Grain boundary hierarchy in the EPICA-DML deep ice core, Antarctica

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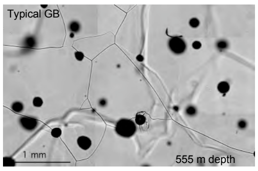
Introduction and Method

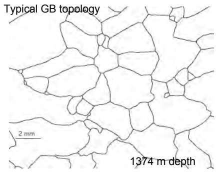
Macroscopic flow of ice results from a number of different mechanisms, each of which dominate the rheology of the ice at a particular range of physical conditions (e.g. temperature, pressure, differential stress, impurity content, ...). The polycrystalline ice of polar ice sheets consists of grains, which deform by the migration of crystal defects on the atomic scale. Microstructural processes like polygonization, grain growth and recrystallization are directly affected by the (sub-) grain boundary arrangement and hierarchy.

Optically visible traces of these processes were recorded along the EPICA Dronning Maudland (EDML) ice core recently drilled in Antarctica. Thick sections (50 mm x 100 mm x 5 mm) were cut parallel to the vertical axis of the EPICA-DML ice core were mapped under a microscope (Kipfstuhl et al. submitted). A digital mosaic image of an entire section in microscopic resolution is reconstructed and used to extract information about the (sub-) grain boundary topology and the occurrence of bulging and pinning.

Grain boundaries (GB)

- They appear as strong black lines.
- GB are connected to each other (grains are closed).

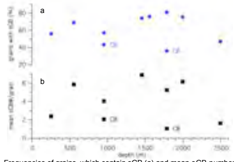




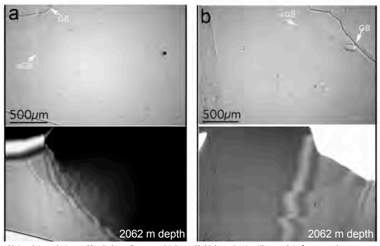
- Foam textures characteristic for normal grain growth expected within the upper hundreds of meters (~500 m) is not observed. Qualitatively, the appearance of the GB topology does not change with depth.

Sub-grain boundaries (sGB)

- They appear as thinner, fainter lines.
- Between crossed polarizers a sample shows misorientation across sGB.
- sGB can fade out (sub-grains seem open).
- > 50% of all grains contain sGB independent on depth.
- Mean number of sGB per grain varies between 1 and 7. However, many grains show more than 30 to 50 individual sGB.



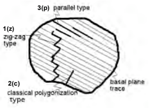
Frequencies of grains, which contain sGB (a) and mean sGB number per grain (b) with depth. (CB=cloudy band)



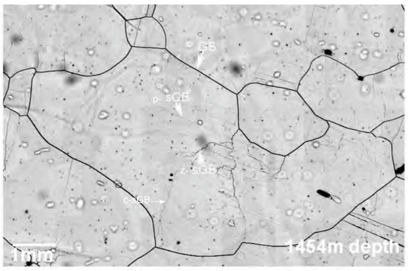
Note: pictures between X-polarizers (lower row) taken with high contrast settings -> interference colours between grains are black and white, whereas sGB show interference differences in grey. Pictures from second EPICA core at Dome C.

Sub-grain boundary types

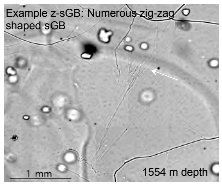
Shapes and intensities (grey values) of sGB are manifold.
1 (z). Irregular (zigzag- or step-shaped), building networks one direction at high angle and one parallel to the basal plane trace
2 (c). Regular, straight and orthogonal or at high angle to basal plane, solely or in groups of few sub-parallel
3 (p). Regular, straight and parallel to basal plane, in swarms of many exactly parallel sGB in one grain.

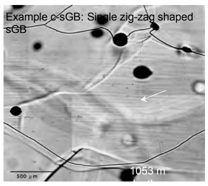


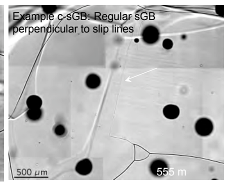
Not all sGB can be doubtlessly classified especially if they show no distinct shape.

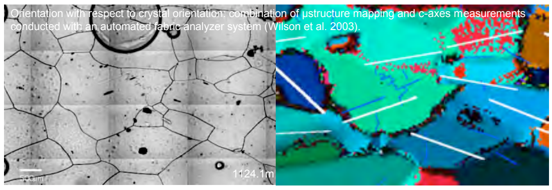


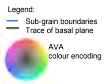
Sub-grain boundaries perpendicular to basal plane

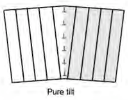






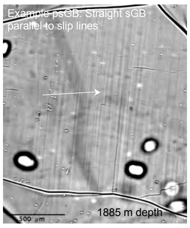


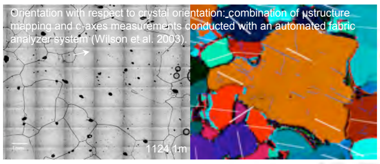


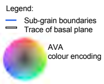


Interpretation: (1) c-type sGB (classical polygonization): edge dislocations induced by deformation start to arrange during recovery and form arrays of edge dislocations (tilt boundaries).
(2) z-type sGB: seems to represent a mixture of c- and p-types, e.g. alternating parts of a tilt and a twist boundary.

