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Sub-grain boundary features in ice cores from EDML, Antarctica

Introduction - Method

The deformation of ice in polar ice sheets on the grain scale is performed by several processes. One important is the bending of grains and splitting into smaller grains. In this polygonization process the formation and evolution of new grain boundaries viz. sub-grain boundaries plays an important role. Study on these micro-structural features shall give insight into the deformation behaviour of ice. By sublimation of polished (microtomed) surfaces of thick sections grain boundaries (GB), sub-grain boundaries (sGB), slip lines and air inclusions (bubbles and clathrate hydrates) are made visible in microscopic resolution. GB appear as thick, dark and smooth lines in microphotographs whereas sGB are thin grey lines. As the misorientation across sGB is very small high contrast enhancement during taking of photographs is needed to see difference in interference between crossed polarizers (Fig.1). Detailed studies on sGB in selected depths (255m, 555m, 953m, 1454m, 1785m, 1995m and 2495m) reveal that sub-grain boundaries are frequent features. Examples are shown in Fig.2.

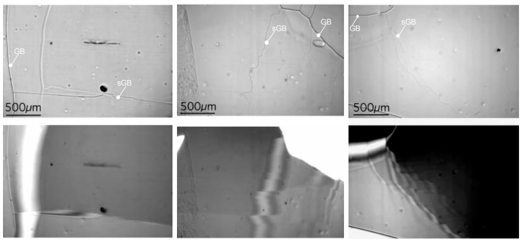


Fig.1: Microphotograph examples of sGB from EDC (2062m depth). Upper and lower picture each showing the same region of sample. Upper picture taken in plain light. Note that pictures between crossed polarizers (lower row) are taken with high-contrast settings. Therefore interference colours between grains are black and white whereas sub grains show interference difference in grey values (misorientation probably around 1°). Grain boundaries (GB), and sub-grain boundaries (sGB) are indicated.

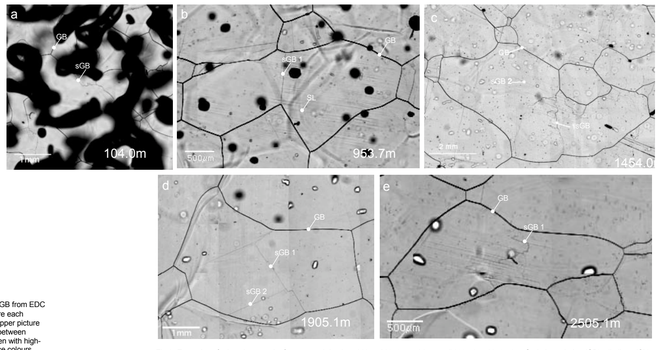
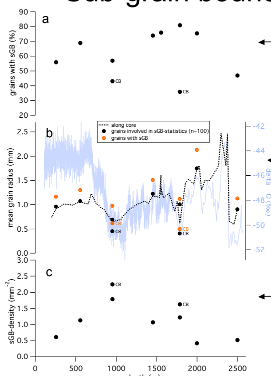


Fig.2: Examples of microphotographs from several depths. a)104m b)953.7m c)1454m d)1905.1m e)2505.1m. Grain boundaries (GB), slip lines (SL) and sub-grain boundaries of the two main types (sGB 1 and sGB 2) are indicated. Type definition see below. Note: Different grey values in different pictures are due to changes in light conditions and capturing settings. Different grey values in the same pictures are due to size of the etch groove produced by sublimation depending on number of bonding neighbours of atoms (viz. order of the region, number of dislocations). The different grey values have been interpreted as different stages of sGB-formation (light-young, dark-old) by Wang et al. 2003.

Sub-grain boundary frequencies and densities



Frequency of sGB-containing grains does not change with depth.

Frequency of sGB-containing grains increases with grain size.

Measured 2D grain size of grains with sGB is significantly higher than average grain size.

sGB-density does not change with depth.

sGB-density decreases with grain size.

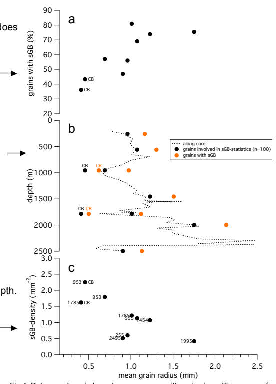


Fig.3: Data on sub-grain boundary occurrence with depth. a)Frequency of grains showing sGB (CB=cloudy band). b)Mean grain radius (left axis) of whole samples, for statistics selected sample area and within these of sGB-bearing grains (see legend) and stable oxygen isotope record (Oerter 2004 pers. comm.). c)Mean sGB-density per area. (Note: sGB-density is not length of sGB per area but number of sGB per area.)

