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FLOW AND FRACTURE OF ICE AND ICE MIXTURES

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Frozen volatiles make up an important volume fraction of the low-density moons of the outer solar system. Understanding the tectonic history of the surfaces of these moons, as well as the evolution of their interiors, requires knowledge of the mechanical strength of these icy materials under the appropriate planetary conditions (temperature, hydrostatic pressure, strain rate). We are conducting ongoing laboratory research to measure mechanical properties of several different ices under conditions that faithfully reproduce conditions both at the moons' surfaces (generally low temperature, to about 100 K, and low pressures) and in the deep interiors (warmer temperatures, pressures to thousands of atmospheres). We report here recent progress in two different phases of our work: rheology of ices in the NH_3–H_2O system at temperatures and strain rates lower than we have ever before explored, with application to the ammonia-rich moons of Saturn and Uranus; and the water ice I→II phase transformation, which not only applies directly to process deep in the interiors of Ganymede and Callisto, but holds implications for deep terrestrial earthquakes as well.

Rheology of NH_3–H_2O Ices to T=130 K. The NH_3 proportion of condensed volatiles on icy moons, taken as a bulk average, may be as high as 0.15 of the H_2O mass fraction (1). Natural refinement, especially through extraction of partial melts, can increase this fraction to that of the pure ammonia dihydrate ($NH_3 \cdot 2H_2O$) composition, about 0.29. We have carried out in the laboratory mechanical tests on samples of ammonia-water mixtures in the compositional range 0 to 29 wt. % NH_3, at temperatures from above the peritectic melting temperature (176 K) to as low as 130 K, at confining pressures of 50 and 100 MPa, and at strain rates from 3.5×10^{-4} to 3.5×10^{-7} s^{-1} (Fig. 1). Our ability to deform at strain rates of 3.5×10^{-7} s^{-1}, and thus induce ductile flow at T<145 K without brittle failure, is the result of a recent hardware change that improved our low strain rate limit by an order of magnitude.

The new results (Fig. 1a) confirm an effect suggested by the trend of earlier results (Fig. 1b): even though ammonia dihydrate melts at 176 K, its strength is more temperature-sensitive than that of water ice, so that below about 135 K it is slightly stronger than water ice. Not surprisingly, mixtures of water ice and ammonia dihydrate are also stronger than water ice at these temperatures. This behavior has important implications for icy moons in cooler parts of the solar system. Near-surface ductility seen on the smaller moons of Saturn and Uranus will be more difficult to rationalize on the basis of ammonia-water. On the other hand, the range of viscosities that can be reached with relatively small (40 K) temperature changes in NH_3–H_2O mixtures may prove to be a convenience in explaining complex features on Triton.

Ice I→II and Deep Earthquakes. Our work on the inelastic deformation behavior of H_2O ices has provided the first systematic exploration of the fracture and plastic flow under planetary conditions (pressures up to 0.6 GPa and temperatures from 77 to 256 K (2)). In the course of carrying out this experimental program, we discovered an unusual form of faulting that has relevance for deep (360-690 km) earthquakes faulting on Earth and that may imply similar deep faulting on Ganymede and other large icy bodies in the solar system. The faulting instability in ice has several unusual properties: faulting strength does not increase with increasing pressure, a transition to ductile behavior does not occur with increasing confining pressure, and faults form in the maximum shear stress orientation (45°) to compression. These events are restricted to low temperatures and elevated pressures. Close thermodynamic parallels exist between the ice transformation and those that occur in the ferromagnesian phases (olivine and the spinel structures) of the earth's upper mantle, and the transformation kinetics in both transformations are slow. Thus the faulting instability can occur in the ice II stability field where ice I persists metastably at low temperatures and elevated pressures, and the cold thermal structure of the descending lithospheric slab in some subduction zones may be favorable for the faulting instability to develop in metastable olivine, as explained below.

There are two distinct manifestations of the transformation under nonhydrostatic stress (Fig. 2). The first, which we call *transformational faulting*, is the unusual faulting we described above. Xray diffraction reveals small amounts of ice II in such faulted samples, and we have suggested (4) that the large volumetric strain and exothermic character of the ice I→II transformation are the destabilizing factors that cause the faulting. The second manifestation is a *bulk transformation* that occurs at warmer temperatures (above about 175 K) where ice II nucleates at a few points in our 30-cm^3-volume sample and grows in a slow and controlled manner.

Green and colleagues (5,6) have confirmed our hypothesis in observing transformational faulting in olivine-spinel transformations in Mg_2GeO_4 and in silicate olivine and have also identified a possible mechanism by which transformational faults may be nucleated by the interactions of microinclusions of the spinel phase. We recently have followed up on our earlier work on transformational faulting in ice (7), refining the faulting strength data, confirming the fault nucleation hypothesis of Green, and pointing out the importance of earlier work by Goto et al. (8) that the volume changes involved in phase transformations in subducting lithosphere can also give rise to large regional deviatoric stresses that can stimulate transformational faulting.

