DFG-Antrag
zum Schwerpunktprogramm 1158
„Antarktisforschung“

Modelling of deformation and recrystallisation microstructures in polar ice: Numerical studies

— NUMOPOLI —

Joint proposal *(Gemeinschaftsantrag)*

by

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1. General information (*Allgemeine Angaben*)

The grant application entitled "**Modelling of deformation and recrystallisation microstructures in polar ice: Numerical studies**" **(NUMOPOLI)** is a new proposal in the framework of the *DFG priority program 1158 „Antarktisforschung".* It is a **joint proposal (Gemeinschaftsantrag)** of the Institute for Geosciences, Tübingen University, the Alfred Wegener Institute (AWI), Bremerhaven and the Geowissenscaftliches Zentrum Göttingen (GZG), University of Göttingen.

It belongs to the **proposal bundle** "**Polar ice microstructure**", which also includes the following proposals:

- "Modelling of deformation and recrystallisation microstructures in polar ice: Fundamental studies" (FUMOPOLI by Faria, Bons and Kipfstuhl);
- "Deformation of ice on the grain scale by means of high-resolution crystal-orientation measurements" (HIRESOMI by Hamann).

The project will be based at Tübingen.

1.1 Applicant(s) (*Antragsteller*)

Prof. Dr. Paul D. Bons (Principal Investigator)

Dr. Sérgio H. Faria

Dr. Sepp Kipfstuhl

1.2 Topic (*Thema*)

Modelling of deformation and recrystallisation microstructures in polar ice: Numerical studies (NUMOPOLI)

(Modellierung von Deformations- und Rekristallisationsmikrostrukturen in Polareis: numerische Untersuchungen)

1.3 Scientific discipline and field of work (*Fachgebiet und Arbeitsrichtung*)

- **Discipline of the research project:** glaciology, computational earth sciences, materials science.
- **Bons**: Earth sciences; field of work: structural geology, computational earth sciences.
- **Faria**: Geosciences; field of work: materials science, ice core physics.
- **Kipfstuhl**: Geophysics; field of work: glaciology, ice core physics.

1.4 Scheduled total duration (*Voraussichtliche Gesamtdauer*)

- Start of project: **October 2008**
- Duration of project: **3 years**, which is the time frame for the PhD-research envisaged in this project

1.5 Application period (*Antragszeitraum*)

Funding requested: initially 2 years, with intended extension to a third year.
The initial funding should start on 01 October 2008 and run until 30 September 2010.

1.6 Summary

Knowledge of the deformation mechanisms of polar ice is of crucial importance to predict the flow of polar ice caps and hence their influence on the global climate. Deformation of ice also impacts on one of the best climate record on Earth: the individual ice layers observed in deep ice cores. Microstructures form the main record of in situ deformation, by revealing the deformation processes that operate during the flow of an ice sheet. New microstructural analysis techniques developed at AWI[1] now allow a much more detailed and extensive assessment of these microstructures than ever before. We will use the comprehensive modelling platform "Elle" to systematically model the range of microstructures that form under a variety of deformation rates, temperature and stress conditions relevant for ice sheet flow. Model results will then be quantitatively compared with theoretical analyses and the unique microstructure dataset available at AWI of several firn and ice cores (in particular the EPICA–DML[2] deep ice core; cf. other projects in this bundle). In particular we will critically reassess the role of grain boundary formation and migration that continually reworks the microstructure. The results of this project will improve our knowledge of the mechanical behaviour of polar ice and refine the analysis of climatic records, which are essential to ice sheet and climate modelling.

Key words: polar ice, recrystallisation, numerical modelling, ice core, texture, grain boundary.

