PLANETARY ICES: A COMPARISON OF RHEOLOGIES AT T < 200 K; W. B. Durham, UCLLNL, Livermore, CA 94550; S. H. Kirby, USGS, Menlo Park, CA 94025

Tectonics on icy bodies at warm temperatures depends strongly on the mechanical properties of water ice because water ice generally dominates both composition and rheology at these temperatures. In contrast, processes at 200 K and below in the outer solar system involve and depend on the properties of a wider range of materials. Given that there is large-scale tectonic activity all the way out to Triton, some fundamental questions about the composition and origin of the icy satellites of Jupiter and beyond can be addressed by studying rheologies at very low temperatures.

In Figure 1 we compare the flow of several important planetary ices as measured in our laboratory over the past several years. The plot includes only the results for $T < 200$ K, which applies roughly to the near surface of Jupiter's icy moons and to more significant depths in the moons of Saturn and beyond. Our experiments have been done under high pressures and low temperatures that bracket conditions in the interiors and on the surfaces of the icy moons. One shortcoming of the laboratory experiments is that they fail to simulate planetary strain rates. The requirement that we develop observable strains in our samples in a reasonable time forces us to deform our samples at rates that are at best several (> 4) orders of magnitude faster than strain rates expected on the icy moons, which in turn forces us to make very large extrapolations in applying our results to the outer solar system.

