Recrystallization Dynamics Derived from Grain Boundary Networks

Tobias Binder[1], Christoph Garbe[1], Dietmar Wagenbach[2], Johannes Freitag[3], and Sepp Kipfstuhl[3]

[1] Interdisciplinary Center for Scientific Computing (IWR), University of Heidelberg, Speyerer Straße 6, 69115 Heidelberg, Germany, Tobias.Binder@iwr.uni-heidelberg.de

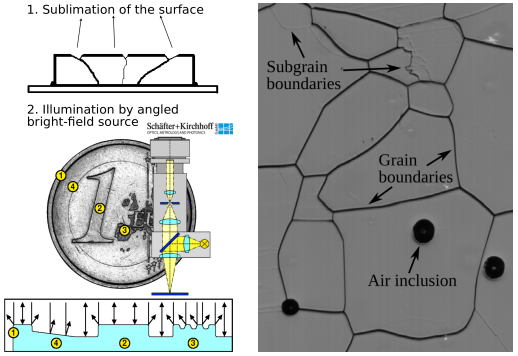
[2] Institut für Umweltphysik (IUP), University of Heidelberg, Germany, [3] Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

Objectives

- **Introducing a new image processing framework for microstructure analysis of polar ice cores based on images of grain boundary networks taken at microscopic resolution.**
- **Presenting an overview on the software framework, its actual functional range along with first results related to recrystallization dynamics.**

Methods

Grain boundary grooves developing on the surface of carefully microtomed ice core sections are scanned by a Large Area Scanning Macroscope (LASM). 4 x 9 cm large sections are imaged at a resolution of 5 μm/pixel. This method reveals a direct image of a grain boundary in microscopic resolution, its principles are shown below.



Left: Principles of image acquisition, right: image of a NEEM ice core section (at 322m)

Image Processing - Background

Ice cores through a 3000 m thick ice sheet provide large numbers of images to be processed. Since existing image processing tools cannot extract grain boundaries automatically and are not designed for large images, a more efficient image processing framework is needed.

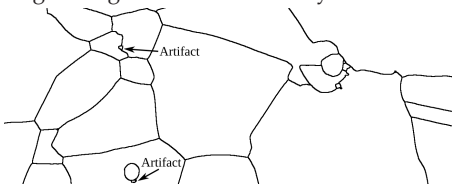
At IWR general concepts of image processing have been developed and successfully utilized in various applications, amongst others for the extraction of air bubbles in ice core sections. The present software framework is currently further developed.

A) Segmentation

In the first image processing step called 'Segmentation' candidates for grain and bubble boundaries are identified by means of 'Machine Learning':

1. About 400 pixels in one section have been classified manually into 'boundary pixels' and 'no boundary pixels' allowing all images of the same mapping type to be classified automatically. The advantage of this implementation is the easy adaption or improvement of the automatic classification by the user.
2. 'Watershed Region Growing' is an algorithm to create a graph of boundary candidates. Grain areas are reliably closed up leaving only few boundary artifacts.

Currently, the focus is laid on grain boundaries, i.e. bright subgrain boundaries may vanish.



Artifacts among the boundary candidates

B) Extraction of Grain Boundaries

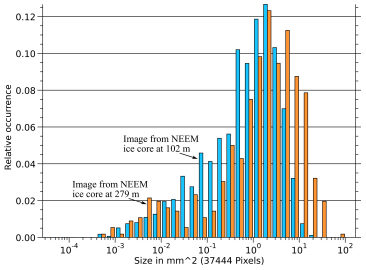
An individual image processing step has been developed to find grain and bubble boundaries among the candidates given by the Segmentation, whose position is obtained at one pixel resolution. Artifacts caused by oversublimation, microtoming or previous image processing may be effectively removed.

C) Grain Boundary Network

In the past mainly mean grain size has been used to characterize the evolution of microstructure, the number of next neighbors or dihedral angles at grain triple junctions were shown in addition only occasionally. The present approach is based on the idea to derive as many parameters as possible to describe the grain boundary network as comprehensive as possible since different parameters characterize the different properties of the network.

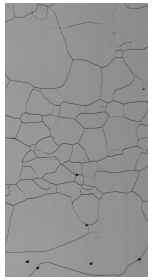
1) Grain Size Distribution

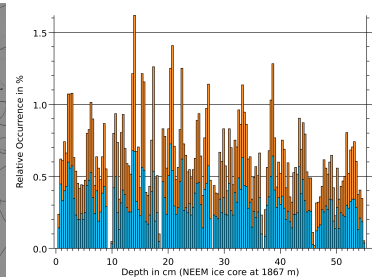
A wide range of grain sizes is covered.



3) Cloudy Bands

Characteristic of Greenland ice cores are cloudy bands up to a few centimeters in width in sections from glacial periods. In cloudy bands the grain size is significantly reduced compared to the clear ice in the vicinity with the same climatic and thermal history. To identify the small scale variability in glacial ice grain center of mass positions are calculated and summed up within a depth range of 3.5 mm. An example image is shown below (left).





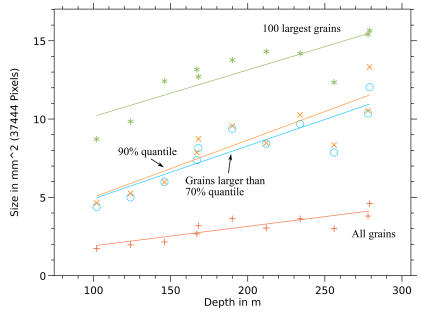
Right: Two horizontally displaced images are used at every depth, blue bars show the occurence of grains on one side, orange bars the occurence on both sides together.

5) Summary

The development status of the present software framework is advanced, first results may be promising. Comprehensive analysis of the grain boundary network allows for a more detailed description of microstructure and recrystallization dynamics than it has been possible with average grain sizes. The next step is to process a dataset along the NEEM ice core, where in steps of 20 m sections of 55 cm have been imaged by 6 images.

2) Grain Growth

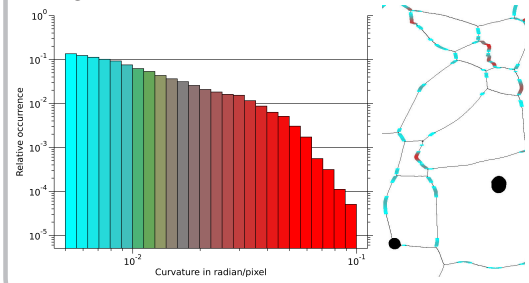
Grain growth is by definition the change of average grain size in an unit area with time (depth). With increasing resolution the problem arises which grain sizes to consider for the average grain size of a section. Small grains either disappear or indicate formation of new grains. The quality of grain boundaries in the images is far to high to exclude arbitrarily a fraction of small grains.



Grain growth at the NEEM ice core found for consideration of all grains, 100 largest grains, 90% quantiles or 30% largest grains (grains larger than 70% quantile)

4) Local Curvature

Using different smoothing techniques continous curvature values are calculated for every grain boundary pixel taking into account 5 pixels on each side. Assuming static equilibrium the driving force for grain boundary migration is proportional to the curvature. High curvature most likely indicates high stored strain energy and strain induced boundary migration. Identifying curvatures allows in principle to produce maps of areal distribution of the driving force within a section and to estimate the energy available for recrystallization through an ice sheet.



Left: curvature distribution, right: color-coded curvature map