Research Networking Programmes

Science Meeting – Scientific Report

The scientific report (WORD or PDF file - maximum of seven A4 pages) should be submitted online <u>within two months of the event</u>. It will be published on the ESF website.

***Proposal Title*: "Measurements of ice structures by means of image analysis"**

***Application Reference N°*: 5822**

1) Summary

The internal structure of polar ice sheets and mountain glaciers has been analyzed for several decades by increasingly sophisticated imaging techniques. This workshop focused on the current state of available methods of image analysis applicable for micrometer- to hundred meter-scale structures. The objective of this workshop was also bringing together researchers from a variety of backgrounds to compile the current state of already available and possibly derivable data.

2) Description of the scientific content of and discussions at the event

2a) Image acquisition

The workshop started with providing an overview of different image acquisition methods used for structural analysis of ice. This includes:

- land-based and aerial photography of mountain glaciers,
- microstructure mapping (analysis of ice section using a light microscope) and its further development where the microscope is replaced by a scanner (LASM),
- stratigraphic line-scan analysis of ice cores,
- electron backscatter diffraction (EBSD),
- automatized scanning of ice thin sections between crossed polarizers (fabric analyzer) and the alternative approach CIP (computer-integrated polarization microscopy),
- visualization of microstructure simulations performed by Elle,
- even though ice penetrating radar and synthetic aperture radar (SAR) are not natively image acquisition methods the obtained data can be represented and thus processed as images.

This introduction was complemented by a visit of the ice lab at AWI.

Imaging of microstructures is especially important if they cannot be preserved robustly in the sample itself, as it is the case for natural ice. The high homologous temperature of natural ice causes accelerated relaxation effects due to the pressure relieve after drilling. It is thus preferable to record microstructures shortly after drilling of ice cores, even on-site if logistically possible.

During the workshop the characterization of sub-grain boundaries in the NEEM ice core using EBSD has been discussed. Fifty samples of five different depth sections were mapped and analyzed. This method allows characterizing sub-grain boundaries and determining the lattice rotation configurations of each individual sub-grain. In addition to the classical boundaries made up of basal dislocations, sub-grain boundaries made of non-basal dislocations were identified as well.

Space-borne sensors operating in the microwave frequency range are well-suited to observe processes in the polar regions, since they are independent of solar illumination and cloud cover. With synthetic aperture radar (SAR), spatial resolutions on the order of several meters can be realized. SAR measurements allow a closer look at small- to medium-scale cryospheric processes and can be useful for spatial upscaling of point-based field measurements.

We realized that different remote-sensing systems are required to characterize the surface and bed of the (mountain) glaciers. On the example of the Malaspina glacier in southeastern Alaska the combination allows us to partially understand internal and external structure on a variety of scales from sub-meter to kilometer.

Image processing often deals with compensating problems of image acquisition. During the workshop we discussed to role of

- frost on the surface of polished ice sections,
- the thickness of ice core sections for fabric measurements,
- ice sample storage conditions.

For the Malaspina glacier photographic time series have been taken with different optical systems. This causes distortions when image overlays are generated even if the position and viewing direction are identical. It has been demonstrated how image calibration methods (e.g. provided by Photoshop) can solve this problem.

2b) Image analysis

Given lectures dealt with the question how images are digitized and can be modified, e.g. by filters. The methods of image analysis have been divided into different levels of complexity. On the lowest level gray values are analyzed, e.g. by generating gray value histograms. Even these methods can be powerful. For instance, the auto-correlation function allows quick structural estimations.

The universal software solutions ImageJ, Fiji, ImageSXM as well as the customizable C++ library vigra have been introduced and applied together with the participants.

Due to the variety of scientific background some misunderstandings occurred:

- An image with two different pixel values is sometimes referred to as bitmap whereas it can also be called binary image.
- Different gray value conventions exist. Gray value “0” often corresponds to dark (no light intensity), but correspondence to white (no ink on white paper) is common as well.

The medium level of image analysis focus on segmentation where objects in an image are detected and their outlines are determined. One challenge for segmentation is the concurrent detection of different boundary types (edges, corners, and junctions). The discretization of objects given by the grid in which the image is stored makes it difficult to extract, for instance, the position of grain boundaries or the angle of grain boundary triple junctions accurately.

However, the chosen methods can also be the limiting factor, i.e. the resolution is unnecessarily worsened. Modern image analysis techniques allow almost rotationally invariant boundary detection. The local (pixel-wise) direction of edge gradients can be determined by different tensorial quantities based on a complex mathematical basis. The potential of these novel concepts has been demonstrated during the workshop.

It became obvious that the variety of methods to obtain a representation of the physical structures can lead to inconsistencies in the set of derivable and physically meaningful quantities. Grains visible in sections are sometimes approximated by circles which cannot replace the connected extraction of the grain boundary network in which grain boundaries are dimensionless (no spatial extension).

