Journal of Structural Geology 61 (2014) 2–20

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Review article

The microstructure of polar ice. Part I: Highlights from ice core research

Sérgio H. Faria[a,b,*], Ilka Weikusat[c], Nobuhiko Azuma[d]

[a] Basque Centre for Climate Change (BC3), Alameda Urquijo 4-4, 48008 Bilbao, Spain
[b] IKERBASQUE, Basque Foundation for Science, Alameda Urquijo 36-5, 48011 Bilbao, Spain
[c] Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Am Alten Hafen 26, 27568 Bremerhaven, Germany
[d] Department of Mechanical Engineering, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka, 940-2188 Niigata, Japan

ARTICLE INFO

Article history:
Received 2 May 2013
Received in revised form
23 September 2013
Accepted 27 September 2013
Available online 30 October 2013

Dedicated to the memory of Sigfús Jóhann Johnsen (1940–2013).

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

ABSTRACT

Polar ice sheets play a fundamental role in Earth's climate system, by interacting actively and passively with the environment. Active interactions include the creeping flow of ice and its effects on polar geomorphology, global sea level, ocean and atmospheric circulation, and so on. Passive interactions are mainly established by the formation of climate records within the ice, in form of air bubbles, dust particles, salt microinclusions and other derivatives of airborne impurities buried by recurrent snowfalls. For a half-century scientists have been drilling deep ice cores in Antarctica and Greenland for studying such records, which can go back to around a million years. Experience shows, however, that the ice-sheet flow generally disrupts the stratigraphy of the bottom part of deep ice cores, destroying the integrity of the oldest records. For all these reasons glaciologists have been studying the microstructure of polar ice cores for decades, in order to understand the genesis and fate of ice-core climate records, as well as to learn more about the physical properties of polar ice, aiming at better climate-record interpretations and ever more precise models of ice-sheet dynamics. In this Part I we review the main difficulties and advances in deep ice core drilling in Antarctica and Greenland, together with the major contributions of deep ice coring to the research on natural ice microstructures. In particular, we discuss in detail the microstructural findings from *Camp Century*, *Byrd*, *Dye 3*, *GRIP*, *GISP2*, *NorthGRIP*, *Vostok*, *Dome C*, *EDML*, and *Dome Fuji*, besides commenting also on the earlier results of some pioneering ventures, like the *Jungfraujoch Expedition* and the *Norwegian–British–Swedish Antarctic Expedition*, among others. In the companion Part II of this work (Faria et al., 2014), the review proceeds with a survey of the state-of-the-art understanding of natural ice microstructures and some exciting prospects in this field of research.

1. Introduction

Ice is one of the oldest known minerals (Adams, 1990; Faria and Hutter, 2001) and manifests itself in diverse forms, most commonly as snow, frost, hail, icicles, ice plates, permafrost, firn, and massive polycrystals. Although it is neither as ubiquitous as quartz nor as precious as diamond, ice is highly regarded by its environmental and economic importance, as well as by the exceptionally large deposits of "pure" ice found in continental-sized polar ice sheets (the impurity content of polar ice typically lies in the ppb range; Legrand and Mayewski, 1997). These ice sheets cover virtually all Greenland and Antarctica with more than 2.7×10^{16} m^3 of ice, corresponding to ca. 2.5×10^{19} kg of freshwater, or 64 m of sea level rise equivalent (Lemke et al., 2007).

Like any usual crystalline solid, ice undergoes creep at sufficiently low stresses and temperatures higher than around half of its pressure melting point (Petrenko and Whitworth, 1999; Durham et al., 2001). Seeing that temperatures naturally occurring on Earth generally lie within that range, it should be no wonder for contemporary scientists to witness glaciers and ice sheets creeping slowly under their own weight. Notwithstanding, more often than not one still can find expositions in the modern literature attributing the creep of glaciers and ice sheets to an odd fluidity of ice. Such a pseudodoxy is nourished by the charm of the old glaciological literature (beautifully described by Clarke, 1987; Walker and Waddington, 1988), ancient beliefs (Adams, 1990; Faria and Hutter, 2001), and the long list of real peculiarities of this material, which range from its abnormally low mass density to the persistence of

---

* Corresponding author. Basque Centre for Climate Change (BC3), Alameda Urquijo 4-4, 48008 Bilbao, Spain. Tel.: +34 94 4014690.
E-mail addresses: sergio.faria@bc3research.org (S.H. Faria), ilka.weikusat@awi.de (I. Weikusat), azuma@mech.nagaokaut.ac.jp (N. Azuma).

0191-8141/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jsg.2013.09.010

brittle properties up to its melting point (Hobbs, 1974; Petrenko and Whitworth, 1999; Schulson and Duval, 2009).

While the creep of large ice masses can itself be considered an unsurprising phenomenon, the microscopic mechanisms that drive it are far from trivial and have been challenging scientists for decades. Here we review some of these studies, with special emphasis on polar ice from deep ice cores, and present an up-to-date view of the modern understanding of natural ice microstructures and the deformation processes that may have produced them.

This work is divided in two correlated publications. Here in Part I, we review the advances in the research on natural ice microstructures during the last eight decades, using deep ice cores from Antarctica and Greenland to draw the storyline. In the companion Second Part (Faria et al., 2014) —from now on called *Part II*— we discuss several aspects of our current understanding of natural ice microstructures, including deformation mechanisms, induced anisotropy, grain growth and recrystallization, among others. The whole review ends with a summary of key concepts in the form of a glossary, for quick reference (Glossary in Part II).

