Advancing Understanding of Ice Rheology Via X-Ray Beamline Studies

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Abstract - Knowledge of the rheological behavior of ice I and its high-pressure polymorphs is fundamental for understanding a variety of large-scale geophysical phenomena, from the flow and fracture of glaciers and ice sheets to the internal dynamics of large icy planetary bodies. While fundamental progress has been made in understanding the flow of terrestrial and planetary ice bodies via laboratory experiments on ice I, the rheological behavior of the high-pressure ice polymorphs, with implications for the dynamics of icy planetary interiors, is comparatively poorly known. Phase relationships between the many high-pressure phases of ice are known from hydrostatic experiments using the diamond anvil cell (DAC); however, the rheological behaviors of such phases, which require the application of a differential stresses at very high pressures to study, are not well known. To fill these knowledge gaps, we outline future research directions in which fundamental and likely transformational progress can be made in understanding the rheological behavior of ice I and its high-pressure phases using the deformation-DIA (D-DIA) apparatus on the x-ray beamline. In addition, we describe our vision for studying the effects of partial melting and melt topology on the permeability structure and flow behavior of ice, which can be applied, for example, to shearing ice stream margins, which exert primary control on mass loss from the ice sheets. Lastly, we describe studies of partially molten cryomaterials other than water ice that could be enabled by x-ray beamline technology.

The rheological behavior of ice and its high-pressure polymorphs

Phase relationships amongst the high-pressure polymorphs of ice have been established under hydrostatic pressures in the diamond anvil cell and other apparatus (REFS). Studies of the rheological behavior of these high-pressure phases are relatively sparse, however, as they require the application of a differential stress at very high pressure, a capability not available in most existing deformation apparatus. Limited studies of the flow behavior of ice II, III, V and VI have been obtained using a cryogenic high-pressure gas apparatus (many Durham REFS); however, more detailed studies of the rheological behavior of some of these ice phases, particularly at lower temperatures, are precluded by the inability to apply enough confining pressure to suppress fracturing during deformation.

As shown in Figure 1, however, many of the high-pressure polymorphs of ice exist in ranges of pressure that are accessible in the D-DIA apparatus on the x-ray beamline. The D-DIA apparatus is currently configured for ambient to elevated temperatures obtained by resistance heating of a furnace around the samples. D-DIA experiments on ice VII were conducted in this temperature range by Kubo et al. (20XX; 20YY), using Teflon-encapsulated charges of water, which became ice VII on pressurization of water at room temperature. Temperatures of up to X deg C were then applied to the solid samples, and they were deformed. Innovations that would allow the cooling of samples in the D-DIA would allow us to study ice VII and VIII, and perhaps ice XV, over a broad range of temperature.

The advantages of conducting deformation experiments on high-pressure phases of ice in the D-DIA apparatus are manifold and allow for unique studies of rheological behavior. First, as noted above, the broad ranges of pressures, and, with modification, temperatures available in the D-DIA would allow us to access ice phases VII and VIII, and perhaps XV, at conditions unobtainable in the high-pressure gas apparatus. Second, x-ray diffraction allows us to monitor in real-time the various ice phase transitions, and quantify the kinetics of phase transformation. Third, the existing ability to apply a sinusoidal load to the samples in the D-DIA, and to simultaneously measure the sample strain using XRD, allows for studies of attenuation in ice in both linear viscoelastic and non-linear viscoelastic regimes, the former to understand, for example, the influence of tidal heating of icy satellites on their internal evolution, and the latter to understand tidal heating on icy exoplanets with highly eccentric orbits. Finally, the existing ability to cycle either the temperature or pressure across a phase boundary allows us to study transformation plasticity of ice, a proposed mechanism of rheological weakening in Earth's interior, and by extension large icy satellites. Such experiments are currently being conducted on beamline 6BMB at Argonne on olivine and other minerals, and could be extended to experiments on ice.

The permeability and rheological behavior of partially molten ices

Shear deformation of ice in the margins of ice streams, the boundaries between grounded bounding ice and ungrounded ice streams, exerts a primary control on mass loss from the ice sheets (REFS). Much recent theoretical work has focused on melting in ice stream margins due to shear heating, with negatively buoyant melt percolating to the ice stream bed and facilitating ice stream motion (Rice and company). The permeability of partially molten ice is unknown, as is the extent to which water in 3-grain and 4-grain junctions in ice may form so-called "melt bands", features which have been observed, for example, in olivine-basalt aggregates deformed in simple shear (DLK and company), the dominant state of stress in ice stream margins. The presence of such bands could result in highly anisotropic permeability in the ice within the margin, and facilitate or retard the flow of water to the ice stream bed. The presence of such melt bands is also expected to significantly influence the rheology of the marginal ice and enhance its flow behavior (REFS).

More broadly, the development of anisotropic permeability in other cryogenic materials, such as sodium chloride-water ice (REF?) and ammonia-water ice (Goldsby REF), could have profound influences on melt transport and rheological behavior, which may facilitate, for example, resurfacing processes in icy satellites. The development of melt bands in shearing ice may also serve as an analogue for the formation of melt bands in other non-icy material systems.

The x-ray beamline appears to be an ideal way to explore melting and the evolution of melt geometry in ice, given the ability to image the melt geometry in situ with x-rays. LOTS OF QUESTIONS HERE - IS THERE ENOUGH PHASE CONTRAST FOR THIS? IF NOT, CAN THE MELT BE DOPED WITH SOMETHING? The dihedral angle for partially melted pure water ice is about 20 deg (REF), such that melt forms a percolating network along 3- and 4-grain junctions. We envision that the melt topology in samples of water ice could be studied initially in undeforming samples on the x-ray beamline, in a cold chamber to maintain the samples close to their melting point. The evolution of the melt geometry with deformation could then be studied by deforming samples in simple shear in a 1-atm torsional deformation apparatus designed for the beamline. If necessary to prevent fracturing, samples could also be deformed in a comparatively low-pressure gas apparatus designed for the beamline. By imaging samples during deformation, the evolution of the melt geometry could be studied as a function of shear strain. One key addressable question would be, Is there a rheologically critical melt fraction below which ice effectively loses its strength? (REF). The placement of thermistors within the deforming ice would allow us to simultaneously ascertain the effects of shear heating on melting. With a carefully designed deformation apparatus, we also envision being able to simultaneously measure the permeability of the samples as the microstructures of the samples evolve with deformation.

We note that melting in pure water ice may be difficult to control at temperatures near the melting point. A way around this problem is to conduct experiments in the eutectic NaCl-water ice system, which allows for a fixed melt fraction as a function of temperature below the normal melting temperature of pure-water ice (REFs). Conducting experiments in the NaCl-water ice system may also be more relevant for icy satellites like Europa (REFS?). Another planetologically interesting and possibly relevant material is ammonia-water ice. Partially molten ammonia-water ice has long been considered as an attractive resurfacing agent on icy satellites, as it becomes partially molten and rheologically weak above a peritectic temperature of ~-100 deg C (Goldsby REF; Durham REF). Like the NaCl-water ice system, the ammonia-water ice system exhibits a fixed melt fraction at a given temperature. However, the lower temperatures required for ammonia-water ice compared to water ice and NaCl-bearing ice would require a more sophisticated cooling system for the D-DIA apparatus.