Both with ImageSXM and the image analysis software developed in close collaboration with the AWI (www.ice-image.org) comprehensive micro-structural parameterization is possible – the highest level of image analysis. In the later approach, the grain boundary network is represented object-based which paves the way for novel parameters describing grains in relation to their neighborhood.

Of particular importance is the question how to describe grain size. It is possible to derive an equivalent radius or the long, resp., short axis of the equal area ellipse for single grains. Additionally, grain boundary densities can be calculated which are proportional to the reciprocal radius. Caution is required for the analysis of two-dimensional grain cross-sections in general and lognormal distributions since both may hide errors. It was discussed whether the auto-correlation function can serve as first estimate of mean grain size. This approach is reasonable if image values inside individual grains are similar and differ from neighbors which is not always the case.

The strip star tool (developed by Renée Heilbronner) for conversion of two-dimensional grain cross-sections into volume fractions has been introduced. This correction is commonly applied for geological studies, but not in glaciology. This makes it difficult to compare grain size studies. Going back to the linear intercept method, a manual way to determine grain size where the strip star tool cannot be applied, the underestimation of grain sizes is sometimes corrected by a fixed factor.

Supplementing the lectures, participants presentedt methods of / open tasks for image analysis. It became obvious that image analysis allows detecting and quantifying already known structural conspicuities in shape and distribution. Only occasionally previously undetected pattern are detected (as the case for fractal geometry calculations).

The image analysis software developed in close collaboration with the AWI paves the way for segmentation and parameterization of large data sets (microstructure mapping and fabric analyzer) fully automatic. Additionally, it is coupled to the simulation platform Elle so that simulated structures can be described in the same way and quantitative comparisons are possible.

The software FAME for grain identification derived from MTEX (Matlab toolbox for EBSD data) has been introduced. It is an alternative approach for processing fabric analyzer data. FAME offers the plotting of c-axis misorientation maps. Out of a range of different options, a suitable representation of the c-axis misorientation can be chosen. Disorientation maps provide an indication of the strain distribution in the material and are a first approximation to the dislocation density. Using artificial strain marker added during an ice deformation experiment, these can be used for an extensive strain analysis. Based on image correlation and tracking algorithms, 2D or 3D displacement maps can be generated, which provide information about the non-uniformity of the flow field during the deformation. Furthermore, the progress of deformation can be comprehended using a strain vs. time diagram.

Recent advances of FAME are the coupling to Elle by the module “Fame2Elle” and the calculation of boundary angles from the retardation profile at grain boundaries. This three-dimensional grain boundary reconstruction yields similar information like the LASM/fabric analyzer matching. However, the FAME reconstruction is currently not possible for ice sections as a sample thickness of less than 100 µm would be required.

One aspect of SAR processing is pattern matching to determine a motion field. Tracing layers visible in ice penetrating radar measurements is currently a very time-consuming task as it is performed semi-automatically.

3) Assessment of the results and impact of the event on the future directions of the field

The composition of participants allowed convening researchers from a variety of background in order to compile the current state of already available and possibly derivable data. Both invited lecturers (Renée Heilbronner and Mark Peternell) have extensive methodical experience in micro-structure analysis and data processing complementing the glaciological background of other participants.

The workshop showed that the ideas on measurements in relation to images can be quite different. Some argue that images are only visualizations, whereas images are sometimes regarded as measurements possibly requiring conversion. There are considerable differences between the qualitative and quantitative description of revealed structures. The decision between manual/semi-automatic and fully-automatic image processing techniques should take the individual data set, capacities and expectations into account. For instance, the auto-correlation function may be sufficient to describe the preferred alignment of objects in an image whereby the complex and challenging segmentation step can be skipped. It has to be further discussed whether the tracing of layers in radargrams can benefit from modern image analysis techniques.

One result is that error estimation for fabric analyzer measurements is crucial. Comparisons between different instruments (for instance, with the CIP method) have revealed weaknesses of the G50 instrument which is currently used for ice core studies. Different methods for processing of fabric analyzer data have been compared and it became obvious that the extraction of grain boundaries for fabrics with single maximum orientation is a challenging task.

We discussed the influence of dynamic recrystallization on two-dimensional grain cross-sections. The more frequent occurrence of small grains is related to nucleation and grain boundary bulging which can hardly be distinguished in images. The assumption of spherical grains underlying the strip star tool does not adequately describe the relation between small and large cross-sections in case of dynamic recrystallization.

Clustering of small grains is observed in different materials, but the controlling processes may be different. Ice is characterized by its contrast in impurity content, porosity and bubble pressure. Most models considering air inclusions as second phase do not capture the complex compression (and relaxation) processes occurring in natural ice. It became obvious that novel parameters have to be established. The impurity content in ice correlates with obvious changes in grain size and small scale foldings, but it remains unclear how a functional description for these relations can be obtained. Furthermore, the consequences for ice deformation demand additional investigation.

