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Slip-band distributions and microstructural fading memory beneath the firn–ice transition of polar ice sheets[☆]

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ABSTRACT

The Antarctic Ice Sheet is a continental ice mass with circa 23 million gigatons of ice, which represent roughly 67 % of world's freshwater supply. This colossal mass of ice is by no means static, as the old ice slowly creeps under its own weight towards the ocean, while new ice is continually formed through the sintering of snow deposited on the ice sheet surface. A crucial role in this metamorphism is played by firn, which is the porous material in an intermediate state between the granular snow and the solid polycrystalline ice. Understanding the snow–firn–ice metamorphism is essential not only for a precise determination of the mechanical (creep) properties of polar ice, but also for comprehending the formation and decay of climate proxies widely used in ice-core studies. This work investigates the transition from firn to ice through the spatial and directional distributions of slip bands in bubbly ice. The analysis of high-resolution micrographs of ice sections extracted from the EPICA-DML Deep Ice Core allows us to identify a clear influence of strain-induced anisotropy (viz. *c*-axis preferred orientations) on the evolution of slip-band inclinations in deep bubbly ice. In contrast, we discover an unanticipated behaviour of slip bands in shallow bubbly ice, which prompts the introduction of the hypothesis of *microstructural fading memory* and the definition of a *stabilization zone* that may penetrate hundreds of metres into the bubbly ice. Within this stabilization zone, highly localized concentrations of strain energy and internal stresses once generated by force chains in the ancient firn are gradually redistributed by the newly formed bubbly-ice microstructure. We show that this hypothesis is compatible with the localized dynamic recrystallization episodes observed in polar firn (even at temperatures close to −45 °C), and it may also explain the sluggish rotation of *c*-axes observed in the upper hundreds of metres of polar ice sheets.

1. Introduction

With an average thickness close to 2 km (and in many places surpassing the 3 km mark), the Antarctic Ice Sheet covers a continental area larger than 13×10^6 km^2. This amounts to astonishing 23 million gigatons of ice (or 25×10^6 km^3, including ice shelves), which represent roughly 67 % of world's freshwater supply and a potential contribution to global sea-level rise of 58 m [34,50]. Such a colossal mass of ice is by no means static. Old ice slowly creeps under its own weight towards the ocean, while new ice is formed through the sintering of snow that is continually deposited on the ice sheet surface.

As it occurs with most crystalline solids, ice may undergo *creep* (viz. visco-plastic deformation) at rather low stresses, provided that its temperature is higher than roughly half of its pressure melting point [13,41]. Seeing that this condition is fulfilled anywhere on Earth's surface, it should be no surprise that glaciers and ice sheets creep under their own weight. Even though the creep of such large ice masses is an expected phenomenon, its microscopic mechanisms have been challenging glaciologists for decades. In particular, a fundamental feature of the micro-mechanics of ice is its exceptional propensity to form *slip bands*, which are characteristic, microscopic fringes visible within certain ice grains or crystals undergoing simple shear [27,38]. Considering that such slip bands are microscopic expressions of *basal slip* (viz. simple shear along a particular family of crystallographic planes, called *basal planes*) within an ice grain, we conclude that the occurrence of these fringes depends not only on the macroscopic deformation regime, but also on the crystalline properties of the grain and its interactions with neighbours.

The neighbourhood of a particular ice grain is mainly defined by the positions, crystalline orientations, shapes and sizes of the

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[☆] Dedicated to my mentor and friend, Kumiko Goto-Azuma, on occasion of her 60th birthday.

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surrounding grains, which combined describe the local *orientation stereology* [9,19,22]. Under this perspective, the current neighbourhood of an ice grain is in fact a fading record of the local orientation-stereology history [18], which begins with the deposition of snow crystals on the glacier or ice-sheet surface, and develops through the metamorphism of snow into firn and ice. Such a record is evanescent because it is gradually obliterated by thermomechanical processes of deformation, recovery, and recrystallization (following [19,22], the terms *recovery* and *recrystallization* are used here in a wide sense, including static and dynamic processes of structural change, like grain growth, grain boundary migration, and subgrain rotation). While ice microstructural changes directly related to deformation (e.g. crystalline lattice rotation, grain elongation, etc.) are relatively well understood and reproducible by models [1,3,4,20,25,43], rates of recovery and recrystallization of natural firn and ice are largely unknown [22,42]. This lack of knowledge severely impairs the modelling of ice microstructure evolution and consequently limits the current predictive power of ice flow models and the interpretations of ice-core climate proxies.

This work aims to help clarifying the roles played by recovery and recrystallization in the fading memory of the local orientation stereology of polar firn and ice, therefore paving the way to a future quantification of these thermodynamic processes. This objective is achieved through the analysis of the orientation distributions of slip bands, which are identified in high-resolution, microscopic images of ice sections extracted from eight distinct depths of the EPICA-DML Deep Ice Core, from the EPICA (European Project for Ice Coring in Antarctica) drilling site in Dronning Maud Land (DML), Antarctica.

Precise definitions of the technical terms used in this work can be found in the glossaries presented by Faria et al. [19,22]. The following section introduces the most fundamental concepts and put them into the context of the current study.

