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Semi-brittle behavior of a multi-phase crust and its influence on the tectonics of icy satellites

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Our ability to observe and interpret reasonably the tectonics of icy satellites hinges on our understanding of the viscoelastic and plastic rheologies and microstructural evolution of the material comprising their icy outer shells. The morphological diversity observed on the surfaces of the satellites may be due in part to the rheological influence of the various cryominerals that are present in addition to water ice on many of these icy bodies. Our experimental investigation explores the affects of secondary minerals on the phase behavior and physical properties (both plastic and anelastic) of ice at conditions approaching those of the icy satellites. Using uniaxial compression creep experiments (T = 230–250K; P = 0.1 and 50 MPa), we characterize the transient and steady-state deformation behaviors of eutectic aggregates (made via crystallization of liquid solution) of ice-I and MgSO4•11H2O ("MS11"; meridianiite) and compare them to the deformation behaviors of pure polycrystalline ice-I tested at the same conditions on the same apparatus. The ice/hydrate aggregates display a higher sensitivity to stress than does pure polycrystalline ice at the same conditions. One significant role that the second phase plays in ductile deformation is to pin grain growth, keeping grain sizes small and deformation within the grain/colony size sensitive creep regime. The mechanical and microstructural observations from this study indicate that the hydrate phase, which is distinctly stronger than pure ice, additionally offers a framework of support that resists ductile deformation at low stresses; the aggregates display at least an order of magnitude higher effective viscosity than do samples of pure polycrystalline ice at the same conditions up to 6MPa. At higher stresses, however, the hydrate phase promotes semi-brittle flow and cavitation, both of which are forms of strain weakening. Semi-brittle flow in the icy shell of a planetary body would decrease the depth to the brittle-ductile transition by 55% and reduce the strength in both the plastic and the brittle regimes, thereby blunting the ends of a lithospheric strength envelope, effectively reducing the failure limit for contractional surface features from 10MPa to ∼6MPa. Our study thus provides a potential explanation for zones of weakness, such as folds and buckling, observed in the crusts of icy satellites. We have derived a constitutive equation for the eutectic aggregates that includes eutectic-colony boundary sliding, intracolony flow and cavitation. The stress-strain relationships we have obtained will improve our understanding of tectonics and surface features on icy moons of the outer solar system.