For the sake of brevity, we concentrate attention here to a limited number of ice cores only, which we consider most representative of the advances in ice microstructures occurring in a given period. Inevitably, in some situations we have faced the dilemma of choosing between two or more cores equally relevant within the same period. In such cases we have given preference to the core with the largest amount of information available for us. Admittedly, this pragmatic attitude generates a selection bias towards those ice coring projects we have been directly or indirectly involved with. Information about other important polar ice cores, not discussed here (e.g. Law Dome, Taylor Dome, Siple Dome, Talos Dome, WAIS, NEEM and others), is available in the review by Bentley and Koci (2007) and in the Ice Core Gateway of the U.S. National Oceanic and Atmospheric Administration (NOAA; http://www.ncdc.noaa.gov/paleo/icecore), among other resources.

Summaries of the most relevant microstructural, geophysical, and geographical data about the ice cores discussed here are given in Table 1 and Figs. 1–3.

Remark 1. For the description of ice cores we adopt here the convention *from top to bottom*, unless explicitly specified otherwise. In usual cases of ordered stratigraphy, this convention implies inverse chronological order, viz. *from younger to older*. It is in this sense that a phrase like “transition from the Holocene to the Last Glacial” may appear, indicating the fact that the Last Glacial is older than the Holocene. Climatologists may feel a bit uncomfortable with this convention, but it is the most logical choice for describing the physical features of an ice core.

2. Early research in natural ice microstructures

It is usually a great injustice to attribute a scientific innovation to a single person, team, or publication. Nevertheless, such a regrettable act is often justified by the fact that the human mind cannot easily grasp history unless the latter is reduced to a plain timeline decorated with milestones. In this vein, we apologetically commit such an injustice here by naming milestones that, in our opinion, exemplify well scientific trends in decisive periods of ice microstructure research.

2.1. The Jungfraujoch expedition

We start with a field expedition that has not only boosted research in ice microstructures, but also marked a turning-point in the way Glaciology is organized today. Gerald Seligman, a former businessman and skillful ski-mountaineer, was president of the Ski Club of Great Britain and author of an influential treatise on snow structure (Seligman, 1936). That work motivated him to consider the role of ice microstructure in the metamorphism of snow into ice. With this aim he led in 1937 a pioneering party to study this process on the Jungfraujoch, Switzerland, which included John D. Bernal, F. Philip Bowden, T. P. Hughes, Max F. Perutz and Henri Bader (Remark 2).

Remark 2. It is impossible to overestimate the importance for modern Glaciology of the constellation of scientists involved in the Jungfraujoch Expedition. Bernal discovered (together with Ralf H. Fowler) the essential principles that determine the arrangement of atoms in the ice lattice (Bernal and Fowler, 1933), nowadays known as the *ice rules*. Bowden and Hughes laid the foundations of our modern understanding of the frictional behavior of snow and ice (Bowden and Hughes, 1939; Bowden, 1953). Perutz became one of the pioneers of the modern (non-Newtonian) theory of ice creep (Perutz, 1948, 1949, 1950a,b, 1953). Finally, Bader joined his Ph.D. supervisor Paul Niggli in the Swiss Snow and Avalanche Commission as snow crystallographer in 1935, soon turning into one of the key proponents of a permanent laboratory for snow and avalanche research in Davos, Switzerland, which quickly evolved (in 1943) to the renowned Swiss Federal Institute for Snow and Avalanche Research, SRF (Achermann, 2009). Bader left Switzerland prior to SRF’s inauguration, however, moving to the Americas in 1938 to become, among other things, an international prime mover of polar deep ice coring (Bader, 1962; see also de Quervain and Röthlisberger, 1999; Langway, 2008). Seligman, on the other hand, was named in 1936 President of the newly-founded Association for the Study of Snow and Ice, which after the World War II hiatus evolved to the British Glaciological Society (publisher of the influential Journal of Glaciology) and in 1962, still under Seligman’s lead, to the (International) Glaciological Society.

The results of the Jungfraujoch Expedition have been published in four papers, describing various aspects of the crystallography, metamorphism, mechanics and thermodynamics of snow, firn and ice (Perutz and Seligman, 1939; Hughes and Seligman, 1939a,b; Seligman, 1941). As commented by Seligman (1941) in his general review of the Expedition:

> The work of earlier investigators and my own had traced the transition of new powdery snow into hard firn snow, but no one had systematically studied how this white, air-filled firn turned into the blue air-free ice of the lower glaciers. This was the ground of the present research. Glacier movement had been supposed to play a part, and this had to be investigated, including of course the flow of the névé. My long-cherished desire to use polarized light to reveal the detailed development of firn and ice crystals required the help of a crystallographer, which led to unexpected and valuable results. With the exception of a few desultory photographs polarized light had never been used: a surprising omission in glaciological research.

Details of these crystallographic investigations on the Jungfraujoch have been described by Perutz and Seligman (1939). Firn and ice samples were collected from the walls of crevasses or from grottoes and pits dug in the accumulation and ablation zones of the Great Aletsch Glacier and its surroundings. They prepared thin sections and determined crystalline orientations using a technique described by Bader et al. (1939) for snow studies. Among other results, Perutz and Seligman (1939) noticed a conspicuous microstructural contrast between the “small regular” crystallites of firn and the “large irregular” grains of ice. They observed a lattice preferred orientation in the upper meters of firn, with *c*-axes lying perpendicular to the glacier surface and gradually giving way to more isotropic (“random”) *c*-axis distributions below a few tens of meters of depth. In the deeper ice, however, strong lattice preferred