2. Fundamental concepts

Under the natural conditions typically found on Earth's surface, ice occurs in the ordinary hexagonal form named *ice Ih*. With an atomic packing factor of less than 34 %, ice Ih has a rather open, wurtzite-like crystalline lattice [15,27], which is characterized by oxygen ions arranged in layers (called *basal planes*) of “puckered” hexagonal rings piled in an alternate sequence of mirror images normal to the axis of optical and crystallographic (hexagonal) symmetry of the crystal, viz. the *c axis*. Hydrogen nuclei (protons) remain statistically distributed in the oxygen lattice, building covalent and hydrogen bonds along the lines joining pairs of oxygen ions [6,40]. This *proton disorder* plays a fundamental role in ice plasticity, as it affects the motion of the main agents of plastic deformation of ice: *dislocations* [23,24,41].

Experience shows that the plasticity of monocrystalline ice is strongly anisotropic, with ice single crystals deforming very readily when the applied shear stress acts on the basal plane [14,27], through a process called *basal slip* and epitomized more than a century ago by McConnel's [35] “deck of cards” metaphor. This phenomenon was later beautifully illustrated by Nakaya [38], who used shadow photography to reveal *slip bands* in deformed monocrystalline ice bars. Not long after, Bryant and Mason [8] found grouped etch pits and channels along slip bands in resin replicas of deformed ice monocrystals, corroborating the prevalent hypothesis that slip bands consisted of microscopic layers with high density of dislocations undergoing basal slip. In contrast to laboratory tests, the optical observation of slip bands in polar ice turns out to be much more challenging, because of the very low strain rates typical of ice-sheet flow. Nevertheless, modern microscopy techniques, like the microstructure mapping (µSM) method adopted in this study, have revealed that slip bands are indeed a common feature also of polar ice [17,31,52].

3. Methods

All ice samples investigated here stem from the EPICA-DML Deep Ice Core [19]: a 2774.15 m long ice core extracted from the EPICA (European Project for Ice Coring in Antarctica) drilling site at Dronning Maud Land (DML), Antarctica (75°00′09″S, 00°04′06″E, 2892 m a.s.l.). Eight ice samples were selected, consisting of vertical thick sections ($\approx 50 \times 100 \times 5$ mm) cut lengthwise the EPICA-DML Deep Ice Core at roughly 100 m intervals. Details of the samples are described in Table 1. Following the usual convention of the ice-core physical-properties community, all depths are *rounded down*. The sampling approximately covered the upper 850 m of ice, i.e. the last 16 ka BP [45]. The reason to chose this depth range is threefold, being mainly related to changes in the physical properties of the ice core, as well as changes in the ice flow and climatic conditions in Antarctica, namely:

1. Below 800 m depth commences the EPICA-DML bubble–hydrate transition zone, where air bubbles are no longer thermodynamically stable and start transforming themselves into air hydrates [5,16,21,49].
2. Even though no well-defined “brittle zone” has been discerned in the EPICA-DML site, the ice-core quality between 800 m and 1000 m depth was conspicuously lower [16,19,55].
3. The onset of the Antarctic Ice Sheet retreat from its Last Glacial maximum extent is estimated to have occurred not longer after 16 ka BP [11].

Ice samples were prepared and analysed through the method of *Microstructure Mapping* (µSM), which is essentially a digital form of optical microscopy [17,31,52,54]. The µSM method consists of a digital video camera with automatic gain control mounted on an optical microscope equipped with a computer-controlled *xy*-stage. The microscope automatically scans the whole sample, mapping a variety of microstructural features inside the ice (ranging from microinclusions and dislocation walls to air bubbles, clathrates, and slip bands) with a microscopic resolution of ca. 3 µm per pixel. Up to 1800 photomicrographs may be needed to reconstruct a high-resolution digital mosaic image of a 50×100 mm section. Micrographs are usually taken in transmitted light, with a standard size of 2.5×1.8 mm and a typical overlapping of ca. 0.5 mm, which facilitates the later reconstruction of the full mosaic image through the matching of neighbouring micrographs.

All µSM micrographs analysed in this work are freely available at the Pangaea digital data library [29].

The preparation of µSM samples follows the usual procedures for ice microscopy [31,54]. Band saws and microtomes are respectively used for cutting and polishing the sections. Clear surfaces are achieved by exposing the polished section to the free atmosphere: sublimation smooths the ice surface through the removal of superficial imperfections (e.g. microtome scratches), while it simultaneously highlights the sites where grain boundaries and other high-energy structures meet the surface, through the formation of characteristic thermal-etching grooves and pits [27,33,37,39]. A sublimation time varying between half an hour and half a day is usually necessary to obtain a clear surface, with well-developed grain-boundary grooves. This sublimation time strongly depends on the conditions of temperature, humidity, and air circulation above the sample.

After the first (lower) surface of the section is sufficiently clear, it is sealed off with a thin film of silicone oil and frozen onto a glass plate. The second (upper) surface is treated in the same manner, but it is sealed off with silicone oil and glass only after the first surface scan is completed, in order to optimize the quality