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# The down-stress transition from cluster to cone fabrics in experimentally deformed ice

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ABSTRACT

During plastic deformation of polycrystalline ice 1h, ice crystals become crystallographically aligned due to dislocation glide, primarily on the basal slip system. Such crystallographic preferred orientation (CPO) introduces a viscous anisotropy in ice, and thus strongly influences the kinematics of the flow of glaciers and ice sheets. Two key mechanisms exert different controls on CPO. In axial compression, recrystallization dominated by lattice rotation yields a cluster of *c*-axes parallel to compression, and recrystallization dominated by grain boundary migration (GBM) yields a cone-shaped distribution of *c*-axes with the cone axis parallel to compression. The transition between these dominant mechanisms of CPO formation has not been well quantified. In this study, we explore how this transition varies with stress. Ice deformation experiments were conducted using a high-pressure, gas-medium apparatus to prevent fracturing of samples at relatively high stresses. Samples were deformed in uniaxial compression at a temperature of ∼−10 °C and a confining pressure of 10 MPa. Fabricated ice samples with starting average grain sizes of either ∼0.23 mm or ∼0.63 mm were each deformed to an axial strain of ∼0.2 at a nominally constant strain rate in the range $1.2 \times 10^{-6}$ to $2.4 \times 10^{-4}$ $s^{-1}$, yielding flow stresses of 1.17 to 4.31 MPa. High-quality electron backscatter diffraction reveal the grain size, shape, subgrain structure, and CPOs formed at different stresses. All deformed samples have strong, non-random CPOs with *c*-axes concentrated in cones. The cone angle and CPO strength are observed to decrease with increasing stress. As stress increases, the fraction of grains with highly curved or lobate grain boundaries decreases and the fraction of polygonal grains with straight grain boundaries increases. Based on these observations, we propose that a transition in the dominant mechanism of CPO formation occurs with increasing stress, from GBM, which consumes grains with low Schmid factors at low stress, to lattice rotation caused by slip primarily on the basal slip system, which causes *c*-axes to rotate to become parallel to the shortening direction at high stress. Mapping out the transition from cluster (rotation-dominated) to cone (GBM-dominated) CPOs as a function of stress (this study) and temperature (future studies) allows for a robust extrapolation to, and a fundamental understanding of the CPOs formed at, glaciological stresses and temperatures.

## 1. Introduction

Crystallographic preferred orientations (CPOs) induced by plastic deformation translate the kinematics of deformation into anisotropy in the microstructure of rocks (e.g., Wenk and Christie, 1991), including ice sheets and glaciers (e.g., Faria et al., 2014). In return, such anisotropic microstructures may result in a "viscous anisotropy" (Azuma, 1995; Hansen et al., 2016; Tommasi et al., 2009), enhancing plastic deformation in some orientations of the CPO relative the ambient stress state, and impeding it in others. The patterns of CPOs change with the kinematics and other conditions (temperature, stress and strain) of deformation (Schmid and Casey, 1986; Alley, 1992; Karato et al., 2008). The CPOs and microstructures that develop during deformation are influenced significantly by the operative deformation mechanisms (Warren et al., 2008) and, at high homologous temperatures in the dislocation creep regime, via dynamic recrystallization (Law, 2014; Signorelli and Tommasi, 2015).

Glaciers and ice sheets are major rock bodies on the Earth's surface that develop very strong CPOs as they deform (Alley, 1992; Budd and Jacka, 1989; Hudleston, 2015; Wilson et al., 2014). These CPOs may impart significant anisotropy to ice flow (Azuma, 1995; Castelnau et al., 1998; Duval et al., 2010) which may have an important influence on the development of large-scale ice structures

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(Bons et al., 2016; Hulbe and Whillans, 1997; Pettit et al., 2007). Such effects thus need to be understood mechanistically, quantified and incorporated into robust constitutive models of ice flow (flow laws) that can be employed in models of glaciers and ice sheets (Gagliardini et al., 2013). Sophisticated models exist for CPO development in ice (Kennedy and Pettit, 2015; Llorens et al., 2016); however, these theoretical models require comparisons with and inputs from observations of CPOs that develop for a particular set of deformation conditions. Laboratory deformation experiments provide the best observational data on CPO development to test such models.

Ice also comprises a large fraction of the surface and subsurface layers on other astronomical bodies in the solar system. The rheological behavior of ice has been incorporated into many different models to understand convection and thermal evolution in the ice crusts of Europa and Ganymede, icy satellites of Jupiter (e.g., Ruiz, 2010; Freeman et al., 2006), to understand viscous relaxation of topography, such as cryovolcanoes and craters, on the dwarf planet Ceres (e.g., Sori et al., 2017), and to explain the existence of "mountains" on Pluto, which are far too viscous to be comprised of solid nitrogen (e.g., Moore et al., 2016). Although a composite flow law for ice (Goldsby and Kohlstedt, 2001) has been widely adopted in these models, the existence of CPOs and their influence on the viscosity of ice have not been considered. As ice is a highly anisotropic material, a strong CPO can significantly weaken the ice, depending on the orientation of the CPO relative to the ambient stress field. This viscous anisotropy might weaken ice and accelerate the convection process in current planetological models, but might also strengthen the ice if the kinematics of deformation changes from that which gave rise to the initial CPO.