1.6 *Zusammenfassung*

Ein grundlegendes Verständnis des Deformationsprozesses von polarem Eis ist unerlässlich für die Vorhersage der Bewegung der großen Eisschilde und ihres Einflusses auf das Klima, aber auch für die Rekonstruktion der Klimazeitreihen aus diesem einzigartigen Archiv. Aus der Mikrostruktur, in der sich die in situ-Deformationsbedingungen in einem Eisschild ausdrücken, lassen sich die während des Fließens aktiven Prozesse ableiten. Neue, am AWI entwickelte Verfahren, ermöglichen nunmehr die Aufnahme und Auswertung der Mikrostruktur von Eiskernen, wie sie bislang weder im Detail noch im Umfang erreicht wurden. Für die Modellierung der Mikrostruktur in dem weiten Bereich an Randbedingungen von Deformationsraten, Temperaturen und Spannungskonfigurationen, wie er für das Fließen von Eis in einem Eisschild relevant ist, wird die Modellplattform "Elle" eingesetzt. Die Modellergebnisse werden quantitativ mit theoretischen Analysen und dem am AWI vorhandenen Mikrostrukturdatensatz, der mehrere Firn und Eiskern umfasst (insbesondere komplett den EPICA-DML-Kern; siehe die anderen Projekte innerhalb dieses Bündelantrags) verglichen. In besonderem Maße werden wir uns kritisch mit der Rolle der Bildung und der Bewegung von Korngrenzen, die ständig die Mikrostruktur um- und überarbeiten, auseinandersetzen. Die Ergebnisse dieses Projektes werden das Verständnis des mechanischen Verhaltens von polarem Eis erheblich verbessern und dazu beitragen, die Analyse der Klimarekords zu verfeinern, die wiederum eine wesentliche Grundlage für die Eisschild- und Klimamodellierung darstellen.

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[1] AWI = Alfred Wegener Institute.

[2] EPICA = European Project for Ice Coring in Antarctica; DML = Dronning Maud Land, Antarctica.

2. State of the art, preliminary work (*Stand der Forschung, eigene Vorarbeiten*)

2.1 State of the art (*Stand der Forschung*)

2.1.1 The need of numerical modelling of microstructures

With global warming becoming a generally accepted proposition by scientists, the general public and governments, research into the dynamics of polar ice sheets has gained further impulse. Indeed, polar ice forms a large part of the global fresh water budget and as such, prognoses of future sea-level and climate changes are strongly dependent on the precise understanding of the flow behaviour of polar ice caps (IPCC 2007).

Knowledge of the mechanical properties of ice mainly derives from two streams of research: laboratory experiments and analyses of deep ice cores. Laboratory experiments are hampered by limited sample sizes, restricted stress conditions and by deformation rates that are inevitably several orders of magnitude higher than natural rates. This makes the extrapolation of laboratory results to naturally deformed ice rather unreliable, in particular because unnatural deformation mechanisms may become active under laboratory conditions. Polar ice core studies do not suffer from these shortcomings: the *microstructures*[3] seen in ice cores are invaluable records of the true in situ deformation processes and mechanisms that operated during the flow of the ice sheet. Notwithstanding, the interpretation of the complex deformation history of polar ice is challenging and continues to be matter of intense research. In fact, two other proposals belonging to this bundle (viz. FUMOPOLI and HIRESOMI, see Sect. 1) deal especially with the observation, analysis and interpretation of these microstructural records.

Be that as it may, even the best currently available analyses of ice core microstructures cannot yet yield quantitative interpretations, as ice cores provide only a static “snapshot” of the whole cumulative deformation history. Thus, fundamental observations and interpretations must be complemented and tested by “virtual deformation experiments”, i.e. numerical simulations that provide possible kinematic/dynamic descriptions of the microstructural evolution. Such simulations shall show us which combinations/sequences of processes may eventually produce the microstructures observed in ice cores, under realistic (and often time-dependent) boundary conditions.

2.1.2 The current microstructure paradigm

At the conditions found on Earth’s surface, ice possesses a hexagonal crystalline structure called *ice Ih*, the major feature of which is the existence of basal planes, viz. crystallographic planes perpendicular to the axis of six-fold symmetry of the lattice, called the *c-axis*. It is a well-known fact that the peculiar properties of basal dislocations in ice give ice crystallites a strong plastic anisotropy (Hondoh 2000). More precisely, ice Ih deforms easily by dislocation creep via basal slip.

As ice deforms, the initially random distribution of lattice orientations is modified and specific non-random c-axis fabrics develop. Considering the large plastic anisotropy of polar ice, much attention has been given to the evolution of c-axis fabrics in polar ice sheets. The likely effect of grain size and other

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[3] Polar ice is a polycrystalline mineral and, as such, its microstructure consists of all microscopic features produced and/or affected by the deformation; in particular dislocations, grain and subgrain boundaries, inclusions, grain stereology (viz. the spatial arrangement of sizes and shapes of grains in the polycrystal) and the lattice or crystallographic preferred orientations (LPO or CPO, respectively) of the grains (often termed "fabric" in the glaciological community, or “texture” in the materials science jargon).

microstructural parameters on the development of c-axis fabrics is not yet well understood and remains a matter of intense discussion. The main complicating factor is that several coupled and competing processes affect the microstructure, and hence the c-axis fabric: e.g diffusional creep, grain boundary sliding and recrystallisation.

