

CREEP OF ICE: FURTHER STUDIES

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In the past year we have completed detailed studies of (1) the flow of high-pressure water ices II, III, and V, and (2) frictional sliding of ice I_h. Preprints describing both studies are now being circulated among interested colleagues before submittal for publication. In addition, we began work on the second phase of the current proposal--the study of the effect of impurities on the flow of ice. We summarize the results of these three projects below.

Flow of high pressure ice. Over the past two and one-half years we have tested 36 different samples of high pressure ice to pressures as high as 550 MPa and temperatures as low as 158 K. The appropriate portion of the H₂O phase diagram is shown in Figure 1. From our tests we have derived 77 independent measurements of strength (flow stress as a function of temperature, confining pressure, and strain rate) and a host of other data related to phase transformation kinetics and phase metastability in ice. The flow results for ices II, III, and V are summarized in Figure 2. Ice II is the strongest of the phases, having a strength slightly higher than that of ice I_h, and ice III is the weakest. The low strength of ice III is striking: under a fixed set of conditions ice III will flow approximately 100-1000 times faster than ice II or ice V. This is important to the evolution of a large icy moon such as Ganymede or Callisto. An ice III layer, situated between a layer of ice V and a layer of ice I_h or II, will behave over long periods essentially as a liquid, unable to transmit meaningful levels of shear stress between the layers bounding it.

We have found that on the laboratory time scale of a few days, important metastable relationships exist between the phases of ice. The strongest of

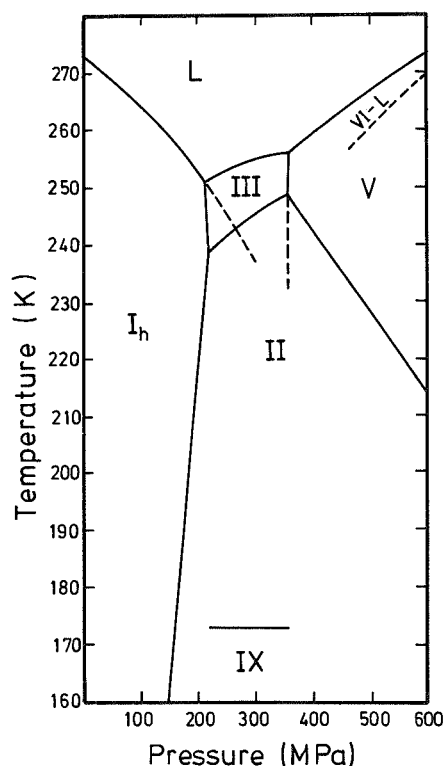


Fig. 1. H₂O phase diagram.

these is the metastable existence of ice III in the warmer portion of the ice II stability field, a phenomenon known for many decades. What we have found is that these metastabilities endure even under large amounts of deformation, where local structural rearrangements might be expected to seed the transformation from ice III to ice II. Ice III deformed at temperatures as low as 210 K does not revert to II during deformation. The transformation from ice III to V and back (dashed line in

Figure 1 at P=350 MPa) can also occur within the ice II

field without producing any sign of ice II, even when the transformation is accompanied by deformation of the sample. Although it seems unlikely that such metastabilities endure over geologic time scales, the point is interesting because of the low strength of ice III and the probability that present and past temperature profiles within the icy moons are very close to the ice II-III phase boundary.

Frictional sliding in ice I_h. We can simulate sliding along existing large-scale faults in the crust of an icy moon by means of triaxial mechanical testing of cylinders of ice composed of two pieces that slide with respect to one another. The Voyager photos suggest such faults exist on the moons' surfaces, so our laboratory data should further constrain evolutionary models of the moons. We performed tests at temperatures from 77 to 115 K, near the expected surface temperatures of the moons, and at confining pressures from 0.3 to 250 MPa. The results from tests at 77 K are shown in Figure 3. Temperature turns out to play no noticeable role in the frictional characteristics of ice, nor does rate of sliding, which varied from 10⁻² to 10⁻⁴ mm/s. The variable of overriding importance is the normal

