

1. Executive summary

An ESF Exploratory Workshop on Modelling and Interpretation of Ice Microstructures was held in Göttingen on April 9-11, 2008, organised by:

- Prof. Paul D. Bons, Institut für Geowissenschaften, Universität Tübingen, Germany;
- Dr. Sérgio H. Faria, GZG, Section of Crystallography, Universität Göttingen, Germany;
- Dr. Sepp Kipstuhl, Alfred Wegener Institut, Bremerhaven, Germany.

The workshop was supported by a 14,000 € grant from the ESF, of which approximately 11,300 € was spent. 18 scientists from glaciology, geology and metallurgy were invited from 12 different countries, including Japan and the USA. In selecting the candidates, a balance was sought between country of origin, discipline and senior/junior researchers.

The workshop was hosted by the University of Göttingen, Section of Crystallography, who provided the meeting venue. All participants were hosted in the Best Western Hotel Am Papenberg near the meeting venue. The close proximity of the meeting venue and accommodation ensured that all participants remained together during meals and free time in the evenings.

The ultimate aim of the workshop was to explore ways to better integrate the knowledge gained on microstructure with (a) large-scale (rheological) models of the flow of ice caps and (b) interpretation of climatic records from polar ice cores. The workshop was structured as a series of short talks, each followed by ample discussion time. The presentations were structured into 6 sessions:

- Session 1: The role of ice microstructure in modern glaciology
- Session 2: Open questions in ice microstructure research
- Session 3: Lessons from ice microscopy, diffraction and deformation experiments
- Session 4: Microstructures in metals
- Session 5: Microstructures in minerals and rocks
- Session 6: The importance of interdisciplinarity in ice microstructure research

In the final discussion it was agreed to:

- Try to organise a research conference in Grenoble in 2010 (coordinator Montagnat)
- Try to set up a research network (potentially funded by the ESF) to link research methods, analytical facilities and data sets (coordinator Bons)
- Write a joint research paper on terminology of (ice) microstructures (coordinator Faria)

2. Scientific content of the event

Ice sheet flow models used for the interpretation of ice core (climate) records and the simulation of the evolution of these large ice sheets suffer from the poor representation of the rheology of polar ice. The ice microstructures in polar ice still lack a coherent interpretation framework. The purpose of the workshop was to explore ways to overcome the fragmentation between different materials communities by bringing together European experts on microstructures in ice, rocks and metals.

The workshop was based on two propositions put forward by the organisers:

- The direct extrapolation of laboratory experiments to processes in ice caps at a much larger scale and much lower strain rate (Fig. 1) may be flawed if the full microstructural record in natural ice is bypassed.
- Natural microstructures, laboratory experiments and theory can only be linked properly with improved numerical models that include all active processes during deformation of ice.

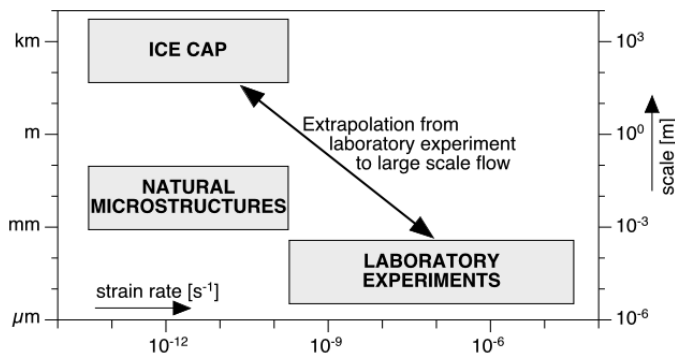


Fig. 1. Scale versus strain rate diagram showing the position of laboratory experiments relative to natural grain-scale processes and large-scale flow of ice caps.

The workshop intended to bring together a selection of the main European players in the field of modelling of microstructures in ice, rocks and metals with the aim to:

- define open questions and unresolved issues in ice deformation research;
- explore the analogies and differences between ice, rocks and metals;
- review the main potential deformation mechanisms in crystalline materials and their microstructural signature;
- provide an overview of the existing numerical methods to model multiple, competing and coupled deformation processes at the grain scale in crystalline materials;
- initiate cooperation between the different materials research communities.

