

Mechanical response: The mechanical response of the polyphase aggregates can be characterized by the Dorn or “power-law” model, in which the steady-state strain rate is thermally activated and a non-linear function of stress, i.e.,
\[ \dot{\varepsilon} \propto \sigma^n \exp(-E_a / R T) \]
where \( E_a \) is the activation energy (which is a function of pressure) and \( n \) is the stress exponent [7]. \( n \) is, in part, an indicator of the deformation mechanism and can be discerned by plotting differential stress v. strain rate on a log-log plot. In the ice-mirabilite aggregates, the volume fraction of mirabilite is 0.06. Consistent with the behavior of polyphase metals, the mechanical response of such an aggregate is dominated by the phase in abundance, that is, both samples in the H2O-Na2SO4 system behaved all-but-identically to pure ice. The volume fraction of hydrate in system H2O-MgSO4, however, is 0.36 for the ice-MS12 aggregates and 0.27 for the (metastable) ice-MS7 aggregates. We found that all three H2O-MgSO4 samples required higher stresses than does ice I to achieve the same strain rate, i.e. they were notably stronger (Fig. 3). Additionally, we found these samples achieved a stress exponent of \( n = 6 \pm 0.3 \). Whether this value is evidence of a deformation mechanism not previously seen in pure ice, or is a case of power-law breakdown is unclear. Additional investigation is ongoing.

Implications: Based on our observations, we feel that if any or all of the crust on Europa formed via crystallization from a brine, then use of viscosity models for pure ice in tectonic modeling/analysis is questionable. The nature of the eutectic
microstructure in the systems presented here, as well as in most other water-hydrate eutectic systems considered, is that the stronger hydrate phase forms a continuous or near-continuous network (i.e., it exceeds the percolation threshold) throughout the aggregate. With systems that have significant volume fractions of salts at their eutectic, this means an increase in strength. Further, eutectic metal aggregates, despite demonstrating strength increases, demonstrate, too, enhanced attenuation—notably greater than that anticipated from the creep behavior: phase boundaries are potent dissipaters of mechanical energy [8]. Our continuing research focuses, in part, on the role such phase boundaries play in dissipation processes as anticipated, e.g., from tidal loading.


Figure 1: Equilibrium phase diagrams for the systems (a) H₂O-Na₂SO₄ and (b) H₂O-MgSO₄ at 1 atm.

Figure 2: CSEM secondary electron images showing (a) “broken lamellar” microstructure in the system H₂O-Na₂SO₄ and (b) “complex regular” in system H₂O-MgSO₄. In both images, the hydrate stands in relief against the darker, mottled ice phase.

Figure 3: Results from creep tests for three samples of system H₂O-MgSO₄. Samples 3 and 5 were prepared using temperature cycling to ensure formation of MS12. In that sample 4—which was not cycled- plots to the right suggests that the MS7 phase is stronger than MS12.