We think deep earthquakes occur because the reconstructive phase transition olivine→spinel is kinetically retarded for millions of years and hundreds of kilometers depth as a slab of cool lithosphere descends into the mantle. When the transformation finally does occur, and we suggest it occurs progressively from

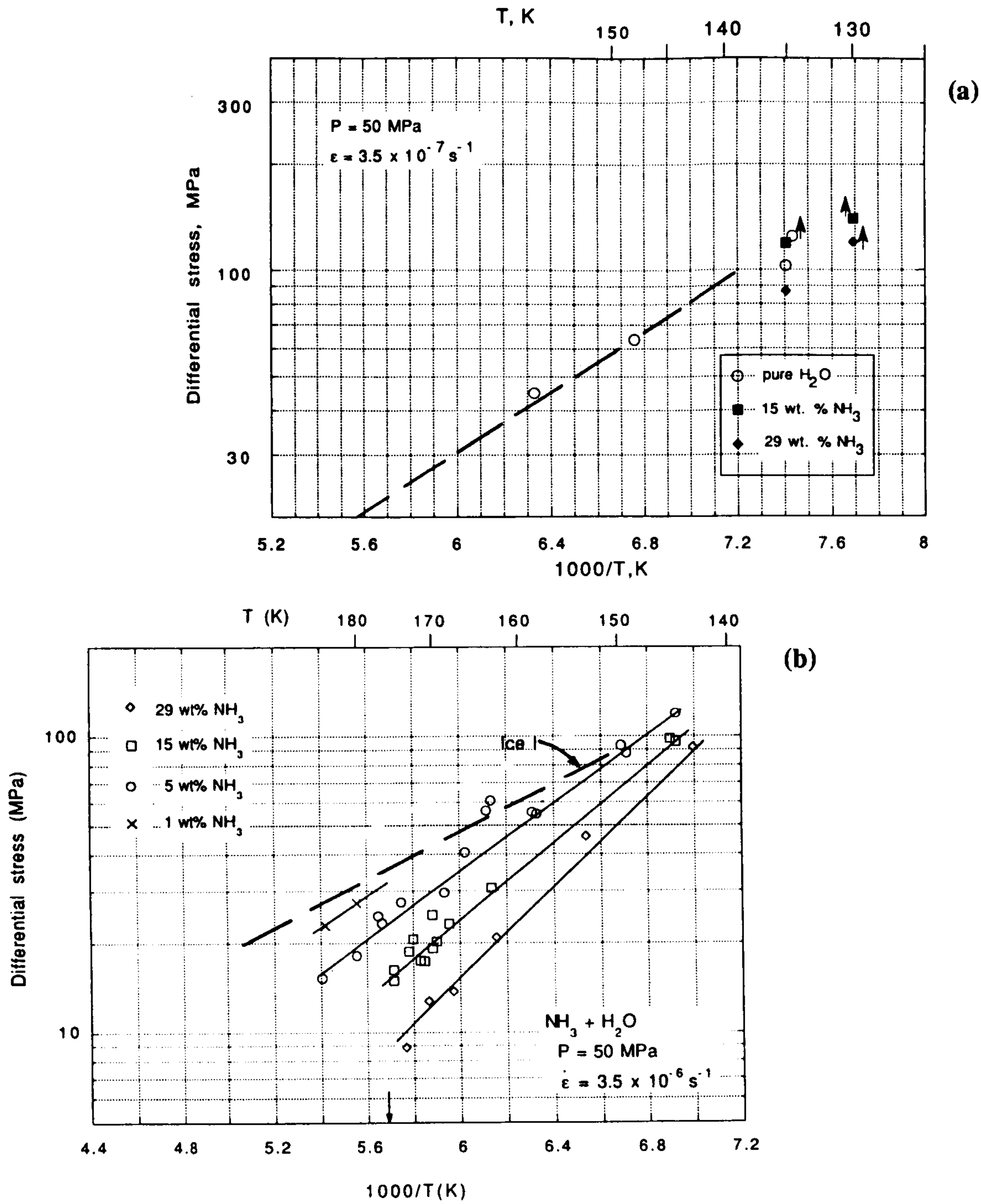

Figure 1. Flow of ices in the NH_3–H_2O system in the compositional range from pure H_2O to ammonia dihydrate (29 wt. % NH_3). (a) Latest results at an imposed strain rate of $3.5 \times 10^{-7}\ s^{-1}$. (b) Earlier results at $3.5 \times 10^{-6}\ s^{-1}$. The figures are offset so that the temperature axes align. Dashed lines in both figures are the latest flow laws for ice I from *Durham et al.* ["The Rheology of Ice I: The Effect of Particulate impurities and Initial Grain Size," manuscript in preparation]. Up arrows in (a) indicate where brittle failure occurred before steady-state ductile flow. The arrow on the horizontal axis in (b) marks the 176 K peritectic melting temperature above which partial melting occurs and mechanical strength drops dramatically. Trends of the higher strain rate measurements (b) suggested that the strength of ammonia dihydrate (diamonds) was approaching that of pure water, but experiments were not feasible at T<143K because stresses exceed the breaking strength of ice. With the ability to deform at lower rates we are able to measure ductile strength almost to 130 K. Strength of water ice and ammonia dihydrate clearly are comparable at 130 K, but the results are confused by an unexpected shear instability in the ammonia samples and by unusual strain-dependent effects in water ice (the two open circles near 135 K are clearly distinct).