The current paradigm of the microstructure of polar ice is based on the assumption that three flow regimes can be distinguished as a function of depth in polar ice sheets (Alley 1992; De La Chapelle et al. 1998):

- The upper “normal grain growth regime": In the upper 0.5 to 1 km depth: Measurements of grain size in this region show that the mean grain size increases steadily with depth. Grain growth driven by surface-energy is supposed to control the microstructure.
- The middle “polygonisation regime": Grain size remains approximately constant in the middle region, where grain growth is believed to be balanced by grain size reduction due to polygonisation or rotation recrystallisation. Rotation recrystallisation involves the organisation of dislocations into subgrain boundaries that develop into full grain boundaries by progressive rotation (polygonisation).
- The lower "migration recrystallisation regime": The basal part of ice caps is characterised by high temperatures and dominantly simple shear deformation (as opposed to mostly vertical compression in upper regions). Competition between grain nucleation, grain growth and grain boundary migration are supposed to control the resulting microstructure.

In all three regimes, basal glide is assumed to be the main deformation mechanism, although a component of diffusional creep and grain boundary sliding (at least at certain depths) is favoured by some researchers (Azuma et al. 2000; Goldsby & Kohlstedt 2001).

The three-regime model is appealing, mainly for its simplicity. The fitting parameters of the usual flow law for ice (Glen’s flow law) can then be “tuned” to each region and used for large-scale geophysical models (Staroszczyk & Morland 2001; Gillet-Chaulet et al. 2005). Large-scale flow is then stable, i.e. no strong variations in flow rates are expected. This is important, since strong flow localisation may significantly disturb the vertical climatic record, and dramatically change the flow rates of ice caps.

Recently, criticism against the three-regime model has increased considerably (Azuma et al. 2000; Kipfstuhl et al. 2006; Faria et al. in press; Hamann et al. in press). The main critique is that this model results essentially from a symptomatic analysis of average properties, like mean grain size, average aspect ratio and mean dislocation density, which do not reflect the strong heterogeneity of the ice deformation on the grain scale. For example, observations on the microstructure show that polygonisation and strain-energy induced grain boundary migration already operate at shallow depths in the "normal grain growth regime". At greater depths, grain boundary sliding may significantly affect the rheology of ice, without having any significant impact on average properties such as grain size and c-axis fabrics. This means that the true dynamics of ice flow, including the possibility of shear localisation, are probably not fully captured by the usual flow laws for ice.

However, no new model has yet been proposed to replace the three-regime scheme. It is the aim of this proposed research project, together with the other two projects in the bundle, to address this problem.

2.1.2 Numerical modelling of microstructures

One of the main difficulties of the modelling of microstructures is the fact that changes in grain shape and particle motion are coupled in processes of major concern such as dynamic recrystallisation. This coupling is complex because the microstructural elements (grain boundaries, subgrain boundaries, phase boundaries) can all *migrate through* the material during recrystallisation as well as *move with* it during deformation. The challenge to understanding such processes is therefore to work out what the complex coupling is between particle motion and the motion of these non-material microstructural elements.

The behaviour of polar ice caps has been the subject of geophysical modelling for over two decades (Oerlemans 1982; Payne et al. 2000, Huybrechts et al. 2004). In contrast to this, the numerical modelling of microstructures is a relatively new undertaking. Taylor-Bishop-Hill models (e.g. van Houte 1982) suffer from the problem that deformation in ice is very heterogeneous. Furthermore, these models, as well as self-consistent (Castelnau et al. 1996), FLAC models (Wilson & Zhang 1994, 1996; Zhang & Wilson 1997) and the n-site FFT method (Lebensohn 2001) heavily focus on the development of fabrics, at the neglect of grain boundary migration, which is of crucial importance to ice microstructure (Kipfstuhl et al. 2006). Others have modelled grain boundary migration, but under simplified conditions (Faria et al. 2002) or restricted to processes driven only by the grain boundary surface energy, with disregard of fabric development (Durand et al. 2006).

