INTER-LABORATORY INVESTIGATIONS OF THE EFFECTS OF PARTICULATES ON FLOW OF FINE-GRAINED ICE. D.L. Goldsby[1], W.B. Durham[2], and A. Pathare[3], [1]Department of Geological Sciences, Brown University, 324 Brook Street, Providence, RI 02912, David_Goldsby@brown.edu; [2]Department of Earth Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, wbdurham@mit.edu; [3]Planetary Science Institute, pathare@psi.edu.

Introduction: Polycrystalline ice at planetary temperatures creeps by a variety of processes, including grain-size-sensitive (GSS) mechanisms involving grain boundary sliding (GBS) and grain-size-independent (GSI) mechanisms like dislocation creep [1,2]. Previously, Durham et al. [3,4] showed that the presence of particulates in coarse-grained water ice undergoing dislocation creep could greatly affect the rate of deformation in ice-rich Martian landforms.

Here we report on the results of two different sets of laboratory experiments on the rheological behavior of dust-bearing samples of fine-grained water ice deforming in the GSS creep regime. A general observation from both of these experimental studies is that even small fractions of particulates in ice can have significant or even profound effects on rheological behavior, depending on the particle size and fraction. The experiments were conducted in two different laboratories (MIT and Brown), at different confining pressures (50 MPa and 1 atm, respectively), and the samples were fabricated using markedly different methods. In spite of these differences, however, the rheological behavior of these samples is similar.

Sample fabrication. For the MIT experiments, ice samples containing 3 and 10 vol. % dust were prepared by mechanically mixing fine-grained ice and alumina powders, then hot pressing the admixtures at elevated confining pressures into dense samples that were subsequently deformed. Fine-grained (1 to 5 μm) ice powders were prepared by first explosively depressurizing ice samples from the ice II to the ice I stability field [5], repeated again twice, then pulverizing the samples in a cold mortar and pestle. The ice powders were then mechanically mixed with Al_2O_3 powder of particle size 1 μm, in most cases at a concentration of 3 vol%, and the resulting mixtures were packed into an indium jacket and pressurized to a gas confining pressure of 50 MPa, which densified the aggregates. This method resulted in uniform mixtures of ice and alumina, confirmed by scanning electron microscopy. Tests were conducted over the following ranges of strain rate, stress and temperature, respectively: $2 \times 10^{-8} < \dot{\varepsilon} < 3 \times 10^{-6}$ s^{-1}; $2 < \sigma < 8$ MPa; $210 < T < 240$ K.

For the Brown experiments, samples were fabricated by hot-pressing fine-grained, dust-bearing ice powders into fully dense creep specimens. Powders were created by misting a suspension of alumina powder in water into a reservoir of liquid nitrogen, then sieving the powders in liquid nitrogen to <25 μm. Sieved powders were then packed into a stainless-steel piston-cylinder apparatus at 195 K and evacuated, then compacted into fully dense samples under a stress of 100 MPa. The sample was then transformed to ice II and rapidly decompressed to ice I (as for the MIT experiments), pressed out of the molding cylinder and deformed in a high-resolution, 1-atm creep apparatus. Tests were conducted over the following ranges of strain rate, stress and temperature, respectively: $10^{-7} < \dot{\varepsilon} < 10^{-3}$ s^{-1}; $0.4 < \sigma < 5$ MPa ; $236 < T < 266$ K.

Experimental results. As shown in Figure 1, in the high-pressure tests at MIT, the strength of the 3%-dust samples at the test conditions is closer to that of pure ice in the GSS creep field, yet exhibits a high, dislocation creep-like stress exponent (n = 3 – 4, where

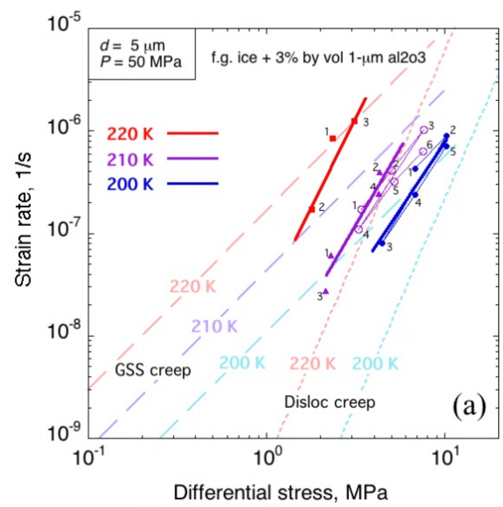

Fig. 1 – Plot of strain rate vs. stress for ice containing 3 vol.% alumina of particle size 1 μm. Numbers indicate the sequence of stresses at which strain rates were measured. Long-dashed lines show the flow law for GBS-limited creep [1] at each temperature; short dashed lines show the flow law for dislocation creep [2].

