LABORATORY MEASUREMENTS OF GRAIN-SIZE-SENSITIVE CREEP OF PARTICULATE-LADEN ICE AT PLANETARY TEMPERATURES. W. B. Durham[1], A. V. Pathare[2], L. A. Stern[3], [1]Massachusetts Institute of Technology (wbdurham@mit.edu), [2]Planetary Science Institute (pathare@psi.edu), [3]U. S. Geological Survey, Menlo Park (lstern@usgs.gov).

Introduction: Polycrystalline ice at planetary temperatures will creep by a multiplicity of mechanisms. Grain-size-sensitive (GSS) mechanisms such as grain boundary sliding/superplasticity [1] or diffusional flow [2] may affect the rate of deformation in ice-related Mars landforms (along with grain-size-independent [GSI] mechanisms such as dislocation creep). Flow laws for GSS and GSI creep of pure water ice are now well documented. The flow of ice deforming in the steady-state (i.e., time- and strain-independent) regime follows the standard constitutive relationship for thermally activated deformation relating the variables strain rate, $\dot{\varepsilon}$, differential stress, σ, hydrostatic pressure, P, temperature, T, and grain size, d:

$$\dot{\varepsilon} = Ad^{-p}\sigma^{n} \exp\left[-(E^{*}+PV^{*})/RT\right] \qquad (1)$$

where R is the gas constant and parameters A, p, n, E^*, and V^* are material constants.

Until recently, the only creep mechanism measured in the lab at $T < 250$ K was dislocation creep (stress exponent $n \geq 3$ in Eq. [1]). The discovery of GSS creep in fine-grained ice at lower stresses [2] was a mini-revolution for planetologists. GSS rheology has low stress sensitivity ($n = 1.8$) and an inverse dependence on grain size ($p = 1.4$). GSI and GSS processes are typically not mutually exclusive, and in a polycrystalline solid under stress both are allowed to operate under the constitutive relationship (1), each with its own set of material constants.

At most conditions of P, T, σ, and d in Equation (1) rheologies under GSS and GSI creep will be very different, with one mechanism normally contributing overwhelmingly to strain rate, to the point of rendering the other insignificant. However, a description of flow based on Eq. (1) and a prescribed grain size does not tell the whole story, because grain size itself is not static. GSI and GSS creep may operate simultaneously, but recent considerations suggest that they are not entirely independent, due to their opposing effects on grain size. As illustrated in Fig. 1, it has been theorized and demonstrated for many materials that grain size during deformation is driven to a distribution that must allow significant amounts of both GSI and GSS creep to be active at all times [3].

The reason for this balance is that GSI creep involves constant generation of dislocations and other crystalline imperfections, which raises the internal energy of the ice grains. Higher stress creates a higher density of intracrystalline defects, and at some stress, the internal energy will rise to a level where grains will spontaneously recrystallize to smaller grains. On the other hand, GSS creep usually involves grain boundary migration or grain boundary sliding. The ice grains themselves remain defect-free, and therefore will tend to grow under thermodynamic forces to reduce total grain boundary energy. Hence we have deformation mechanisms and grain size changes working in opposite directions towards dynamic equilibrium. In GSI creep, grain size will decrease, which favors GSS creep; in GSS creep, grains will tend to grow, which favors GSI creep. Thus the possibility exists that in the steady state, a grain-size distribution will exist that reflects a dynamic balance of deformation mechanisms and grain size change.

In the present study we investigate the effect that hard particulates might have on this balancing mechanism, with an eye toward particulate-laden ice under Martian conditions.

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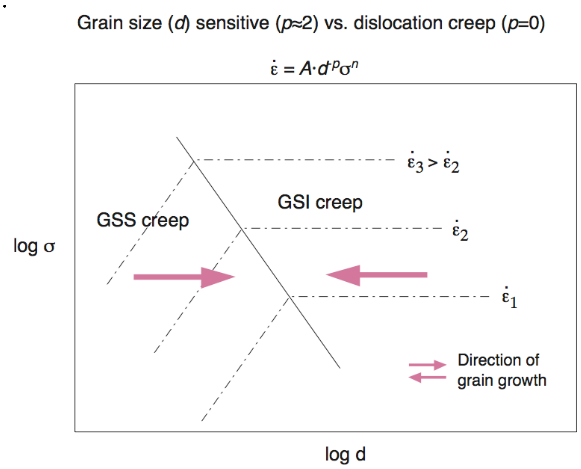

Figure 1 Depiction of dynamic grain size balance, from [3].

