Journal of Structural Geology 61 (2014) 21–49

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Review article

# The microstructure of polar ice. Part II: State of the art

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A R T I C L E I N F O

*Article history:*
Received 23 September 2013
Received in revised form
27 October 2013
Accepted 11 November 2013
Available online 20 November 2013

Dedicated to Sepp Kipfstuhl on occasion of his 60th birthday.

*Keywords:*
Ice
Glacier
Ice sheet
Mechanics
Creep
Recrystallization
Grain growth
Microstructure
Fabric
Texture

A B S T R A C T

An important feature of natural ice, in addition to the obvious relevance of glaciers and ice sheets for climate-related issues, is its ability to creep on geological time scales and low deviatoric stresses at temperatures very close to its melting point, without losing its polycrystalline character. This fact, together with its strong mechanical anisotropy and other notable properties, makes natural ice an interesting model material for studying the high-temperature creep and recrystallization of rocks in Earth's interior. After having reviewed the major contributions of deep ice coring to the research on natural ice microstructures in Part I of this work (Faria et al., 2014), here in Part II we present an up-to-date view of the modern understanding of natural ice microstructures and the deformation processes that may produce them. In particular, we analyze a large body of evidence that reveals fundamental flaws in the widely accepted *tripartite paradigm* of polar ice microstructure (also known as the "three-stage model," cf. Part I). These results prove that grain growth in ice sheets is *dynamic*, in the sense that it occurs during deformation and is markedly affected by the stored strain energy, as well as by air inclusions and other impurities. The strong plastic anisotropy of the ice lattice gives rise to *high internal stresses* and *concentrated strain heterogeneities* in the polycrystal, which demand large amounts of strain accommodation. From the microstructural analyses of ice cores, we conclude that the formation of many and diverse subgrain boundaries and the splitting of grains by *rotation recrystallization* are the most fundamental mechanisms of dynamic recovery and strain accommodation in polar ice. Additionally, in fine-grained, high-impurity ice layers (e.g. cloudy bands), strain may sometimes be accommodated by *diffusional flow* (at low temperatures and stresses) or *microscopic grain boundary sliding* via *microshear* (in anisotropic ice sheared at high temperatures). Grain boundaries bulged by *migration recrystallization* and subgrain boundaries are endemic and very frequent at almost all depths in ice sheets. Evidence of *nucleation of new grains* is also observed at various depths, provided that the local concentration of strain energy is high enough (which is not seldom the case). As a substitute for the tripartite paradigm, we propose a novel *dynamic recrystallization diagram* in the three-dimensional state space of strain rate, temperature, and mean grain size, which summarizes the various competing recrystallization processes that contribute to the evolution of the polar ice microstructure.



## 1. Introduction

An essential feature of Earth's dynamics is the hot deformation of large rock masses in a slow and continuous flow regime called *creep*. The study of creeping rocks is complicated by various factors; among them *diversity* and *inaccessibility*. The former means that rocks are seldom monomineral; rather, they are usually made of complex and variable compositions of minerals with distinct properties. The latter (inaccessibility) expresses the fact that field observations of creeping rocks are often very difficult or even impossible to perform, because most high-temperature deformation processes occur in Earth's interior.

For these reasons (not to mention other well-known reasons stemming from climatology; Lemke et al., 2007), the creep of ice turns out to be very interesting for geoscientists (Hudleston, 1977; Wilson, 1979, 1982; Burg et al., 1986; Kirby et al., 1991; Zhang and Wilson, 1997; for a deeper discussion see Wilson et al., 2014). The abundance, purity, and low melting point of natural ice make the

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http://dx.doi.org/10.1016/j.jsg.2013.11.003

field study of creeping glaciers and ice sheets a feasible task. Polar ice sheets over Greenland and Antarctica are particularly appealing in these respects, because of their immense mass (2.7 and $22.6 \times 10^{18}$ kg, respectively; Lemke et al., 2007) and purity (polar ice typically has an impurity content in the ppb range; Legrand and Mayewski, 1997), as well as their relatively simple and steady flow, when compared to smaller ice bodies like glaciers and ice caps (Paterson, 1994).

Evidently, the investigation of creep and recrystallization of polar ice sheets has also its shortcomings, mainly related to the complex logistics and drilling technology necessary for retrieving old ice samples from several kilometers of depth. A brief review of the difficulties and advances in deep ice core drilling in Antarctica and Greenland has been presented in the first part of this work (Faria et al., 2014)—from now on called *Part I*—together with the major contributions of deep ice coring to the research on natural ice microstructures. Through that historical synopsis we could appreciate how the current paradigm of natural ice microstructures has emerged, and also how it started being challenged in recent times.

Here in *Part II* we discuss in detail these recent challenges and show how they may reveal to us a new perspective of the mechanics and microstructure of natural ice. To achieve this aim, we carefully reconsider several aspects of our current understanding about natural ice microstructures and the deformation processes that may have produced them, including strain-induced anisotropy, grain growth, and dynamic recrystallization, among others. The whole review ends with a new paradigm for the microstructure evolution of natural ice. For convenience, the key concepts invoked in this work are summarized in a glossary in Appendix A.

As it will become evident in the next pages, in spite of many insightful studies of natural ice microstructures and deformation mechanisms, our knowledge about this subject is still imperfect and incomplete. On the other hand, we do have enough information to propose novel plausible models, which together with modern technologies are helping to make this field of research more promising and exciting than ever.