The reason that the full microstructural development in ice has not yet been numerically simulated is simple: it is difficult to combine all complexly coupled processes into one single model. At present, the numerical code Elle is the furthest advanced in modelling multiple, competing and coupled processes in Earth materials, such as ice and rocks (Jessell et al. 2001; Bons et al. *in press*). The advantage of Elle is that it combines an "image" of the microstructure with a hybrid modular set-up, which allows multiple modelling techniques (finite elements/differences, front tracking, particle codes, etc.) to be combined. Each individual operating process can thus be modelled with the most appropriate technique and can act on a realistic microstructure, not on a statistical representation or approximation. This has brought significant advances in the modelling of e.g. polycrystalline quartz (Piazolo et al. 2002, 2004).

2.2 Preliminary work, progress report (Eigene Vorarbeiten, Arbeitsbericht)

Previous work - working group Bons: Bons has been using numerical modelling as the main tool for his research since 1992. He has applied the modelling to recrystallisation processes (Bons et al. 2001; Bons & Urai 1992; Bons & den Brok 2000; Piazolo et al. 2002, 2004), rheology and microstructures in polyphase materials (Bons et al. 1997; Bons & Cox 1994; Passchier et al. 1993; Tóth et al. 1994), vein microstructures (Bons 2001; Bons & Bons 2003; Koehn et al. 2000, 2001; Nollet et al. 2005), strain localisation (Jessell et al. 2005) partial melt microstructures (Becker et al. 2003, *in press*), and finally magma accumulation (Bons et al. 2004). Three publications deal with more general aspects of the numerical modelling of (micro-) structures (Jessell et al. 2001; Jessell & Bons 2002; and the book "Microdynamics Simulation", edited by Bons et al. *in press*).

A significant part of the numerical modelling by Bons is related to the application and development of the software Elle (Jessell et al. 2001), of which Bons was one of the initiators and main developers ever since. This means that he has an intimate knowledge of the structure, possibilities and limitations of the software to be used for the proposed projects. Bons has been funded by the DFG for research with Elle before (BO 1776/3 & 1776/4). The last project, "3D modelling of polycrystalline substructure development, with particular emphasis on ice and NaCl", which runs until November 2008, is part of the ESF-EuroMinScI-funded Collaborative Research Project "Mineral Substructure Dynamics" with partners in Tübingen, Stockholm, Liverpool, Aachen, Lille and Toulouse. The current project to extend Elle to 3D for recrystallisation and deformation of polycrystalline materials and the project in Toulouse, which integrates FFT-based lattice reorientation modelling of ice into Elle together form the ideal base for the proposed project. Bons is closely involved in the Toulouse project and will spend 3 months of his sabbatical in Toulouse (early 2008).

Previous work - working groups Faria & Kipfstuhl: Since several years Kipfstuhl and Faria jointly investigate the microstructure of polar ice. These studies started more than five years ago, when Kipfstuhl began to develop a new method to investigate the microstructure of ice cores, later called *Microstructure Mapping*. During that initial period, Faria was already working on the theoretical and numerical modelling of ice microstructures (Faria & Hutter 2001; Faria et al. 2002; Placidi et al. 2003; Faria et al. 2003; Faria 2006). Both researchers joined forces in 2003 (Faria & Kipfstuhl 2004; Faria & Kipfstuhl 2005, Faria et al. 2006), and since that time they carried out, together with their colleagues, the first comprehensive mapping of a deep ice core, the EPICA-DML core (Kipfstuhl et al. 2006).

Currently, Faria and Kipfstuhl are the principal investigators of the DFG/SPP-1158 project entitled “Distribution and chemistry of micro-inclusions in the EPICA–DML deep ice core”, which is projected to run until August 2010 and involves investigations of microscopic inclusions in polar ice via microstructure mapping, energy-dispersive X-ray analysis and micro-Raman spectroscopy. They are also convening, together with Paul D. Bons, a ESF-Workshop on “Modelling and interpretation of ice microstructures”, to be held in Göttingen in the period 7-11 April, 2008.