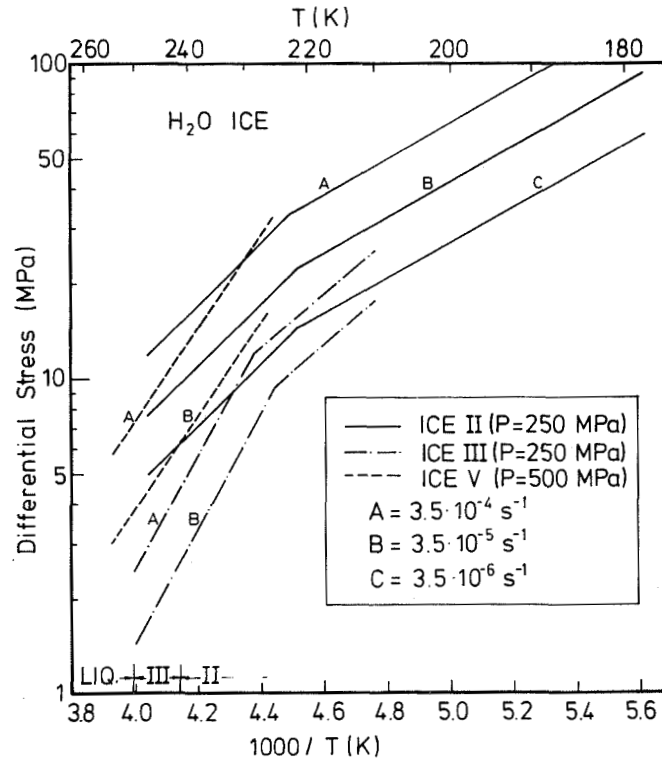


Fig. 2. Flow of ices II, III, and V

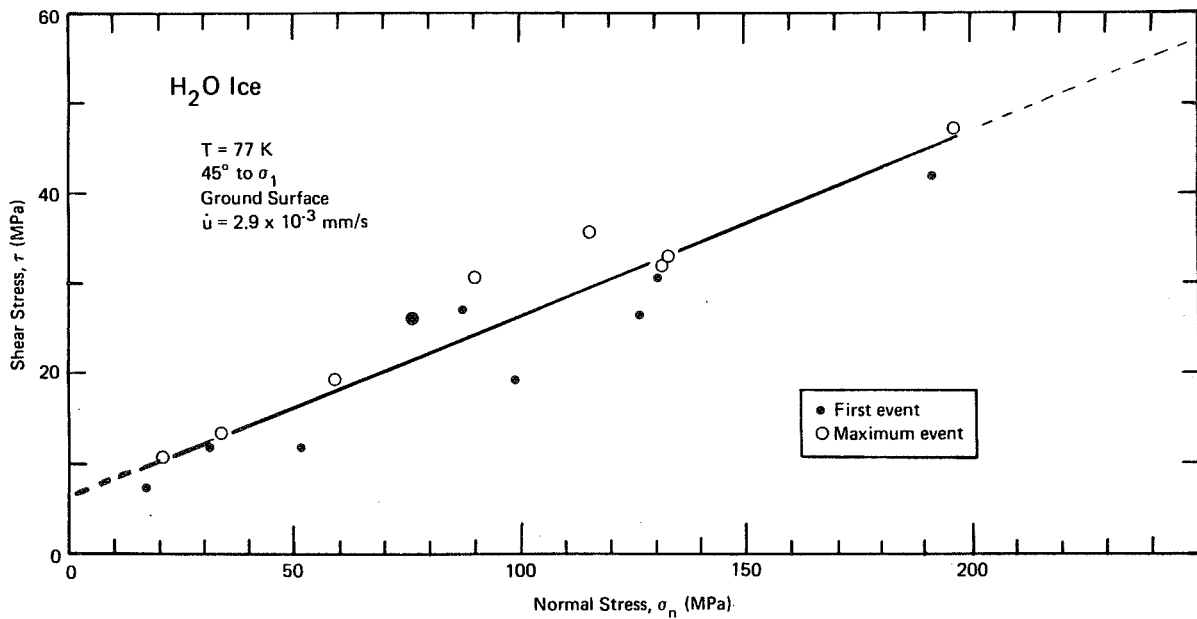


Fig. 3. Frictional strength of ice.

stress across the fault: the frictional strength rises 2 MPa for every 10 MPa increase in the normal stress (Figure 3). This strength is considerably less than that for most rocks. Applying these results to icy moons, weaker fault strength means increased tendency for deeper faults, that is, the depth at which plastic flow becomes favored over frictional sliding becomes deeper. Under extensional stresses of the order of 10 MPa, sliding on existing faults would be expected to extend to a depth of approximately 10 km in ice.

Effect of impurities on the flow of ice. This phase of the project began very recently. The first series of tests on samples of ice I_h from the important "intermediate" temperature regime (243 K to 195 K) has shown unambiguously that small amounts (less than 1%) of particulate impurities have no effect on the plastic flow properties of ice. The work will be extended to different temperature regimes, different amounts of particulate impurities, and perhaps different phases of ice. The study of dissolved impurities in water ice, especially methane and ammonia, is the subject of a current proposal to NASA.