The participants were left free to decide which topics they would like to bring forward for discussion during the meeting. This enabled us to identify the most critical and polemic issues in the field to date. Interestingly, several issues were addressed by different participants from very different angles (e.g. the 3-layer model for ice caps). The main issues addressed during the workshop can be roughly ranked as follows:

- characterization and modelling of grain growth and recrystallisation processes: 15%
- new techniques of microstructure observation and ice deformation: 12%
- heterogeneity of ice deformation on the microscopic scale: 12%
- characterization and modelling of crystallographic texture ("fabric"): 12%
- analogies and differences between the microstructural processes in ice, metals and rocks: 10%

- dominant deformation mechanisms in natural ice: 10%
- interdisciplinary difficulties and perspectives: 8%
- link between microstructural processes and large scale flow: 8%
- modelling of ice sheet flow: 8%
- boundary effects, flow disturbances and subglacial processes: 5%

Several numerical models were presented. These can be roughly divided into two groups: continuum models (e.g. Morland and Placidi) and discrete, grain-scale models, such as *Elle* (Griera and Jessell). These models are applied to, or derive their input from different data sets from nature (like drill cores; e.g. Kipfstuhl, Thorsteinsson) or experiments (e.g. Montagnat, Hamann, Azuma, Goldsby). Much discussion time was spent on how to integrate and link these methods to gain better insight in the behaviour of polar ice caps.

A common outcome of the different approaches (observations on natural ice, experiments and numerical modelling) is that the current three-layer model of ice caps is too simplistic. However, this insight needs to be translated to a coherent model of the behaviour of ice caps, including improved rheological laws, to be of practical use to geophysics and climatology. Clear analogies were recognised here with geology and metallurgy.

3. Assessment of the results, contribution to the future direction of the field

The two main results of the workshop were:

1. It was felt that there is a lack of understanding between the "ice microstructure and rheology community" and the geophysics and climatology community. As a result, the increasing and more detailed insight into the behaviour of ice does not effectively filter through to large-scale ice flow and climate models. These models too often rely on outdated, sometimes even "dogmatic" theories on the behaviour of ice.
2. New analysis (EBSD, synchrotron, microstructure mapping, etc.) and modelling techniques challenge currently established models on the microstructural and rheological behaviour of ice. It was realised that this is not only the case for ice, but also for other crystalline materials and minerals, with metallurgists, geologists and glaciologists facing the same questions.

There was a general consensus that ways should be sought to communicate these results to the wider community, specifically including large-scale geophysical modellers and climatologists. To this effect, it was proposed to organise a research conference, to be held in Grenoble in 2010, with Dr. Montagnat as coordinator. The ESF Research Conference Scheme is suggested as a potential funding source.

With some new bilateral collaboration plans already emerging during the workshop, it was generally felt that there is a need to establish a network to link the numerous research groups that work on microstructural development and rheology of ice and other crystalline materials (metals, geological minerals). This network should bundle expertise and make specialised facilities available to collaborators within the network. Prof. Bons will investigate the possibility to submit an ESF Research Network Programme proposal in 2008.

Bringing together scientists from different communities highlighted the confusion that exists in terminology. Terms such as "grain growth", "texture", "fabric", etc. are used by all groups, but with different definitions or connotations. Dr. Faria will take the lead in writing a research paper with the aim to bring some clarification into the matter, especially for the ice community.

4. Final programme

TUESDAY 8 APRIL 2008

Arrival of participants

20:00 - 23:00 *Dinner in Restaurant "Mazzoni"*

WEDNESDAY 9 APRIL 2008

9:00 - 9:15 **Paul Bons, Sérgio Faria and Sepp Kipfstuhl:** Welcome and practical matters

9:15 - 9:30 **Kai Rankenburg:** Presentation of the European Science Foundation (ESF)

SESSION 1: THE ROLE OF ICE MICROSTRUCTURE IN MODERN GLACIOLOGY

9:30 - 10:20 **Leslie Morland:** Opening Lecture: Ice core data interpretation

10:20 - 11:00 **Ryszard Staroszczyk:** Ice viscosity evolution in simple shear and uni-axial compression due to crystal rotation