Experimental Setup: Creep experiments on fine-grained ice + hard particulate mixtures were carried out at elevated pressure P and low temperature T in the same cryogenic gas creep apparatus used and described by [4]. We measured the rate of axial shortening of cylindrical samples under a state of constant differential stress. Fine-grained ice was generated by triple application of the "pressure-drop" method where high-pressure ice II is created from ordinary ice I and then rapidly depressurized back to ice I [4]. Fine-grained material was then disaggregated and mixed with fine alumina powder by aggressive mixing. Based on cryogenic SEM (CSEM) examination of test specimens, this technique of first creating pure fine-grained ice and then mixing with particulates (Fig. 2, top) yields

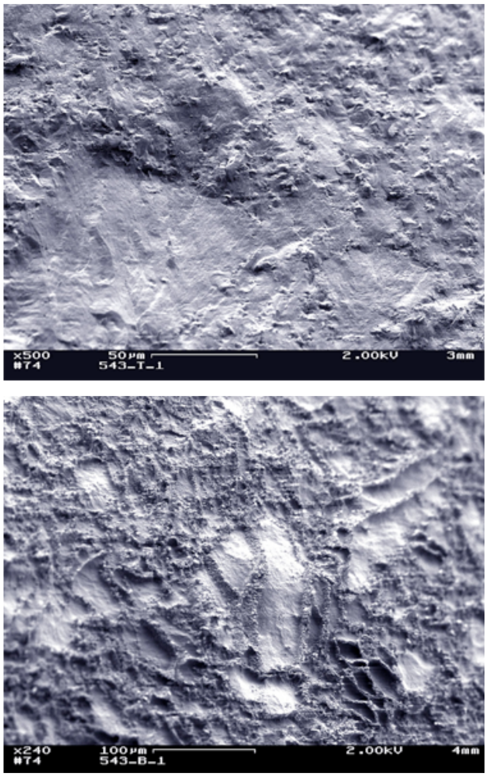

Figure 2 CSEM micrographs of two kinds of mixtures of fine-grained ice (grain diameters 5-10 µm) plus fine quartz sand (1-5 µm). Ice-ice grain boundaries are invisible at the scale of these images. Quartz particles are recognizable by a very slightly darker shading, and tend to stand in raised relief against the ice phase due to ice sublimation under the high vacuum conditions. The preparations of the samples differ by reversing mixing and pressure-dropping steps. The upper sample appears to give a more uniform mix of ice and sand, whereas below the sand has clearly segregated to the boundaries of large clumps of fine-grained ice. Upper scale bar is 50 µm, lower one is 100 µm. Note that in the deformation tests here particulates are alumina rather than quartz, and have smaller grain size.

better dispersion of the particles than creating fine-grained ice in the presence of particulates (Fig. 2, bottom).

Preliminary Results: As of this writing, two runs have been completed, at $210 \le T \le 230$ K and $1 < \sigma \le 6$ MPa. Initial ice grain size was 5-10 µm (Fig.2), particulate (alumina powder, Al_2O_3) size was 0.3 and 1.0 µm in the first and second runs, respectively, and the volume ratio of ice to alumina was 90:10 in both runs. Results are shown in Fig. 3, overlying a map of GSI and GSS creep in pure ice. Run conditions were stepped after apparent steady-state was achieved, so each sample yielded several data points.

Early indications are that the presence of particulates suppresses GSS creep. Observed strain rates at lower stress are one order of magnitude or more slower than expected of GSS creep in pure ice of this grain size. Although post-test grain sizes in these samples have not yet been observed by CSEM, we suspect that grain growth, which itself will also suppress GSI creep, is not a factor based on two reasons: grain growth in fine-grained pure ice is negligible for these run times at 220 K (but not at 230 K) [5], and the anticipated effect of particulates, if any, is grain boundary pinning [6]. How particulates then suppress GSS activity remains a matter for speculation, and will be an immediate objective of subsequent experiments.

Further work: At this point we have observed only one volume fraction of particulates; a range of concentrations relevant to Mars will be studied. It is a curiosity that the *number* of particulates per unit volume, which differed by a factor of 1000 in these two runs, did not have an observable effect. That matter will require close coordination between sample preparation, experimental flow results, and CSEM analysis.

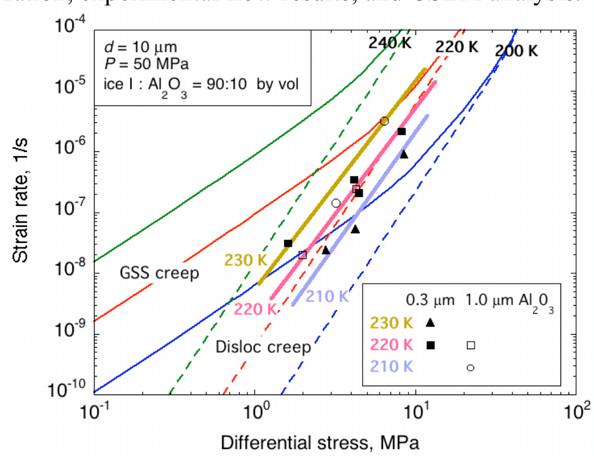

Figure 3. Preliminary results, from two deformation experiments with differing size of alumina particulates. Solid and dashed curves show GSS and GSI creep for pure ice I [5] at temperatures separated by 20 K. The three broader lines are estimated fits to the current data set, at temperatures separated by 10 K.

References: [1] Goldsby and Kohlstedt (2001) *J. Geophys. Res.*, *106*, 11017-111030.. [2] Goodman et al. (1981) *Philos. Mag., 43, 665-695.*. [3] de Bresser et al. (1998) *Geophys. Res. Lett.*, *25*, 3457-3460. [4] Stern et al. (1997) *J. Geophys. Res.*, *102*, 5313-5325. [5] Durham et al. (2001) *J. Geophys. Res.*, *106*, 11031-11042. [6] Baker R. W. and Gerberich, W. W. (1979) *J. Glaciol., 24*, 179-194.