## 2. Crystalline structure and dislocations

Under natural conditions on Earth's surface, ice occurs in the ordinary hexagonal form of ice *Ih*. This should not be confused with its closely related cubic variant, ice *Ic*, which presents a similar tetrahedral coordination of oxygen atoms, but is metastable at all temperatures (Bartels-Rausch et al., 2012). Ordinary ice Ih has a rather open lattice, with an atomic packing factor of less than 34%, which accounts not only for its abnormally low density compared to liquid water, but also for the pressure-induced reduction of its melting point at high temperatures (Schulson and Duval, 2009).

Oxygen ions build the essence of the ice lattice (from now on the term "ice" refers to ordinary hexagonal ice Ih, except when explicitly mentioned otherwise). They are arranged in a structure which resembles that of wurtzite or high-tridymite (Hobbs, 1974; Evans, 1976; Poirier, 1985), viz. layers of puckered hexagonal rings piled in an alternate sequence of mirror images normal to the *c*-axis (Fig. 1). Hydrogen nuclei (protons) remain statistically distributed in the oxygen lattice, building covalent and hydrogen bonds along the lines joining pairs of oxygen ions (Pauling, 1935). This *proton disorder* is however not completely arbitrary: it must conform with the *Bernal–Fowler rules* (also called "ice rules"), which require that two protons should be close to any oxygen, with only one proton per bond (Bernal and Fowler, 1933). Hence, each oxygen is involved in two covalent and two hydrogen bonds.

The violation of the ice rules, either by an excess or a deficiency or protons, gives rise to particular point defects in the crystalline structure, known as *ionization* and *Bjerrum defects*. These point defects, together with more conventional molecular defects (*vacancies* and *interstitials*) play a fundamental role in the mechanics of ice, as they influence the motion of the main agents of deformation in ice: *dislocations* (Glen, 1968; Goodman et al., 1981; Okada et al., 1999; Petrenko and Whitworth, 1999; Louchet, 2004).

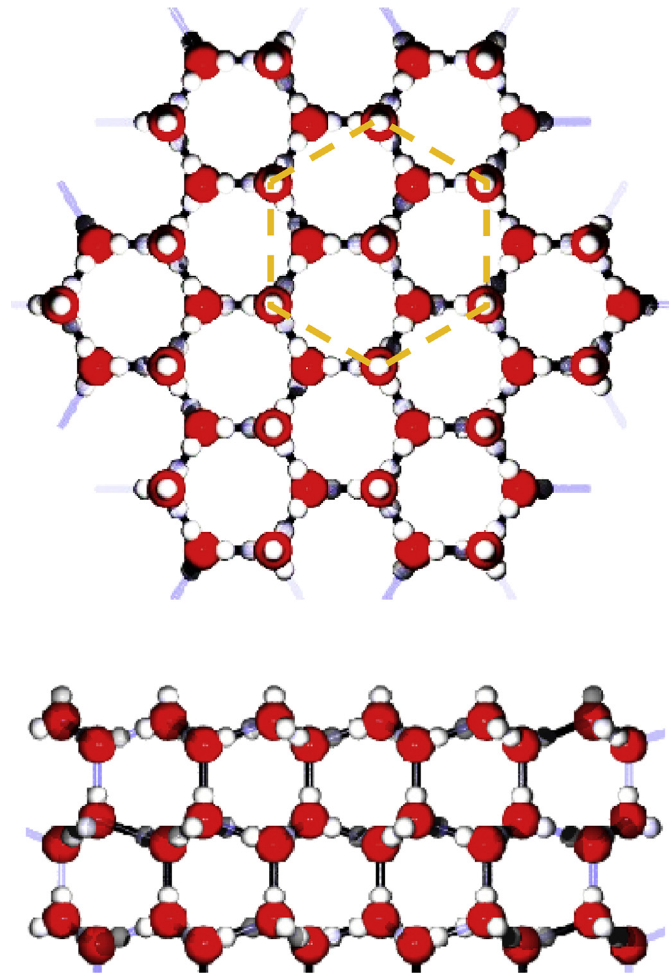

**Fig. 1.** The crystalline lattice of ice Ih. Red and white spheres represent oxygen and hydrogen atoms, respectively, while gray rods symbolize hydrogen bonds. *Top*: view along the *c*-axis. *Bottom*: view along an *a*-axis. The hexagonal symmetry of the lattice is highlighted by the yellow dashed line (after Faria and Hutter, 2001).

### 2.1. Slip systems and plastic anisotropy

According to the fundamentals of dislocation theory (Hirth and Lothe, 1992; Weertman and Weertman, 1992), possible slip systems in ice can in principle be found on the basal, prismatic, and pyramidal planes, as described in Table 1 and Fig. 2.

**Table 1**
Possible slip systems in ice. After Hondoh (2009).

| Slip plane | Slip system |
|---|---|
| Basal | $(0001)\ \langle 11\bar{2}0\rangle$ |
| Primary prismatic | $\{1\bar{1}00\}\ \langle 11\bar{2}0\rangle$ |
| | $\{1\bar{1}00\}\ \langle 0001\rangle$ |
| | $\{1\bar{1}00\}\ \langle 11\bar{2}3\rangle$ |
| Secondary prismatic | $\{\bar{1}\bar{1}20\}\ \langle 0001\rangle$ |
| Primary pyramidal | $\{\bar{1}011\}\ \langle 11\bar{2}0\rangle$ |
| | $\{\bar{1}011\}\ \langle 11\bar{2}3\rangle$ |
| Secondary pyramidal | $\{\bar{1}\bar{1}22\}\ \langle 11\bar{2}3\rangle$ |