

THE TRANSITION FROM DISLOCATION TO DIFFUSION CREEP IN ICE Goldsby, D.L. and D.L. Kohlstedt, Dept. of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455

The rheology of Ice I has been investigated extensively at both 1 atm and high confining pressures (*e.g.*, Duval *et al.*, 1983; Durham *et al.*, 1992). The rheology of ice can be described by a power-law creep equation of the form $\dot{\epsilon} = A(\sigma^n/d^m)\exp(-Q/RT)$, where $\dot{\epsilon}$ is strain rate, A a material parameter, σ stress, d grain size, and Q the activation energy; RT has the usual meaning. It is well-established that ice deforms by dislocation creep at sufficiently high stresses and large grain sizes (Duval *et al.*, 1983), with $n = 3-4$ and an activation energy $Q = 78$ kJ/mol. Evidence for diffusion creep ($n = 1$) in ice, however, is ambiguous. A handful of studies have reported creep results consistent with Newtonian flow (*eg.*, Bromer and Kingery, 1968; Colbeck and Evans, 1973), but these experiments were conducted at very low stresses and strain rates, so that transient creep may have dominated the creep response. Yet, diffusion creep should be the dominant deformation mechanism over a wide range of temperatures, tectonic stresses, and grain sizes occurring in icy planetary interiors. We have therefore conducted a series of creep experiments at one atmosphere total pressure on very fine-grained water-ice to determine constitutive laws for both diffusion creep and dislocation creep.

Diffusion creep in ice is difficult to measure, due to slow diffusion rates in ice and to the generally large-grained (≥ 1 mm) samples used in the laboratory. Diffusion creep for these coarse-grained samples can only be measured at very low stresses (≤ 0.2 MPa) and strain rates ($\leq 10^{-9}$ s $^{-1}$), so that transient creep may dominate over steady state creep. The diffusion creep field (in the σ - T plane) is enlarged for smaller grain sizes, making creep experiments at practical strain rates ($\geq 10^{-8}$ s $^{-1}$) possible. Fine grain sizes also minimize microcracking caused by thermal and elastic anisotropies, and increase the fracture strength (by decreasing the size of Griffith flaws). Hence, we devised a method for fabricating very fine-grained samples (≤ 30 μ m). First, ice powders were prepared by misting distilled water into a liquid nitrogen (LN $_2$) reservoir. Second, these powders were wet-sieved in LN $_2$ to ≤ 25 μ m. Third, the powders were uniaxially hot-pressed at $0.71 T/T_m$ (where T_m is the melting temperature) for 2-4 h at $\sigma = 100$ MPa. Samples were placed into a cryogenic chamber in the 1 atm creep rig also maintained at $0.71 T/T_m$, to prevent thermal shock. The temperature in the cold cell was allowed to drift upward to the first experimental temperature, $T = -37^\circ\text{C}$. All changes in temperature were made at a controlled rate of 2-3°C/h to prevent microcracking from thermal expansion mismatch. Samples were deformed over the following ranges of temperature, stress, and strain rate: $-58^\circ \leq T \leq -37^\circ\text{C}$; $0.5 \leq \sigma \leq 15$ MPa; and $10^{-8} \leq \dot{\epsilon} \leq 10^{-4}$ s $^{-1}$.

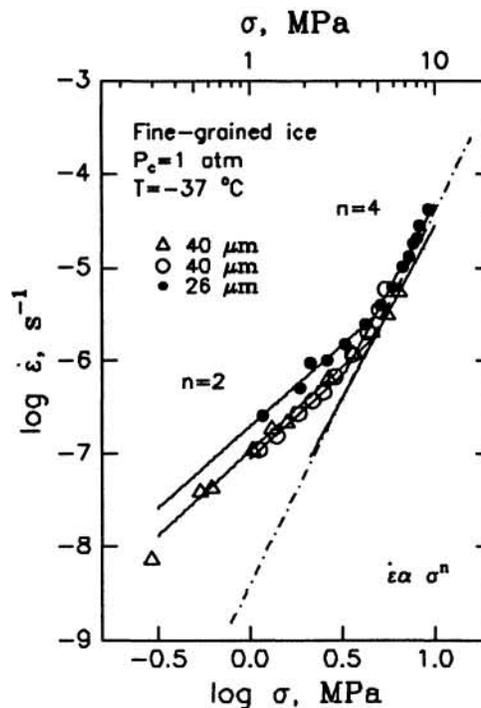
After deformation, samples were quenched in LN $_2$ and later analyzed in an environmental scanning electron microscope (ESEM). Grain sizes were determined from digitized ESEM micrographs using a linear intercept method.

The creep data exhibit a clear transition from dislocation creep ($n \approx 4$) to a rheology characterized by $n \approx 2$, as shown in Figure 1. Figure 1 also compares the data of this study and the high pressure data of Durham *et al.* (1992). The excellent agreement between the 1-atm data and the high-pressure data demonstrates that microcracking did not contribute significantly to the strain rate in our experiments. The activation energy in the dislocation creep regime is 73 kJ/mol, in good agreement with previous studies (Frost and Ashby, 1982); in the $n = 2$ regime $Q = 48$ kJ/mol. Comparison of creep data for samples of 26 and 40 μ m grain size yields a grain size exponent m of 2.3; further experiments will be required to determine more accurately this value. These data are consistent with a transition from dislocation creep to dislocation-accommodated grain boundary

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sliding, GBS. Creep models for GBS (*e.g.*, Langdon, 1994) predict $\dot{\epsilon} \propto d^{-2}$ and $n = 2$. In these models, dislocations generated at grain boundary ledges glide across sliding grains and pile up at opposing grain boundaries. The sliding rate is determined by the rate at which lead dislocations are removed from the pile up by dislocation climb in the grain boundaries, which likely involves grain boundary diffusion. The activation energy for volume diffusion Q_v in ice is $Q_v \approx 60$ kJ/mol (Ramseier, 1967), whereas the activation energy for grain boundary diffusion Q_{gb} has not been determined. Frost and Ashby (1982) suggest an activation energy for grain boundary diffusion of 38 kJ/mol based on published values for Q_v . We propose instead that $Q \approx 48$ kJ/mol, determined in our grain-size sensitive creep experiments, is the activation energy for grain boundary diffusion in ice.

Figure 1- Log $\dot{\epsilon}$ -log σ plot of for samples of 26 and 40 μm grain size. Grain sizes determined from ESEM micrographs using a linear intercept method. Dot-dashed line represents high pressure data of Durham et al. (1992), normalized from 50 MPa to 1-atm.



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