The method of Microstructure Mapping (µSM): There is hardly any other person in Europe who has studied the various micro-structural features of ice cores more intensively than Kipfstuhl, in the last years mostly in the field on fresh material. He has developed the microstructure mapping method using automated optical microscopy. It provides a fast means to map, with microscopic resolution, the microstructure of fresh ice samples throughout an ice core, while drilling is ongoing. The mapping system consists of an optical microscope, a CCD monochrome video camera, a frame grabber and a xy-stage. Images are usually taken in transmission light with the size 2.5 mm by 1.8 mm (Fig. 1). About 1500 images are needed to map a section of 45 mm by 90 mm. The whole scanning takes about one hour. Despite its conceptual simplicity, the µSM method turned out to be a sophisticated method for studying microstructures in fresh polar ice at an unusually high resolution. During the last five years, Kipfstuhl and colleagues (including Faria) have mapped many hundreds of thin and thick sections of deep polar ice from Greenland and Antarctica, including the GRIP and EPICA–Dome C cores, as well as the full length (2774 m) of the EPICA–DML deep ice core. A number of publications have already profited from µSM data (e.g. Wang et al. 2003; Faria and Kipfstuhl 2004, 2005; Faria et al. 2006; Faria 2006; Kipfstuhl et al. 2006, Hamann et al. 2007, Faria et al. in press, Hamann et al. in press, Kipfstuhl et al in press) and the range of applications increases steadily.

Originally, the µSM method was conceived for the observation of bubbles and clathrates, but soon it started to be used also for the study of grain and subgrain boundaries, slip bands, dislocation walls, sub-grain islands, cloudy bands, relaxation features and micro-inclusions, many of such structures not much studied so far. Most of these microstructural features will be in the focus of the study proposed here.

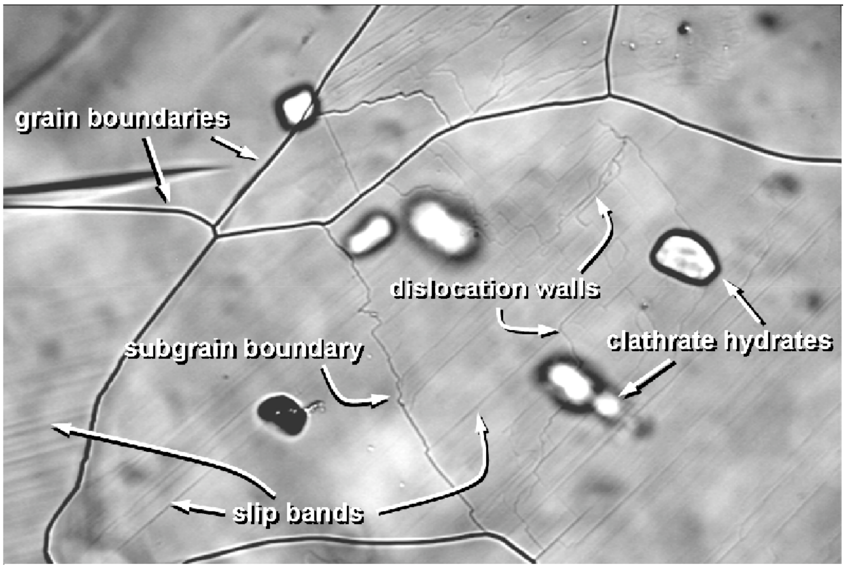

Fig. 1. Diverse microstructural features revealed by microstructure mapping (μSM) of an Antarctic ice sample from 1291 m depth. EPICA-Dome C ice core. Modified from Kipfstuhl et al. 2006. Width of image is 2.5 mm.

The software code Elle: The aim of the Elle Project is to develop a generalised framework for the numerical simulation of the evolution of microstructures during deformation and metamorphism. This framework consists of (1) the data structure, being a numerical description of the microstructure, (2) low-level base libraries that handle general data management and changes in the microstructure, and (3) process modules that calculate how the microstructure changes, depending on driving forces and boundary conditions. These are tied together by an experiment script, which sets the boundary conditions of a numerical experiment, activates process modules and handles the graphical and statistical output (Fig 2). The strength of Elle is that the user can activate different process modules and define the way these act on the microstructure.

The "decentralised" modular architecture means that modellers need only make new process modules, or modify existing ones for their own modelling, without having to change the base libraries. An ever-increasing number of process modules are available from all developers within the consortium. The number of partners in the consortium is steadily increasing, with partners in Australia, Austria, France, Germany, South Korea, Sweden, UK, USA, etc..