Ice is also an excellent material with which to develop an understanding of the fundamental controls on CPO development in other materials. Ice has been considered as an analogue for quartz, given their similar crystal structures (Wilson et al., 2014). Ice microstructures (including CPOs) also have many similarities to those observed in mantle xenoliths (Michibayashi et al., 2007). Understanding the development of viscous anisotropy is equally as important for understanding mantle flow as it is for understanding the flow of natural ice bodies. Moreover, the potential exists to link CPO measurements made in cored ice samples (Faria et al., 2014; Thorsteinsson et al., 1997; Treverrow et al., 2016) with seismological observations (Picotti et al., 2015) on the cored ice body, providing a test of our ability to infer physical properties from seismic data in less accessible natural settings, such as in Earth's mantle. Understanding CPO development in ice thus has implications for the mechanics of terrestrial and planetary ice flow and, by analogy, the mechanics of the Earth's crust and mantle (Tommasi et al., 2009).

In this paper, we present the results of new laboratory experiments that constrain the role of strain rate (or stress) in controlling recrystallization mechanisms in ice and on the microstructures and CPOs that result. A key component of our study is the use of cryo-electron backscatter diffraction (EBSD) (Prior et al., 2015). The EBSD technique provides a level of microstructural detail in analysis of deformed ice samples that has not previously been possible.

## 2. Background

The response of polar ice sheets to global warming and the resulting consequences for sea-level rise are critical scientific questions (Golledge et al., 2015; DeConto and Pollard, 2016). The rate of ice flow depends fundamentally on its material properties (Alley, 1992; Duval et al., 2010). An ice single crystal deforms predominantly by dislocation glide along the basal plane, (0001) (Duval et al., 2010), in a manner analogous to shearing a deck of cards. When polycrystalline ice (e.g., glacier ice) deforms, individual ice crystals deform via glide and rotate to become strongly aligned (Duval et al., 2010; Hudleston, 2015). This CPO may impart a mechanical, or viscous, anisotropy to ice, making shear parallel to the aligned basal planes easy and deformation in other orientations more difficult (Azuma, 1995). When the loading that drives ice flow changes (e.g., following an ice shelf collapse, Scambos et al., 2003), the rate of response will depend upon the inherited CPO and its subsequent evolution in the new stress configuration (Hudleston, 2015). The mechanical response of the ice sheet system to climate forcing thus depends, in part, on the evolution of the CPO (Alley, 1992; Duval et al., 2010; Hudleston, 2015). Furthermore, CPOs measured in natural ice samples (Faria et al., 2014), or calculated from seismic data (Picotti et al., 2015), have the potential to constrain ice deformation conditions and history in the same manner that CPOs for quartz (Schmid and Casey, 1986; Law, 2014) and olivine (Karato et al., 2008) constrain deformation in the Earth's crust and mantle, respectively.

Alley (1992) hypothesized that CPOs in natural ice are controlled by the deformation kinematics (flattening, extrusion, simple shear) and by whether the CPO develops due to dynamic recrystallization by lattice rotation alone (including polygonization/subgrain rotation) or in combination with grain boundary migration (GBM). Alley's description of recrystallization is one in which grains with high resolved shear stresses on the basal plane grow when strain-induced GBM becomes significant (Little et al., 2015; Montagnat et al., 2015). During axial compression, rotation and polygonization are predicted to yield CPOs with [0001]-axes (*c*-axes) concentrated parallel to the compression direction, whereas recrystallization by GBM would yield a hollow cone (a small circle on a stereonet) of *c*-axes, with the cone axis parallel to the compression direction (Alley, 1992).

Constraining how CPO-forming mechanisms and the resultant CPOs are controlled by kinematics and environmental conditions, principally strain rate, stress, and temperature, is crucial to predicting the CPOs in a deforming glacier or ice sheet and their influence on viscous anisotropy. Experimental deformation of quartz aggregates (Hirth and Tullis, 1992) and observations of CPOs in naturally deformed rocks (Stipp et al., 2002) demonstrate that a transition from microstructures and CPOs dominated by lattice rotation and polygonization to those dominated by GBM occurs with increasing temperature and decreasing differential stress (or strain rate).

Laboratory constraints on CPOs in ice (e.g., Kamb, 1972; Budd and Jacka, 1989; Wilson et al., 2014) are primarily derived from experiments conducted at high homologous temperature ($>-15\,^\circ$C, with most $>-5\,^\circ$C) across a relatively narrow range of stresses. This is because at ambient pressure, the relatively high flow stresses that occur at lower temperatures will induce fracture. Necessarily lower stresses mean experiments take an impractically long time to achieve the significant strains ($>0.1$) required for CPO development at low temperatures.

Unlike ambient pressure tests, experiments on ice at elevated confining pressure (Durham et al., 1983, 2001) allow driving stresses approximately equivalent to the confining pressure to be applied to samples without fracture. This enables a much wider range of stresses to be studied and experiments to be conducted at colder temperatures, without fear of fracturing the samples.

Axial compression experiments on ice at temperatures $>-15\,^\circ$C all yield CPOs characteristic of GBM, i.e., cones of *c*-axes (Kamb, 1972; Budd and Jacka, 1989; Wilson et al., 2014). At such high homologous temperatures, GBM enables rapid CPO development (Montagnat et al., 2015) within strains of 0.1 or less. The few published data from long-duration, lower-temperature experiments show a decrease of CPO strength with decreasing temperature (Jacka and Jun, 2000). The CPO observed at $-15\,^\circ$C in the experiments of Jacka and Jun (2000) is a cone fabric, and the CPOs