

Scientific Report

Project title:

Modeling of Grain Growth and Recrystallization in Polar Ice

Project acronym : GG-Poli

Reference number : 4689

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Unit : LESC

Activity title : Micro-Dynamics of Ice

Activity acronym : Micro-DICE

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Date of visit (starting date) : 13/03/2012

Duration : 3 days

1. Purpose of the visit

The response and contribution of large ice sheets to a changing climate is one of the greatest issues in contemporary climate research. In particular, knowledge of the deformation mechanisms of polar ice is of crucial importance to predict the flow of polar ice sheets and hence their contribution to global sea level rise (Lemke et al. 2007).

Seeing that laboratory experiments cannot reproduce the slow and everlasting flow of polar ice sheets, most of our understanding of natural ice deformation comes from microstructural analyses of ice cores, although the unraveling of this complex deformation history remains a challenge for glaciologists (Kipfstuhl et al. 2006, Faria et al. 2010). As in other geological materials, thermally activated processes, like dynamic recovery and recrystallization (including grain growth), continually modify the ice microstructure. Unfortunately, the mechanisms and rates of in-situ

recovery and recrystallization are very difficult to evaluate through microstructural analyses of ice cores alone. Therefore, most investigations combine ice core analysis with theoretical and numerical modeling (e.g. Montagnat and Duval 2000).

The main objective of this visit was to contribute to these crucial investigations, by paving the way towards a novel, unified theory of dynamic recovery and recrystallization in polar ice. Effectively, the work consisted in combining the applicant's vast experience of the microstructural analysis of ice cores and the theoretical modeling of ice microstructures with the very promising ELLE numerical model for grain growth and recrystallization in polar ice (Roessiger et al. 2011), which is currently under development by Prof. Paul D. Bons and Dipl.-Geol. Jens Rößiger, both at the Institute for Geoscience of the University of Tübingen, Germany.

2. work carried out during the visit

The Applicant arrived at the host institute in the late afternoon of the first day (13 March 2012), after checking in at the hotel. Since this was his first time in Tübingen, the visit started with a tour in the offices. The Applicant was introduced to the members of Prof. Paul D. Bons' group and could learn about their research activities. After the tour, the first day finished with a meeting of the Applicant with the Hosts, Prof. Bons and Dipl. Geol. Jens Rößiger, in which they planned the activities of the following two days.

The second day of visit (14 March 2012) started with Mr. Rößiger introducing the Applicant to the newest developments and issues of the ELLE model applied to grain growth and recrystallization in polar ice. After Prof. Bons joined the meeting, the Applicant and the Hosts discussed the effects of inclusions, in particular air bubbles, on the migration of grain boundaries and the eventual consequences for grain growth and recrystallization. The Applicant presented the conclusions of his analyses of diverse ice cores, while the Hosts discussed how such inclusions have been implemented in the simulations. All participants compared the observations with the predictions of the ELLE simulations.

These discussions continued through the afternoon, with special attention to particular topics like e.g. the different estimates of grain boundary energy in ice and the role of "wetting angles" (the angle formed between the bubble surface and a meeting grain boundary). On a larger scale, the Hosts presented the results of several simulations with different volume fractions of air bubbles, while the Applicant presented the recent results of many ice core analyses performed by his team, in which they could find correlations between bubble size distributions, bubble elongation, air volume fractions, impurity content, and grain size distributions. This topic naturally led to a discussion about ice stratigraphy, in which

the Applicant presented special images of ice core samples, showing consistent variations in distinct strata of ice microstructure, impurity content and bubble characteristics. The applicant emphasized that, in the field, different rates of borehole closure generally coincide with changes in stratigraphy and suggest variations in ice rheology consistent with changes in ice microstructure. This topic led the Hosts and the Applicant to finish the discussion by addressing the issue of folding and boudinage in polar ice, as manifestations of ice rheology variations.

The second day closed with a conversation about the Micro-DICE Special Issue, to appear in the Journal of Structural Geology (JSG), which addresses the topics presented in the Micro-DICE workshop on “Microdynamic Modelling of Ice and Related Materials” that occurred last May in Glasgow, U.K. The Hosts and the Applicant are involved in the preparation of several manuscripts for that special issue (more details in Sect. 5).

In the last day of visit (15 March 2012) the Hosts and the Applicant met to exchange views on a joint manuscript for the Micro-DICE JSG Special Issue, entitled “Influence of Bubbles on Grain Growth in Ice” by Rößiger, Bons and Faria. The Hosts and the Applicant agreed on many changes and improvements to the manuscript.

The visit closed with the planning of future collaborations. These are described in Sect. 4.

3. Main results

The Applicant and the Hosts agreed that the ELLE platform coupled with Fast Fourier Transform (FFT) algorithms provides a very powerful tool to simulate dynamic recovery and recrystallization in ice. Such simulations can help us not only to decipher the in-situ deformation history of polar ice, by comparing them with observed ice core microstructures, but also to produce reliable predictions of the in-situ rates of recovery and recrystallization in polar ice. Even though the ELLE-FFT coupling is not fully accomplished yet, the Hosts and the Applicant are confident that the essential algorithms for nucleation and dynamic recrystallization should be completed soon.

In its current version, ELLE can successfully simulate grain growth and surface-energy-driven grain boundary migration in polar ice, even in the presence of solid inclusions or air bubbles. The resulting simulated microstructures are very similar to those observed in polar ice samples where the stored strain energy plays no significant role for grain boundary migration. For the remainder cases, where the stored strain energy does play a significant role, the algorithms for nucleation and dynamic recrystallization must be implemented.

The simulations indicate that the evolution of ice microstructure must be accounted for when deriving grain growth laws, a fact that has not been carefully considered so far.

Additionally, in contrast to previous theoretical models (e.g. Alley et al. 1986), the ELLE simulations show that air bubbles, in sizes and concentrations usually found in polar ice, can indeed affect grain growth considerably and must be taken into account when modeling the in-situ microstructural evolution of polar ice.

4. Future collaboration with host institution

Collaboration between the Applicant and the host institution will continue through joint research and publications (see Sect. 5).

Furthermore, now that the Applicant has moved to Spain, the establishment of international research networking programs involving Spain, Germany and other countries becomes essential. The Hosts and the Applicant agreed to meet again in some months in Bilbao, together with other scientists from Spain, Japan and Germany, in order to prepare a joint research networking proposal in the area of physics and chemistry of ice cores, to be submitted to the European Commission.

The Applicant also manifested the intention of organizing an international workshop on the subject "Ice and Climate" in the second half of 2013, in which the Hosts are willing to participate.

5. Projected publications

The following publications are expected to derive from this visit:

1. "Influence of Bubbles on Grain Growth in Ice" by J. Röbiger, P.D. Bons and S.H. Faria. Submitted on 30 March 2012 to Journal of Structural Geology.
2. "Multiscale Modeling of Ice Deformation Behavior" by M. Montagnat and others, including P.D. Bons, S.H. Faria and J. Röbiger. In preparation.

References

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