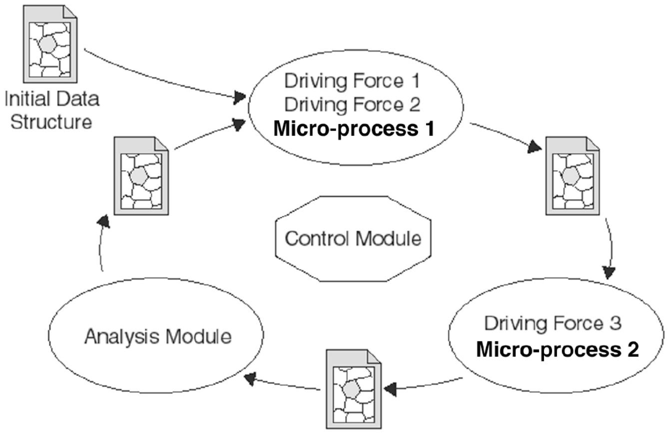

Fig. 2. The initial microstructure is defined by the user, and a central experiment script determines which processes will be applied to the microstructure. Different micro-processes may alter the microstructure depending on different driving forces. An analysis module can be included to save statistical data. From Bons et al. (in press)

The data structure is designed to maximise flexibility and compatibility with a range of modelling techniques (FEM, FD, front racking, phase-field, particle codes, etc.). The base is a contiguous set of *polygons*, which typically represent individual grains or subgrains (Fig. 3a-b). These polygons are defined by linked *boundary nodes* (bnodes). A second layer contains the *unconnected nodes* (unodes, Fig. 3c). Unodes are typically used to achieve a finer resolution (e.g. chemistry, lattice orientation) within polygons, through Delaunay triangulations or Voronoi cells (Fig. 3d-e). The use of wrapping boundaries (Fig. 3a) reduces boundary effects and has the great advantage that the amount of finite strain is unlimited (Fig. 4).

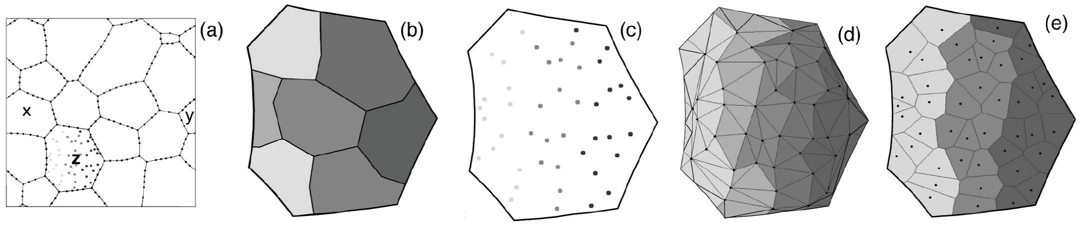

Fig. 3. Description of a polycrystalline microstructure in Elle, and ways of achieving a fine spatial resolution within grains **(a)** A 2D microstructure described by bnodes, which in turn define closed polygonal boundaries. Note that the *Elle* Data Structure allows for cyclic boundaries, so that grains *x* & *y* are in fact parts of the same grain. Unodes are shown only within grain z for clarity, and are shaded according to some property. **(b)** Hierarchical division of grain z into subgrains, each with uniform properties, ignoring unode values. **(c)** Enlargement of grain z, showing distribution of unodes. **(d)** Delaunay triangulation of grain z based on unode distribution only, each triangle within this grain now has properties based on an interpolation of the values of its three apical unodes. **(e)** Voronoi tessellation of grain z, based on unode distribution, Voronoi cells have uniform properties based on central unode value. From Bons et al. (in press)

