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Review article

Microstructure and fabric development in ice: Lessons learned from *in situ* experiments and implications for understanding rock evolution

Christopher J.L. Wilson [a,*], Mark Peternell [b], Sandra Piazolo [c], Vladimir Luzin [d]

[a] *School of Geosciences, Monash University, Clayton, Victoria 3800, Australia*
[b] *Institute of Geosciences, University of Mainz, 55128 Mainz, Germany*
[c] *Australian Research Council Centre of Excellence for Core to Crust Fluid Systems/GEMOC, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia*
[d] *ANSTO Locked Bag 2001, Kirrawee DC, Lucas Heights, NSW 2232, Australia*

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ABSTRACT

In this contribution we present a review of the evolution of microstructures and fabric in ice. Based on the review we show the potential use of ice as an analogue for rocks by considering selected examples that can be related to quartz-rich rocks. Advances in our understanding of the plasticity of ice have come from experimental investigations that clearly show that plastic deformation of polycrystalline ice is initially produced by basal slip. Interaction of dislocations play an essential role for dynamic recrystallization processes involving grain nucleation and grain-boundary migration during the steady-state flow of ice. To support this review we describe deformation in polycrystalline 'standard' water-ice and natural-ice samples, summarize other experiments involving bulk samples and use *in situ* plane-strain deformation experiments to illustrate the link between microstructure and fabric evolution, rheological response and dominant processes. Most terrestrial ice masses deform at low shear stresses by grain-size-insensitive creep with a stress exponent ($n \leq 3$). However, from experimental observations it is shown that the distribution of plastic activity producing the microstructure and fabric is initially dominated by grain-boundary migration during hardening (primary creep), followed by dynamic recrystallization during transient creep (secondary creep) involving new grain nucleation, with further cycles of grain growth and nucleation resulting in near steady-state creep (tertiary creep). The microstructural transitions and inferred mechanism changes are a function of local and bulk variations in strain energy (i.e. dislocation densities) with surface grain-boundary energy being secondary, except in the case of static annealing. As there is a clear correspondence between the rheology of ice and the high-temperature deformation dislocation creep regime of polycrystalline quartz, we suggest that lessons learnt from ice deformation can be used to interpret polycrystalline quartz deformation. Different to quartz, ice allows experimental investigations at close to natural strain rate, and through *in-situ* experiments offers the opportunity to study the dynamic link between microstructural development, rheology and the identification of the dominant processes.

1. Introduction

Deformation in ice occurs on a variety of scales and has been used by numerous workers as an analogue for processes that contribute to rock deformation. The reason for this is that glacier ice and rock at high metamorphic grade deform according to the same non-linear flow laws. Ice is therefore an ideal analogue as it contains folds, faults, boudinage structures and shear zones that can be observed at both the mesoscale and macroscale (Nye, 1953; Hambrey, 1977; Marmo and Wilson, 1998) and has been used successfully as a rock analogue (Wilson, 1981, 1983). In contrast to rocks, in glaciers it is possible to measure directly the strain rate associated with the development of structures in glaciers. By integrating strain rate measurements with constitutive flow laws and material properties one can determine the distribution and history of the stress. It is generally agreed that upon application of a constant stress or constant strain rate, a sample of polycrystalline ice with a random fabric will show an initial elastic deformation followed by a stage of decelerating creep rate, and finally a stage of accelerating creep rate (Budd and Jacka, 1989). The acceleration

* Corresponding author. Tel.: +61 399055764; fax: +61 3 99054903.
E-mail address: Chris.Wilson@monash.edu (C.J.L. Wilson).

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may be a result of; (1) dislocation multiplication and rearrangement on a submicroscopic scale (Montagnat and Duval, 2000), (2) recrystallization and the development of a non-random fabric (Wilson, 1986); and/or (3) formation of microcracks and fractures (Golding et al., 2010, 2012).

As in many crystalline materials, such as rocks and metals, deformation in ice crystals mostly occurs by crystal-plastic mechanisms that give rise to dynamic recrystallization, that involve grain-boundary migration and dynamic recrystallization (Duval et al., 1983). Available evidence indicates that the driving force for flow of ice during natural deformation is caused mainly by temperature and stress differences (Ma et al., 2010) induced by gravitational forces acting on the sloping ice body (Donoghue and Jacka, 2009). Major ice sheets experience cycles of long-range stress fields that lead to plastic deformation (Taupin et al., 2008) or cycles of elastic stress build-up during interseismic periods followed by rapid stress drops during crevasse formation (Van der Veen, 1998). Furthermore, a particular volume of ice will be subject to changing temperature, depth and deviatoric stress conditions, where temperature and depth will change with time. During deformation of natural ice, strain rate increases as temperature increases so that microstructures formed under steadily increasing deviatoric stress are superimposed. These complications make it exceptionally difficult to extract information from natural-ice microstructures and relate it to the evolution of crystallographic preferred orientations, namely *c*-axis fabrics (Fig. 1a–b), and also to a strain history. Experiments show that creep strength in natural ice is also strain rate dependent (Barnes et al., 1971); therefore it must respond to these stress cycles and will not be steady-state. Change in the strain rates accommodated by different creep mechanisms that accompany stress cycling, control creep mechanics (rheology) and resultant microstructures. Most laboratory ice-creep experiments aim to achieve steady-state tertiary creep (Fig. 2) and there is a lack of experiments involving high stress/strain rate deformation that is followed by static annealing that would give some insight into the more complicated stress-temperature histories likely in a glacier (Paterson, 1994).