11:00 - 11:20 *Coffee break*

11:20 - 12:00 **Luca Placidi:** Continuum-mechanical, anisotropic flow model based on an anisotropic flow enhancement factor. CAFFE model and applications

12:00 - 12:40 **Gaël Durand:** Measurements of texture along polar ice cores: consistencies and discrepancies with the description of recrystallization processes

12:40 - 13:00 *Discussion*

13:00 - 15:00 *Lunch*

SESSION 2: OPEN QUESTIONS IN ICE MICROSTRUCTURE RESEARCH

15:00 - 15:40 **Throstur Thorsteinsson:** Fabric resulting from the transformation of snow to ice

15:40 - 16:20 **Joachim Mathiesen:** Competition between size diffusion and fragmentation: a case study of crystal formation in the Greenland NorthGRIP ice core

16:20 - 17:00 **Denis Samyn:** A geological approach as a link between micro-deformation of debris-laden basal ice and macro-behaviour of ice bodies: examples from cold Antarctic glaciers

17:00 - 17:20 *Coffee break*

SESSION 3: LESSONS FROM ICE MICROSCOPY, DIFFRACTION AND DEFORMATION EXPERIMENTS

17:20 - 18:00 **Maurine Montagnat Rentier:** Deformation heterogeneities in ice single and polycrystals. X-rays and EBSD measurements on deformed samples

18:00 - 18:40 **Sepp Kipfstuhl:** The potential of microstructure mapping for studying recrystallization of ice on the grain scale

18:40 - 19:00 *Discussion*

20:30 *Dinner in Restaurant "Mazzoni"*

THURSDAY 10 APRIL 2008

SESSION 3 CONTINUED

- 9:00 - 9:40 **Nobuhiko Azuma:** Is grain growth in polar ice sheets normal grain growth? Differences between ice core studies and laboratory experiments
- 9:40 - 10:20 **Ilka Hamann:** High resolution deformation microstructures in ice: grain-boundary morphology and subgrain boundaries in samples from creep tests and an Antarctic ice core
- 10:20 - 10:40 *Coffee break*
- 10:40 - 11:20 **Peter Sammonds:** Anisotropic deformation of EPICA ice
- 11:20 - 12:00 **David Goldsby:** The rheological behavior of ice: experimental constraints and application to glaciers, ice sheets and planetary bodies
- 12:00 - 12:20 *Discussion*
- 12:20 - 14:20 *Lunch*

SESSION 4: MICROSTRUCTURES IN METALS

- 14:20 - 15:00 **Günter Gottstein:** Deformation mechanisms and microstructure evolution in metals
- 15:00 - 15:40 **Grethe Winther:** 3D studies of deformation and annealing of metals
- 15:40 - 15:50 *Coffee break*

SESSION 5: MICROSTRUCTURES IN MINERALS AND ROCKS

- 15:50 - 16:30 **Paul Bons:** Rock deformation, rheology and microstructure
- 16:30 - 17:10 **Martyn Drury:** Quantitative analysis of deformation and recrystallization microstructures using electron backscattered diffraction
- 17:10 - 17:20 *Coffee break*
- 17:20 - 18:00 **Mark Jessell:** Microdynamics simulation of geological materials
- 18:00 - 18:40 **Albert Griera:** Simulations in microstructure evolution of polycrystalline ice: model set-up
- 18:40 - 19:00 *Discussion*
- 20:30 *Dinner in Restaurant "Schützenhaus Weende"*

FRIDAY 11 APRIL 2008

SESSION 6: THE IMPORTANCE OF INTERDISCIPLINARITY IN ICE MICROSTRUCTURE RESEARCH

- 9:00 - 9:40 **Werner Kuhs:** New experimental opportunities studying ice microstructures
- 9:40 - 10:20 **Sérgio Faria:** Interdisciplinary challenges in ice mechanics
- 10:20 - 10:30 *Coffee break*

SESSION 7: CLOSING DISCUSSION

- 10:30 - 12:00 **All participants:** How to proceed from here?
- 12:00 *End of the Workshop, viewing of laboratories, and lunch*

5. Statistical information on participants

Including the organisers, there were 21 participants that came from 12 different countries (Table 1). Germany and France represented almost half of all participants, which reflects the relatively large contribution to the field of these two countries. Six of the participants are not native to their current host country.