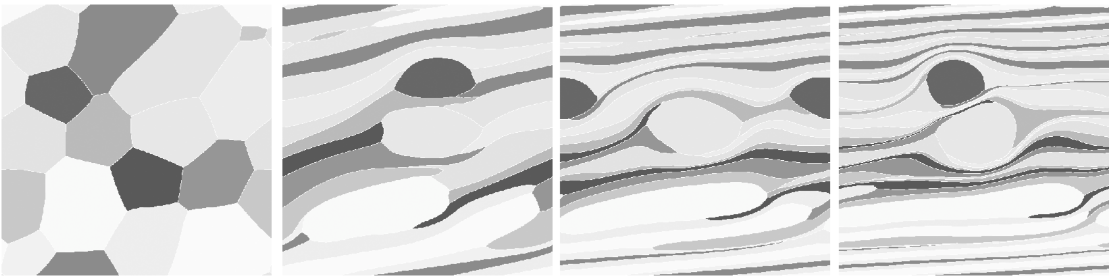

Fig. 4. Four stages of an Elle simulation of simple shear deformation to very high strain. The polycrystalline aggregate contains three grains with a higher viscosity than their matrix. Note that grains that exit at the right reappear on the left. Simulation by Scott Johnson.

In a recent project of Bons, a new basic algorithm was developed for the movement of grain boundaries that is based on a Gibbs free energy minimisation scheme (Becker et al. in press). The algorithm allows the incorporation of any relevant driving force (such as strain energy or surface energy) and any factor that modifies the mobility of grain boundaries, which is an essential prerequisite for the proposed project. A second development, in which Bons is currently involved, is the incorporation of the n-site FFT (or full-field crystal plastic code) of Lebensohn (2001) into Elle (Figs. 5 & 6). The FFT method is a sophisticated way of modelling lattice reorientation by crystal plastic deformation. Until now its application was limited, because it could not simulate concurrent grain boundary migration, which is of crucial importance in ice.

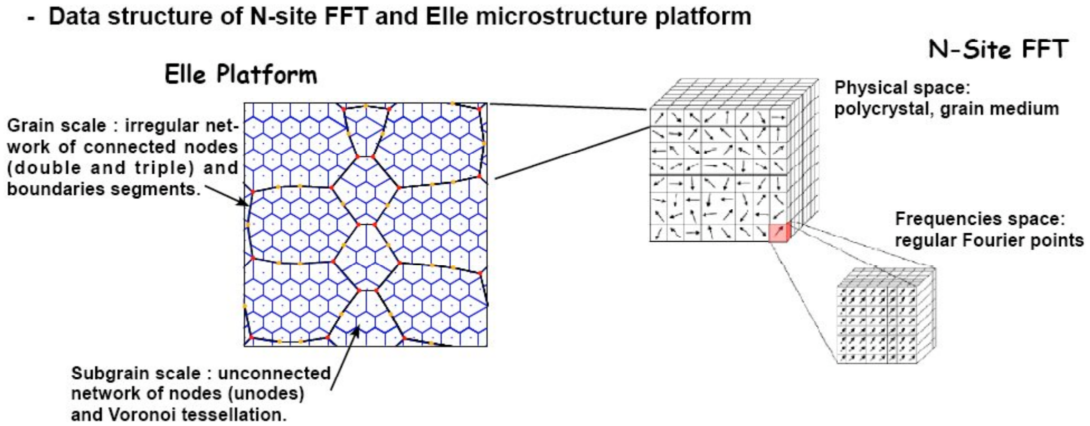

Fig. 5. Schematic illustration of the way the n-site FFT-based method of Lebensohn (2001) is currently being incorporated into Elle by Griera & Jessell in Toulouse.

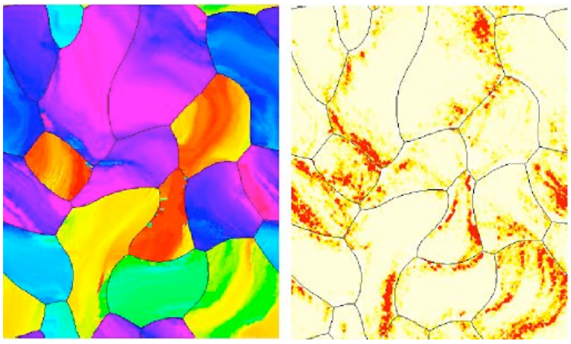

Fig. 6. Combined lattice reorientation (FFT method) and grain boundary migration driven by surface energy. Left: lattice orientations at 10% EW shortening. Right: corresponding dislocation densities. First results by Griera, Jessell, Evans & Lebensohn (unpubl.).

The recent developments described above ensure that, at the end of 2008, the Elle software will have reached the necessary level of sophistication for the proposed project. It will enable systematic simulations without need of significant further software development for pure ice aggregates. The code will also be ready for the implementation of further processes, such as pinning and drag by small particles and the addition of a second phase, such as air-filled porosity.