Both ice core data and ice-deformation laboratory experiments provide very good systems to study the deformation heterogeneity development and dynamic recrystallization mechanisms for highly anisotropic materials. As such they constitute a valuable data set to validate numerical modelling approaches for polycrystal mechanical behaviour (Lebensohn et al., 2007; Montagnat et al., 2011; Griera et al., 2013). Major advances in the characterization of the heterogeneous deformation of ice has been provided by microstructural observations derived from experiments in transmitted light, which permit direct observation of grain-scale processes during dynamic and static recrystallization (Wilson, 1986). Similar advances are found in the geological literature where there is a range of experiments that attempt to quantify microstructural and rheological evolution of rocks (Means, 1980). It is the microstructure of ice and its response to a stress regime that holds the key to understanding the macroscopic rheological behaviour of glaciers and ice sheets and the nature of their flow mechanisms. Thus, to understand the behaviour on a macroscale it is essential to understand substructure dynamics and how this exerts an influence

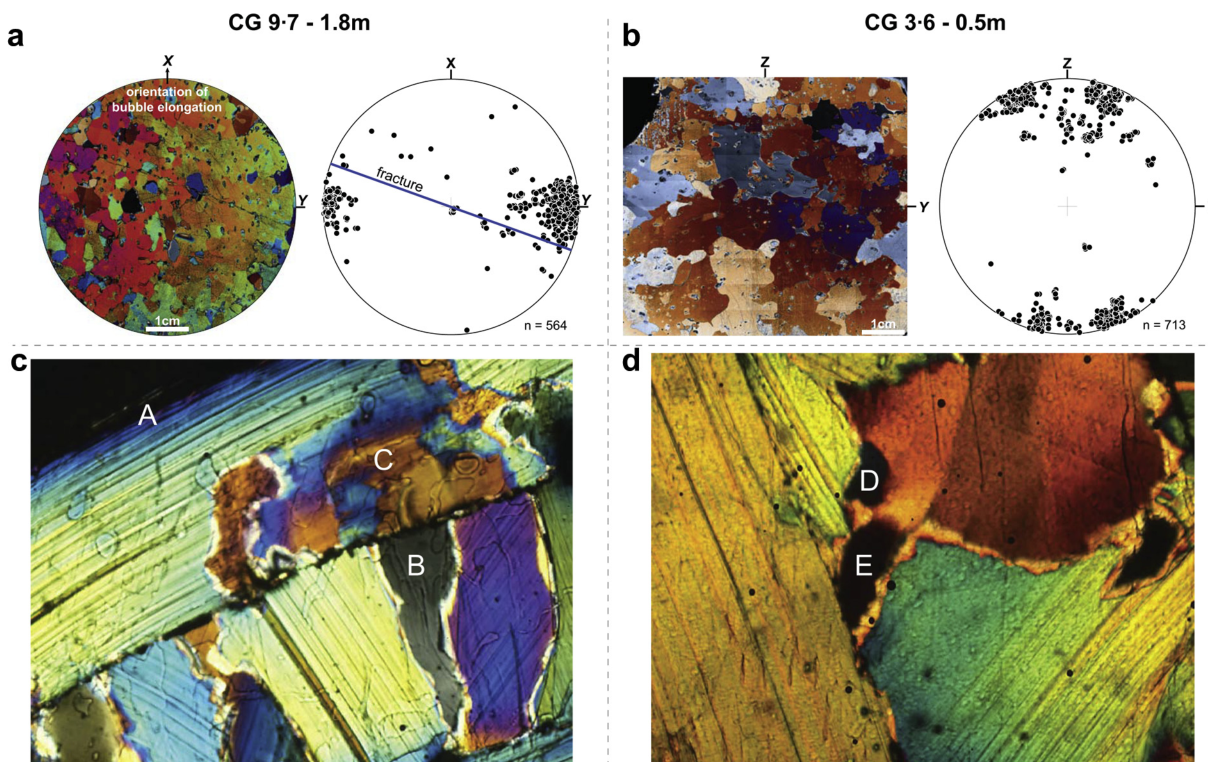

Fig. 1. Examples of grain microstructures and *c*-axis variations in polar ice of the Sørsdal Glacier and experimentally deformed ice. (a) Section cut perpendicular to ice layering in Sørsdal Glacier (1.8 m in CG 9.7; see Wilson and Peternell, 2012) illustrating the interlocking nature of the grains that overgrow air bubbles and cut by a later fracture. The ice crystallographic preferred orientation is characterized by a single maximum *c*-axis crystal orientation pattern perpendicular to the air bubble alignment (×). (b) Ice cut perpendicular to the flow layering and air bubble alignment in Sørsdal Glacier (0.5 m in CG 3.6; see Wilson and Peternell, 2012), illustrating undulose extinction and small-circle girdle of *c*-axes (c) Basal slip lamellae that reflect the basal slip in anisotropic ice grains (e.g. grain A) in a 0.7 mm thick sheet of ice deformed deformed at −5 °C and strain rate of 8.7×10^{-7} s^{-1} during a 2D *in situ* experimental deformation. Other smaller grains (e.g. grain B) have undergone grain-boundary migration. Overgrowing grain A is a set of new grains (C). (d) Experimentally deformed ice with nucleation of new grains (D and E) along grain boundaries, between grains that display slip lines produced by basal slip in differently oriented grains.