$\dot{\varepsilon} \propto \sigma^n$). The apparent activation energy Q (where $\dot{\varepsilon} \propto \exp\left(-\frac{Q}{RT}\right)$ is also significantly higher than that of pure ice in either creep regime. As shown in Figure 1, decreasing $\dot{\varepsilon}$ with strain is observed at a given stress and temperature in all experiments. This strain hardening is observed even at $T \leq 220$ K, where it does not ordinarily occur in pure, fine-grained ice [6], so it is probably not the result of grain growth in the GSS regime (wherein $\dot{\varepsilon} \propto d^{-p}$, where d is grain size and p is the grain size exponent).

We also found that strain rate decreases at a given stress when the dust content increases from 3 to 10 vol%, amounting to nearly an order of magnitude in viscosity. The strength of the ice containing 10% dust is comparable to that of larger-grained (d > 200 μm) pure ice deforming via dislocation creep. Since the dust-bearing ice is not stronger than pure ice deforming via dislocation creep at the same σ and T, we infer that deformation must still be assisted by GSS processes.

Data from an experiment conducted in the Brown laboratory are shown in Figure 2, for an ice sample of ~12 vol.% alumina of particle size 0.3 μm. Neither the

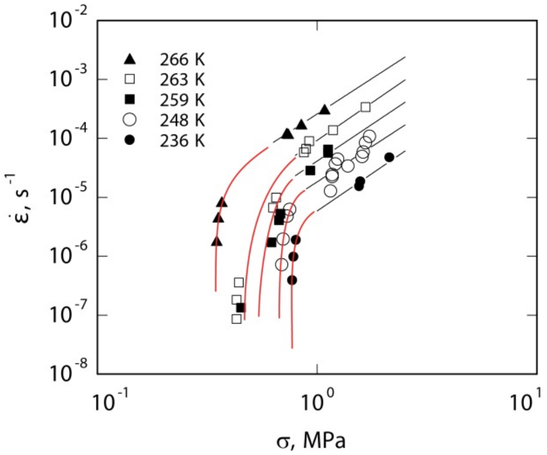

Fig. 2 – Plot of strain rate vs. stress for ice containing 12 vol.% alumina of particle size 0.3 μm. The slope of the straight line segments above ~1 MPa is ~ n=2.4, in accord with expectations from the composite flow law of Goldsby and Kohlstedt [1] for d=1 μm. Red lines illustrate schematically the threshold stress-like behavior at low stresses. Note the temperature dependence of the threshold stress.

distribution of particles in this sample nor the ice grain size is yet known. Two possibilities are that 1) ice I nucleates from ice II at ice/particle interfaces, such that the ice grain size might equal the interparticle spacing in the slurry (i.e., ice I grains nucleate and grow until they impinge on neighboring alumina particles), or 2) ice I grains nucleate at favorable ice-particle interfaces, then incorporate particles in grain interiors as grain boundaries rapidly migrate. However, the good agreement between the observed stress exponent of ~2.4 and that for basal slip-limited creep (i.e., the n=2.4 regime, see [1]), and the good agreement between the magnitudes of the predicted and observed strain rates in the n=2.4 regime together suggest an ice grain size of <3 μm.

A prominent feature of the data from the Brown experiments is the emergence of threshold stress-like behavior at low stresses (<1 MPa), whereby a precipitous decrease in strain rate occurs with decreasing stress. This behavior was not explicitly observed in tests conducted at elevated confining pressures at MIT. However, we note that the data points in Figure 1 do indicate a downward curvature in the data that might be consistent with the data in Figure 2 (see, for example, the data at 220 K and the solid triangles at 210 K). If threshold stress-like behavior is present in the MIT experiments, then the relatively few number of data points in Figure 1 and the limited range of stresses investigated would yield a comparatively high apparent value of n >3 but less than that for dislocation creep (~4), as is observed in Figure 2. The results of additional tests on samples at high confining pressures, over a broader range of stresses, are underway to further test this hypothesis and will be reported.

The origins of threshold behavior in the creep behavior of ice-dust aggregates is not yet known. The behavior may signal the impedance of the motion of grain-boundary dislocations and therefore GBS [7]. The threshold-like behavior might alternatively be due to the Frank-Read (F-R) stress for dislocation nucleation, equal to $\frac{Gb}{d}$ (where G is the shear modulus, b the Burger's vector, and l the length between pinning obstacles, here conservatively taken as equal to d) [8], which is ~1 MPa for ice of 1-μm grain size. This value is close to the value of the threshold stress in Figure 2. Below the F-R stress, no dislocation motion is possible, so that dislocation-accommodated GBS cannot operate. The observed T dependence of the threshold stress, however, is larger than inferred from the T dependence of G in the F-R stress equation over the range of temperatures investigated. Whatever its physical origins, such behavior might have a critical influence on ice flow in planetary environments, particularly for dust-rich ice deposits on Mars, rendering the ice nearly immobile at low stresses.

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