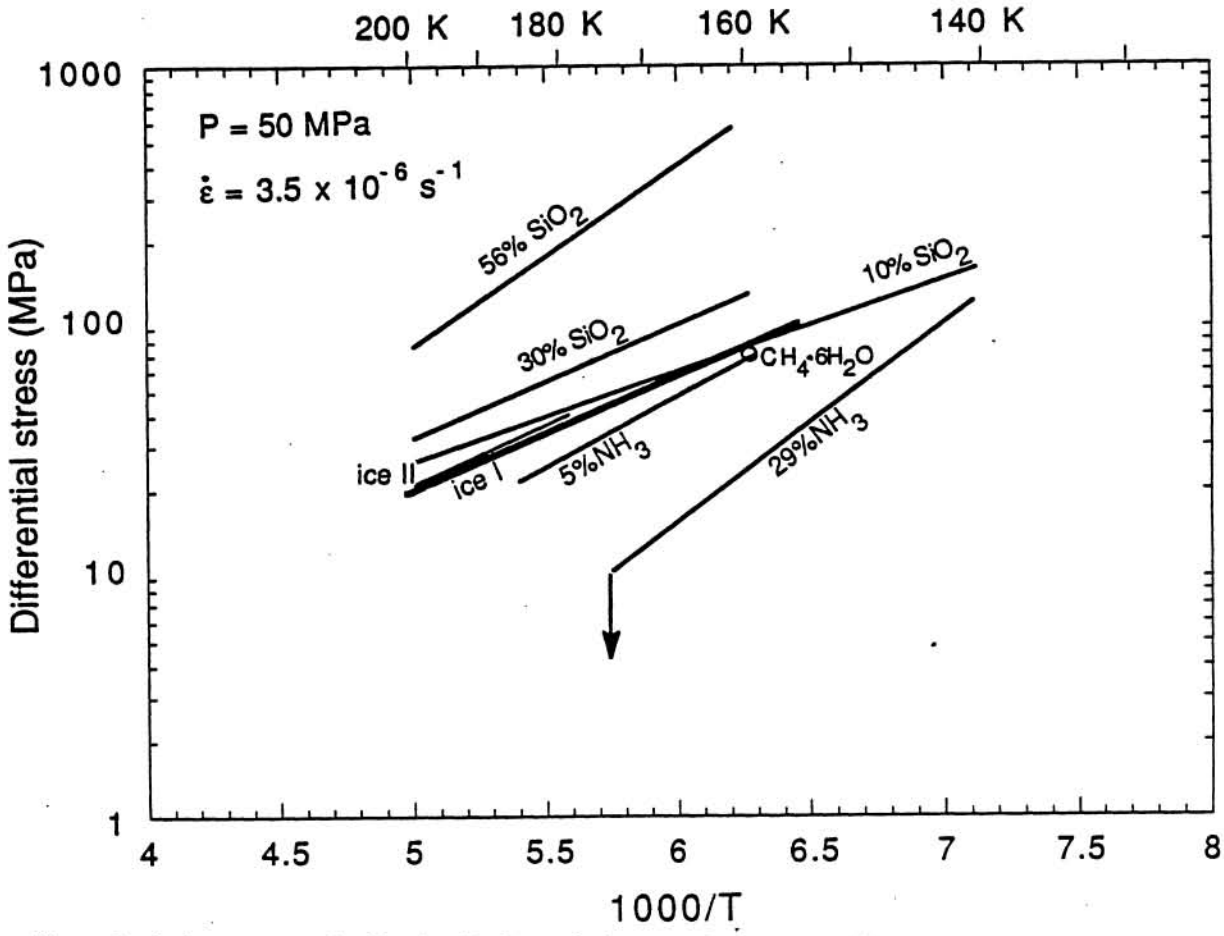

Figure 1. Laboratory results for ductile flow of planetary ices at $T < 200$ K. Lines shown are approximate straight-line fits to measurements (individual data not shown); no extrapolations are involved. The measurements were made at a fixed hydrostatic pressure of 50 MPa and a strain rate of 3.5×10^{-6} s^{-1} and apply to the so called "steady-state" flow regime thought to apply at absolute strains (measured from the last change in stress) above a few percent. Measurements at faster strain rates (not shown) on all these materials indicate that ductile flow under these conditions is highly non-Newtonian (see text). The downward-pointing arrow on the 29% NH_3 (pure ammonia dihydrate) line corresponds to the appearance of a melt phase that is thought to be responsible for much of the resurfacing seen on icy moons of Saturn and beyond.

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RHEOLOGY OF PLANETARY ICES AT T < 200 K: Durham, W. B. and Kirby, S. H.

We have measured the flow and fracture of four varieties of planetary ices in our work to date: (1) pure water ice, including several of its high-pressure polymorphs, (2) mixtures of water ice + particulates, mainly silica, in volume concentrations of <1% to 56%; (3) ices in the system NH_3–H_2O, in concentrations of NH_3 from 1 to 29 wt%; and (4) methane clathrate, with an approximate formula $CH_4 \cdot 6H_2O$.

Because of a logarithmic scale along the differential stress axis in Figure 1, the flow laws for pure water ices I and II, water ice with low concentrations of rock and with low concentrations of NH_3, and the one point for methane clathrate are in close proximity. The differences between these rheologies are more noticeable if one prefers to think in terms of viscosity contrasts because of the strong sensitivity of strain rate ($\dot{\varepsilon}$) to stress (σ). The relationship is observed to be of the form $\dot{\varepsilon} = \sigma^n$ where $n = 4$ to 6 depending on the particular ice involved.

Outside the cluster of rheologies in the center of the figure are a spectrum of planetary materials that is many orders of magnitude more viscous: mixtures of ice and rock at volume concentrations of rock above 30%. These may help explain the slow viscous relaxation of craters on Ganymede and Callisto. There is also a spectrum of much less viscous materials: mixtures of water ice and ammonia dihydrate. The rheological contrast between the NH_3–H_2O mixtures and the other materials confirms the explanation for the absence of a tectonic activity gradient in the outer solar system. In the commonly held understanding of planetary formation, materials with lower melting temperatures condensed farther from the sun and hence have been at a large fraction of their melting points or have melted during their histories, facilitating internal flow. Thus water ice condensed at the orbit of Jupiter, while ammonia dihydrate probably condensed in significant amounts beyond the orbit of Jupiter (1). To a first approximation, the homologous temperature of the outer solar system is constant.

Preliminary results for methane clathrate suggest a break from this simple relationship. Following Lewis's (1) model for equilibrium accretion, methane clathrate is the first methane-rich phase to condense, and, at similar pressures, should appear at solar radii beyond where ammonia dihydrate first condenses. We have observed that methane clathrate at 160 K has approximately the same viscosity as water ice at that temperature (Fig. 1). At 140 K, ductile flow appears to be so difficult under laboratory conditions that brittle failure at high stresses occurs first. Given solar abundances of ammonia, water, and methane, some early models predicted significant if not dominant levels of methane clathrate with respect to ammonia dihydrate on Triton. The magnitude of tectonic activity on Triton shown in the Voyager images allows us to conclude that methane clathrate does not dominate its near-surface (say < 10-km depth) makeup.

Future studies may help clarify the situation. More complex molecules of H, C, N, and O are candidates for solid phases, as are solid N_2 and CH_4 at extremely cold temperatures. Laboratory experiments at lower strain rates will also aid with the extrapolations.

References

(1) Lewis, J. S. (1972) *Icarus, 16*, 241-252.

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