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3. Goals and work schedule (*Ziele und Arbeitsprogramm*)

3.1 Goals (*Ziele*)

Ideally, a microstructure observed in a drill core gives full information on the current and past mix of boundary conditions (P, T, stress field) and operating processes and that contributed to the formation of that microstructure, such as dislocation creep, grain boundary sliding, grain boundary migration types, etc. With such information one can, ideally, determine the history of the ice sample, its rheology, stress, strain, and strain rate path. However, we currently cannot extract all this information, because it is not fully known how the different processes and boundary conditions exactly affect the microstructure

The overall goal of the 3-project bundle is to improve insight in the behaviour of ice, and hence of ice caps, both in terms of ice flow mechanics and of carriers of our earth's climatic record.

Deriving from the abovementioned overarching goal, the main goal of this project is to significantly increase the information content of ice microstructures by means of their numerical simulation.

We in particular aim to address the following questions:

1. What is the importance of strain energy driven grain boundary migration, relative to that driven by surface energy?
    - Can one quantify the role of these two types of migration from a microstructure?
    - What are the effects of stress, strain (rate), temperature, porosity, etc.?
2. To which extent does strain localisation occur in ice?
    - How can localisation in ice be recognised from the microstructure?
    - What are the factors that control strain localisation? (T, stress, strain (rate), etc.)
    - What are the rheological implications?
3. Are the current large-scale geophysical and rheological models of polar ice correct?
    - To what extent does the "three regime model" need modification and what are the consequences of any modification of the model?
    - What are the rheological implications?

The above aims will be achieved by means of:

1. The implementation and expansion of algorithms to simulate the microstructural evolution of ice;
2. Running "virtual experiments", using the software Elle, to systematically and quantitatively explore the microstructural evolution of ice as a function of operating processes, deformation mechanisms and boundary conditions (stress, strain rate, temperature, deformation kinematics, impurity content, etc.).

The results of the proposed project are of immediate importance to our understanding of the rheology and mechanical behaviour of ice. Polar ice can be regarded as a relatively accessible analogue or proxy to rocks and insights in the flow of ice are therefore also applicable to the study of crustal deformation and mantle flow. The proposed project will advance our knowledge of the behaviour of polar ice caps, with an important societal impact in two areas:

- improving the understanding and prediction of the behaviour of polar ice, which both influences and is influenced by future climate changes;
- improving our knowledge of the climate record that is contained in polar ice.

5.3 Foreign contacts and collaborations (Arbeiten im Ausland und Kooperation mit ausländischen Partnern)

The project is embedded within the extensive international research collaborations and networks of the applicants.

The project will use and develop Elle code, which is open-source software developed by an international consortium, with communication via the internet forum, Elle workshops and bilateral visits. Source code is freely exchanged between the partners. The main partners relevant to this project are:

- **Prof. Chris Wilson and Mrs Lynn Evans**, Melbourne University, Australia. Evans is the main programmer of the central Elle code (data handling, etc.), and therefore a crucial collaborator for any Elle project. Chris Wilson also has an in-situ deformation lab for ice to study the development of ice microstructures. The project will extend ongoing collaboration, currently funded by the Australian Research Council with a grant (2007-2009) to CJ Wilson, JP Burg (Zürich), PD Bons, MW Jessell (Toulouse) and K Stüwe (Graz), which funds the position of Mrs Evans. The fact that Bons is one of the PI's funding Mrs. Evans means that she is also available for the currently proposed project. The assistant will visit the lab of Wilson for training early on in the project.

- **Dr. Mark Jessell** at Toulouse University, France, is the coordinator of the Elle project and currently has one postdoc (**Dr. Griera**) to link lattice rotation in ice with the FFT code of **Dr. R. Lebensohn** (Los Alamos, USA) to Elle. This project is funded (2007-2008) by the ESF-EuroMinScI Collaborative Research Project "Mineral substructure dynamics", of which Bons is also a partner. The proposed project will ensure a seamless continuation of this code development.
- The other main members of the Elle project that are involved in similar applications of Elle are **Dr. Sandra Piazolo** (Stockholm, Sweden), **Prof. Jin-Han Ree and Sungshil Kim** (Korea University, Korea) and **Dr. Daniel Koehn** (Mainz).