In different contexts, it became obvious that ice structures change on small (sub-meter) scales. Consequently, single ice core sections are not representative for entire depth regimes and need to be analyzed at the highest possible depth resolution.

The participants discussed possibilities for further development and new collaborations. Some analysis scripts written by Renée Heilbronner in Fortran may be translated to modern programing languages. The functionality of the presented processing tools for fabric analyzer data will be adapted to each other whereby different operating systems and programing platforms create difficulties. In that regard, software exclusively based on open source solutions is often easier portable that software incorporating commercial modules (for instance, Matlab).

The presented fractal calculations (FROST) will be further applied to ice microstructures. It will be investigated how reliable c-axis misorientation inside grains are and in which cases the calculation of misorientation gradient is reasonable. It is worth developing novel functionality to compare synthetic and measured radargrams, resp., simulated and observed microstructures.

4) Annexes 4a) and 4b): Programme of the meeting and full list of speakers and participants

Annex 4a: Programme of the meeting

Monday, 23 February

- Ice breaker

Tuesday, 24 February

- Welcoming and organization of the workshop (Organization team)
- Lecture „Looking at images“ (Renée Heilbronner)
- Poster presentations „Microstructure images“ (Ilka Weikusat, Ernst-Jan Kuiper)
- Lecture „Mapping of the optic axes of ice and introduction to CIP I“ (Renée Heilbronner)
- Visit of AWI ice lab
- Lecture „Mapping of the optic axes of ice and introduction to CIP II“ (Renée Heilbronner)
- Talk „Analysis of the orientations in the grain interiors using the fabric analyzer“ (Tobias Binder)

Wednesday. 25 February

- Talk „Representation and evolution of crystallographic orientation in numerical simulations“ (Florian Steinbach)
- Lecture „Introduction to segmentation techniques“ (Tobias Binder)
- Lecture „Quantification of segmented structures, e.g., size and shape descriptors I“ (Renée Heilbronner)
- Lecture „Quantification of segmented structures, e.g., size and shape descriptors II“ (Renée Heilbronner)
- Talk „Overview of remote-sensing systems at Malaspina Glacier – Visible and hidden information“ (Bruce Molnia)
- Talk „What do we actually see in radio-echo sounding measurements?“ (Daniela Jansen)
- Talk „Introduction to SAR image analysis“ (Stefanie Linow)
- Talk „Ice cores and radio-echo sounding: modelling and tracing internal layers“ (Anna Winter)
- Talk „Analyzing the passive grid of numerical simulations“ (Daniela Jansen)
- Talk „3d grain boundary reconstruction using the Fabric Analyser “ (Daniel Hammes/Mark Peternell)
- Talk „Fractal descriptors“ (Florian Steinbach)

Thursday, 26 February

- Workshop: License-free image analysis software, application to fabric analyzer and LASM data (Tobias Binder/Jan Eichler)
- Talk „Analysis of fabric analyzer measurements using FAME“ (Mark Peternell/Daniel Hammes)
- Talk „Analysis of fabric analyzer measurements and obtained results“ (Jan Eichler)
- Talk „Results of fabric analyzer measurements of an Alpine ice core“ (Johanna Kerch)
- Discussions

Friday, 27 February

- Workshop: MATLAB-based software FAME and FROST (Mark Peternell /Daniel Hammes/Florian Steinbach)

Annex 4b: Full list of speakers and participants

Maddalena Bayer, AWI, Helmholtz-Zentrum für Polar- und Meeresforschung

Tobias Binder, AWI, Helmholtz-Zentrum für Polar- und Meeresforschung

Jan Eichler, AWI, Helmholtz-Zentrum für Polar- und Meeresforschung

Johannes Freitag, AWI, Helmholtz-Zentrum für Polar- und Meeresforschung

Julia Gallas, University Greifswald

Daniel Hammes, University Mainz

Renée Heilbronner, University Basel

Sebastian Hoerz, AWI, Helmholtz-Zentrum für Polar- und Meeresforschung

Daniela Jansen, AWI, Helmholtz-Zentrum für Polar- und Meeresforschung

Johanna Kerch, University Heidelberg

Ernst-Jan Kuiper, Utrecht University

Stefanie Linow, AWI, Helmholtz-Zentrum für Polar- und Meeresforschung

Bruce Molnia, U. S. Geological Survey

Mark Peternell, University Mainz

Christoph Schaller, AWI, Helmholtz-Zentrum für Polar- und Meeresforschung

Florian Steinbach, AWI, Helmholtz-Zentrum für Polar- und Meeresforschung

Anna Winter, AWI, Helmholtz-Zentrum für Polar- und Meeresforschung

Ilka Weikusat, AWI, Helmholtz-Zentrum für Polar- und Meeresforschung