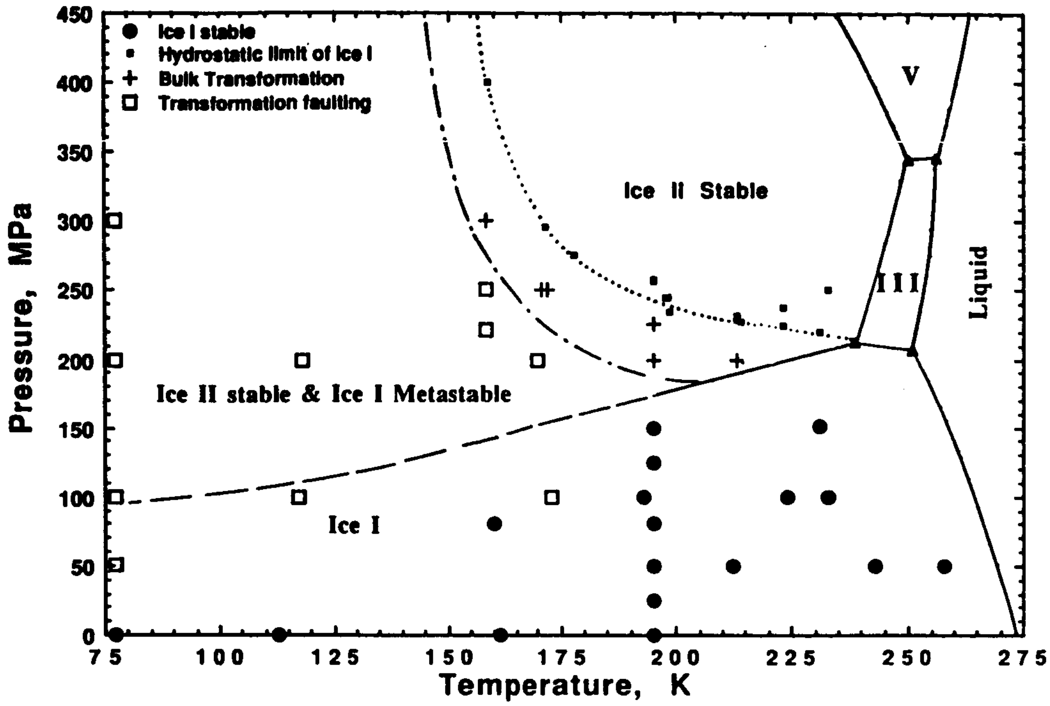

Figure 2. Phase diagram for ice and hydrostatic conditions of the experiments. When ice I is pressurized into the ice II stability field, it does not transform to ice II at the equilibrium boundary. Under hydrostatic conditions (solid boxes), the overpressurization required to cause the transformation to initiate increases sharply as temperature decreases (dotted line). The bulk transformation pressure can be lowered if a differential stress is superimposed on the hydrostatic pressure (crosses). The differential stress required for bulk transformation at any temperature is simply the difference between the actual pressure (crosses) and the hydrostatic limit (dotted line); in other words, the criterion for transformation is a maximum normal stress. At lower temperatures and pressures there seems to be a limit on the maximum differential stress that can be applied, illustrated by the open boxes. Above a shear stress that is weakly temperature sensitive (not shown: about 85 MPa at 77 K, descending to 53 MPa at 170 K) samples fail by macroscopic faulting. The process involves transformation of small amounts of ice I to ice II; hence it is termed transformational faulting, and may be an analog for deep earthquakes in the earth. Such faulting may occur at depths of 40 - 200 km on the large icy moons.

the outer boundaries of the slab inwards as the slab slowly heats up, the negative volume change of the transformation leaves the remaining wedge-shaped core of olivine in a state of slab-parallel compression (8). Stresses eventually rise to the point where transformational faulting, the process we observe in ice in the laboratory, occurs within the olivine wedge, and a deep earthquake is registered seismically.

This unified hypothesis of deep terrestrial earthquakes has implications for deep moonquakes on large, tectonically active icy bodies such as an early Ganymede. A key requirement is that conditions of metastability be present for polymorphic transformations that are strongly exothermic and involve large volume changes (e.g., ice I→II). Earth-style plate tectonics evidently did not occur on Ganymede, but planetary-scale endogenic processes (mostly tensile) certainly did, and some of them could have driven blocks of ice I below its equilibrium boundary. Some downward motion of crust is implied by the extensive resurfacing of Ganymede, for instance by blocks of silicate-laden ice I that have foundered or descended in graben formations. These conditions might also be met during cooling at constant depth and pressure.

References

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