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Microstructural evolution of polycrystalline ice during confined creep testing

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ABSTRACT

The mechanical properties of polycrystalline ice I_h have been observed to change under an applied hydrostatic pressure comparable to that present near the bottom of kilometer-thick ice sheets. To help determine the cause of these changes, we conducted confined creep testing of laboratory-prepared polycrystalline ice at pressures up to 20 MPa (equivalent to ~2000 m of overburden) and subsequent microstructural analysis of specimens deformed by creep using optical microscopy and scanning electron microscopy, including extensive electron backscatter diffraction mapping of crystal orientations. Microstructural observations of the creep-deformed specimens revealed smaller median grain sizes, less regular, and more interlocked grain shapes in specimens deformed at higher pressure compared with those deformed at atmospheric pressure. Variable pressure testing reveals little change in strain rate for pressures less than 15 MPa, leading to alternative hypotheses regarding the influence of confining pressure on the dislocation dynamics and associated creep behavior of polycrystalline ice. Our central hypothesis is that widely dissociated basal dislocations in ice begin to constrict after the confining pressure reaches a critical value. This critical pressure depends strongly on the (currently unknown) lattice dilatation induced in ice by the presence of stacking faults.

1. Introduction

The effects of hydrostatic pressure on the creep properties of ice I_h are of interest for terrestrial ice sheet flow modeling and to gain fundamental insight into the structure of ice and its crystalline defects. Presently, ice sheets on Earth have maximum depths of ~3000 m, yielding hydrostatic pressures P up to 30 MPa, and depressions of the melting temperature T_m down to -2.5°C using the rate of -0.074 °C MPa^{-1} given in Hobbs (1974). The majority of laboratory experimental work has been performed within this range, both on single crystal and polycrystalline ice, and the work presented in this paper also focuses exclusively on the temperature and pressure range relevant to terrestrial ice. Following a review of the possible effects of hydrostatic pressure on creep and fabric development in ice, we review the experimental results to date to place this work in context.

1.1. Unique characteristics of ice I_h and hydrostatic pressure effects on creep

Steady state creep strain rate as a function of hydrostatic pressure is often described (Frost and Ashby, 1982) by

$$\dot{\epsilon} = A\sigma^n \exp\left[-\frac{E^* + PV^*}{k_B T}\right] \qquad (1)$$

where A is a constant, σ is the applied non-hydrostatic stress, n is the creep exponent, E^* is the creep activation energy, V^* is the creep activation volume, k_B is Boltzmann's constant and T is the absolute temperature. We emphasize that this expression uses the absolute temperature, and not the homologous temperature $T_h = T/T_m(P)$ where T_m is the melting temperature, which is a function of hydrostatic pressure. We will frequently refer to both types of temperatures in this paper. Comparisons of strain rate to ascertain pressure effects using Eq. (1) should be done at equal absolute temperatures T, as this expression does not include any provision for pressure melting effects.

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Because most crystalline materials exhibit $V^* > 0$, application of high pressure results in reduced rates of creep (Butcher and Ruoff, 1961, Sherby et al., 1970), slower grain growth (Hahn and Gleiter, 1979) and lower rates of recrystallization (Syrenko et al., 1973, Tanner and Radcliffe, 1962). In contrast, ice displays *negative* activation volumes for grain growth (Azuma and Higashi, 1983) and for creep at $P > 15$ MPa (Jones and Chew, 1983b). The dominant point defect in ice is the interstitial (Hondoh et al., 1987) which increases in concentration with increasing P. Furthermore, ice has one of the lowest known stacking fault energies (γ_F), a result of its open lattice and the very small energy difference between hexagonal and cubic ice structures (Hondoh, 2000). Keeping these unique characteristics in mind, we now examine the possible effects of pressure on creep and the development of fabric and texture in polycrystalline ice.

Following Poirier (1985), the possible effects of increased hydrostatic pressure on creep and fabric development include:

1. Resistance to dislocation formation and multiplication can occur with increasing P, as the presence of a dislocation represents a less perfect and therefore slightly higher volume crystal compared to similar defect-free crystal (Poirier, 1985). In some polycrystals with very large *elastic* anisotropy, dislocations and associated transient plastic flow can be generated under application of high P (Margevicius and Lewandowski, 1991) but this type of dislocation generation is negligible for ice as it is nearly elastically isotropic (Schulson and Duval, 2009). Margevicius and Lewandowski characterized the relative isotropy of hexagonal materials via the ratio of c-axis to a-axis linear compressibilities, k_c/k_a. Using the compliance data of Gammon et al. (1983) for ice, we find that k_c/k_a for ice is 1.14, compared with values of 1.0 for a perfect elastically isotropic material and 8.7 for the strongly elastically anisotropic material cadmium.
2. Changes in dislocation production rate from Frank–Read sources can occur if the shear modulus G of the material changes with P. These sources have been observed to operate in single crystal ice (Ahmad et al., 1986), but are unimportant compared to the production of dislocations at grain boundaries (Liu et al., 1993, 1992). This effect is also likely negligible as G decreases by less than 0.2% from $P = 0.1$ to 20 MPa (Helgerud et al., 2009), yet another unusual characteristic of ice compared to most materials whose shear moduli typically increase with P.
3. Strengths of dislocation–dislocation and dislocation–obstacle interactions are also expected to increase linearly with G (Hirth and Lothe, 1982). Given the negligible change in G with P for ice as discussed above, little change in the dislocation interaction strength is expected in ice.
4. The pressure dependence of the Peierls stress, or lattice friction, can also act to hinder the motion of dislocations under high pressure (Poirier, 1985). Peierls stress variation with P has not been quantified for ice, though it seems that the essentially null result of Cole (1996) for basal slip and the noted absence of lattice friction for non-basal dislocations (Petrenko and Whitworth, 1999) suggests that this mechanism is unimportant for ice, though other opinions exist (Louchet, 2004). We note here that lattice friction is *not* the same as dislocation drag associated with proton disorder effects discussed below.
5. Dislocations in materials with low stacking fault energies often split into two partial dislocations bounding a ribbon of stacking fault between them (Hirth and Lothe, 1982). The width of these dissociated (or extended) dislocations can be described by $w \propto G/(\gamma_F + \alpha P)$ where α is a constant proportional to the lattice dilatation associated with the presence of the stacking fault (Fontaine and Haasen,1969, Poirier,1985). Increasing P will act to constrict dissociated dislocations and enhance the rate of recovery through dislocation climb and cross-slip (Aladag et al., 1970, Nabarro, 2006, Weertman, 1965). Given the extraordinarily low γ_F of ice, we expect that most dislocations are very widely extended on the basal plane (Hondoh, 2000, Landgon, 1973, Tyson, 1971). The pressure sensitivity for the width of these dissociated dislocations depends strongly on the lattice dilation associated with stacking faults.
6. Dislocation motion in ice is thought by some to be controlled in some way by proton disorder (Glen, 1968), though contrary theories have been developed (Louchet, 2004) which point to lattice friction as the rate limiting mechanism for basal dislocation motion. Experimental works by Chan et al. (1965) on polycrystalline ice and Taubenberger et al. (1973) on single crystal ice both demonstrate that proton relaxation times increase with increasing P. This effect is expected to be quite small over the pressure range of our study, with a change in proton relaxation time of less than 5% for a pressure change of 20 MPa. In thermodynamic regions where proton-disorder control of basal dislocation glide is a likely rate-limiting mechanism, dislocation motion and therefore strain rate may decrease slightly with increasing pressure. Petrenko and Whitworth (1999) suggest that the barrier to motion presented by the proton disorder mechanism should be much higher for reconstructed dislocations than for partials.
7. Dislocation climb requires a supply of point defects. In the case of ice at under pressure, the concentration of self-interstitials is slightly higher (Hondoh, 2000, Hondoh et al., 1987) than atmospheric pressure (2.9 ppm at $P = 20$ MPa vs 2.78 ppm at 0.1 MPa). In thermodynamic regions where self-interstitial driven dislocation climb is the rate-limiting process, we might expect a modest increase in recovery and strain rate with increasing P.

We note that the above effects can be expected to have conflicting impacts on both the strain rate and microstructural development of polycrystalline ice.

1.2. Review of single crystal experiments

Studies of hydrostatic pressure effects on the dominant $(0001)\langle 11\bar{2}0\rangle$ basal slip system in single ice crystals have found two very different behaviors. Rigsby (1958) found no pressure effect on basal creep rate at constant *homologous* temperature.

Cole (1996) found no pressure effect on the steady state creep rate at constant *absolute* temperature. These results, though somewhat contradictory, both emphasize that the pressure effect on the basal slip system, if it exists, is small within the P range relevant to ice on Earth.

1.3. Review of polycrystal experiments

Work to date on polycrystalline ice has shown a measurable effect on creep strain rates due to elevated hydrostatic pressure. Early testing was performed by Haefeli et al. (1968) who compared creep strain rates both at constant absolute and constant homologous temperatures at pressures of 0.1 and 29.5 MPa. In contrast to single crystal behavior, they found that elevated hydrostatic pressure increased the creep rate at a fixed absolute temperature, though conducting the test at the equivalent homologous temperature and atmospheric pressure increased it still more. No microstructural analysis of the creep-deformed specimens was reported and applied axial stresses were <0.1 MPa.

Jones and Chew (1983a) tested polycrystalline ice at a variety of pressures from 0.1 up to 50 MPa, an applied axial stress of 0.47 MPa and a constant absolute temperature of −9.6 °C. Significantly, they found that secondary creep rates slowed with increasing P, passed through a minimum at ~15 MPa hydrostatic pressure, and then increased up to the maximum test condition of $P = 60$ MPa. This