Table #: Country of origin (current host institution) of participants

Germany	6*	Italy	1
France	4	Norway	1
UK	2	Poland	1
The Netherlands	1	Denmark	1
Belgium	1	USA	1
Iceland	1	Japan	1

*Permission was granted by the ESF to have 6 participants from the hosting country

Only three women participated, which reflects the fact that the research field is still strongly male-dominated. In selecting invitees to the workshop, it was attempted to have a balance between young researchers and established authorities in the different disciplines that were represented (Table 2).

Table 2: Age distribution and professional status

Junior scientist, non-permanent position	7
Established scientist, permanent position	3
Senior scientist	11
age < 40	9
41-50	5
51-60	5
≥ 60	2

6. The Final list of participants

1. Prof. Paul D. Bons	Institut für Geowissenschaften University of Tübingen Sigwartstr. 10, 72076 Tuebingen, Germany
2. Dr. Sérgio H. Faria	GZG, Abt. Kristallographie
3. Prof. Werner F. Kuhs	University of Göttingen, Goldschmidtstr. 1 37077 Göttingen, Germany
4. Dr. Sepp Kipfstuhl	Alfred Wegener Institute
5. Dr. Ilka Hamann	Columbusstrasse, 27568 Bremerhaven, Germany
6. Prof. Günter Gottstein	Institut für Metallkunde und Metallphysik RWTH Aachen, Kopernikusstraße 14 52056 Aachen, Germany
7. Dr. Gael Durand	Laboratoire de Glaciologie et Géophysique de l'Environnement
8. Dr. Maurine Montagnat Rentier	54, rue Moliere - Domaine Universitaire - BP 96 38402 Saint-Martin d'Herès cedex, France
9. Dr. Mark W. Jessell	Laboratoire des Mécanismes et Transferts en Géologie
10. Dr. Albert Griera	University of Toulouse III - Paul Sabatier Observatoire Midi-Pyrénées - 14 avenue Edouard Belin, 31400 Toulouse, France
11. Prof. Leslie Morland	School of Mathematics University of East Anglia, Norwich NR4 7TJ, UK
12. Prof. Peter Sammonds	CPOM Pearson Building, University College London Gower Street, London WC1E 6BT, UK
13. Dr. Martyn R. Drury	Department of Earth Sciences, Utrecht University Postbus 80021, 3508 TA Utrecht, The Netherlands
14. Dr. Denis Samyn	Laboratoire de Glaciologie, Université Libre de Bruxelles CP160/03, avenue F.D. Roosevelt 50 1050 Bruxelles, Belgium
15. Dr. Throstur Thorsteinsson	Institute of Earth Sciences, University of Iceland Sturlugata 7, IS-101 Reykjavík, Iceland
16. Dr. Luca Placidi	"Sapienza", Università di Roma, Facoltà di Ingegneria Dipartimento di Ingegneria Strutturale Geotecnica (DISG) Laboratorio di prove e materiali Via Eudossiana, 18, 00184 Roma, Italy
17. Dr. Joachim Mathiesen	Physics of Geological Processes, University of Oslo P.O. 1048 Blindern, 0316 Oslo, Norway
18. Dr. Ryszard Staroszczyk	IBW-PAN Koscierska 7, 80-328 Gdansk, Poland
19. Prof. Nobuhiko Azuma	Department of Mechanical Engineering Nagaoka University of Technology Kamitomioka cho 1603-1, Nagaoka 940-2188, Japan
20. Dr. David L. Goldsby	Department of Geological Sciences, Brown University 324 Brook Street, Providence, RI 02912, U.S.A.
21. Dr. Grethe Winther	Risø National Laboratory for Sustainable Energy, Technical University of Denmark, Denmark