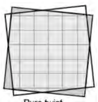
Sub-grain boundaries parallel to basal plane



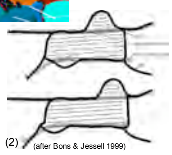




Interpretation: (1) arrays of screw dislocations accumulate and form sGB (twist boundaries) or
(2) micro-shear zones cutting off protruding part of grains (Bons & Jessell 1999), this interpretation is supported by observations of geometries of GB and sGB.



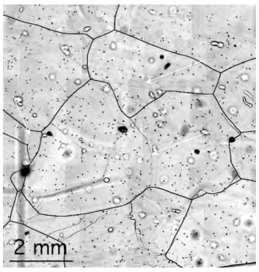
(1) (after Föll, H. 2000).



(2) (after Bons & Jessell 1999)

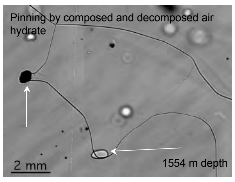
Geometry effects

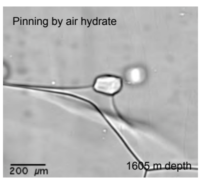
- The occurrence of sGB at necks of bulged or severely exposed parts of a grain, shows that interaction with GB is related to geometry of grains.

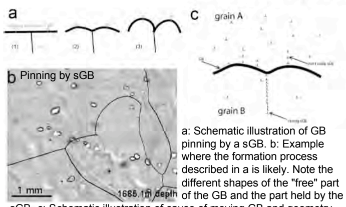


Grain boundary pinning

- Distinct geometries of GB interaction with other features give rise to the interpretation that moving GB can become be by inclusions (air bubble or hydrate clathrate) and sGB (see Drury & Urai 1990).
- 10-20% of all grains show pinning.





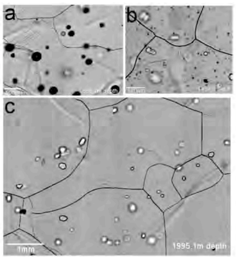


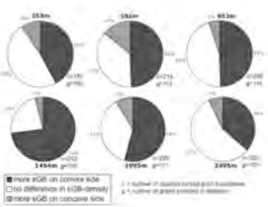
a: Schematic illustration of GB pinning by a sGB. b: Example where the formation process described in a is likely. Note the different shapes of the "free" part of the GB and the part held by the sGB. c: Schematic illustration of cause of moving GB and geometry of curves: Grain A contains randomly distributed dislocation and higher internal energy whereas grain B piled up most dislocations in one well developed sGB.

Grain boundary bulging

- 70-80% of all grains show bulged GB.
- most curves show more sGB on their convex side

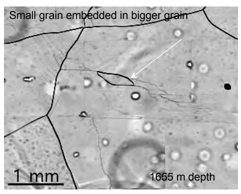
Interpretation: GB move towards the side with higher sGB-density due to locally high internal strain energy.





(Sub-)Grain boundary loops- “Island grains”

- Small isolated grains embedded in larger grains, often in sub-grain bearing parts of a grain
- Two possibilities of formation:
1) 3D-effect (loops as section of out-bulging part of a grain)
2) loop as newly nucleated grain in deformed part of the host grain
- 1-2% of all grains show embedded island grains.



Conclusions

In the upper 2500 m of the EDML ice core we cannot recognize qualitative differences or trends in the appearance of the grain boundary topology, in bulging and pinning. Furthermore occur sub-grain boundaries in all depths without differences in arrangement. This may indicate that the competing processes deformation, grain growth and recrystallization equally contribute to the observed microstructure and work largely independent on depth and age. This is surprising as normal grain growth is assumed to dominate in the upper hundreds of meters of the ice sheet, migration recrystallization in the lowest and polygonization in between.

Arguments for strain induced grain boundary migration above the depth range ascribed to migration recrystallization (lowest part of ice sheet with high temperatures) by standard conception on recrystallization regimes have been presented.

Different types of sub-grain boundaries have been identified, indicating different evolution processes apart from polygonization. Screw dislocation play at least some role in the deformation of ice.

References

Bons, P.D., Jessell, M.W. 1999. Micro-shear zones in experimentally deformed OCP. J. Struct. Geol. 21, 323-334.
Drury, M. R., Urai, J. L. 1990. Deformation-related recrystallization processes. Tectonophysics 172, 235-253.
Föll, H. 2000. Defects in Crystals. Hyperscript. www.techfak.uni-kiel.de/matwis/amat/ def_en/index.html
Kipfstuhl, S., Hamann, I., Lambrecht, A., Freitag, J., Faria, S. H., Grigoriev, D., Azuma,N. 2006. Microstructure mapping a new method for imaging deformation-induced microstructural features of ice on the grain scale, submitted to J. Glaciol.
Wilson, J.L., Russell-Head, D. S., Sim, H. M. 2003. The application of an automated fabric analyzer system to the textural evolution of folded ice layers in shear zones. Ann. Glaciol. 37, 7-17.