Fig.4: Data on sub-grain boundary occurrence with grain size. a)Frequency of grains showing sGB (CB=cloudy band). b)Mean grain radius of whole samples, for statistics selected sample area and within these of sGB-bearing grains (see legend). c)Mean sGB-density per area. (Note: sGB-density is not length of sGB per area but number of sGB per area.)

Correlation of frequency of sGB-containing grains (Fig.3a) and sGB-Density (Fig.3c) with depth are not found. Grain size (Fig.3b) in the upper half of the core is nearly constant and shows a significant increase with depth only in the deepest part of the core and is mainly modulated by climatic (impurity content) changes. Because of these two findings a particular depth of onset of polygonization, which should terminate grain growth and show a significant increase in sGB-occurence, cannot be detected.

Samples with higher average grain size have more grains showing sGB (Fig.4a), which might be due to probability of sample cutting effects (larger area exhibits most probably sGB). This effect is also seen in the higher average grain size of sGB-containing grains compared to all grains (Fig.3b & 4b).

However less sGB per area (smaller sGB-densities) are found in samples with larger grains (Fig.4c). Samples with small grains are from cold periods of last glacial periods (Fig.3b) and cloudy bands. This ice has high impurity concentrations, which leads to more dislocation sources on micro particles. Additionally micro particles and higher GB-density (many grain boundaries due to small grain size) block the movement of dislocations and lead to pile up in sGB (Paterson, 1999, p. 285).

Grain size and sub-grain boundaries

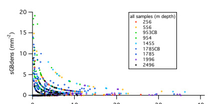


Fig.8: sGB-density by grain size. (Note: sGB-density is not length of sGB per area but number of sGB per area.) "Bead-strings" are due to classification of large numbers of sGB into size-bins during investigation (CB=cloudy band).

Correlation of sGB-density with grain size is also found within the samples (Fig.8). Smaller grains show higher sGB-densities then larger grains. As instead of the length of sGB but the number of sGB has been used for this study, the values for small grains are highly overestimated. Therefore a concrete correlation function cannot be determined.

An other interesting feature is that this dependence is found also in large-grain-size samples, where only few micro particles are present. If taken into account that many of the "small" grains detected in a section are in 3 dimensions actual bulged "arms" of bigger grain, an explanation might be the heterogeneous distribution of sGB within the grain. Indeed a geometrical effect tending to cut off such protruding parts of a grain has often been observed (Fig.9). A second effect is that many sGB appear at the rim of a grain, thus close to GB.

Conclusions

An onset of polygonization/sub-grain rotation recrystallization or an onset of migration recrystallization cannot be found. Indeed shows this study that sub-grain formation is active in any depth of EDML ice core, which indicates that the classical tripartition of recrystallization regimes (1. Grain growth, 2. Polygonization/sub-grain rotation recrystallization, 3. Migration recrystallization) is not easily applicable here and has to be reconsidered.

Samples from the cold stages of last glacial period (containing cloudy bands and high impurity concentration) have the highest sGB-densities. Dislocation productivity and activity is higher leading to more sGB in impurity laden ice, such that micro particles act as source and together with GB as dislocation movement barriers.

Locally very restricted differences in deformation intensity can occur; namely inside single crystals, indicated by heterogeneous distribution of dislocations in grains.

The result that the two types of sGB are similarly often, indicates that edge and screw dislocations play a similar important role in the beginning stage of polygonization. Although it cannot yet be determined if both types develop equally into GB.

Sub-grain boundary types

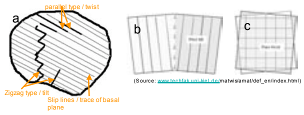


Fig.5: Schematic illustration of sGB-types. a) drawing of types. b) and c) theorethical idea of types

Two types of sGB can be distinguished in all depths and categorised by orientation with respect to the basal plane trace in the section

1. At high angle to trace of basal plane (tilt boundaries): irregular, zigzag or step-like shape, often appear as networks
2. Parallel to trace of basal plane (twist boundaries or micro shear zones): regular, straight shape, often appear in swarms parallel to each other

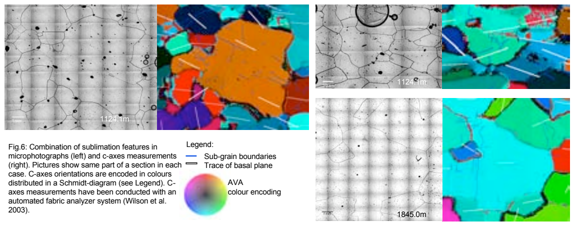


Fig.6: Combination of sublimation features in microphotographs (left) and c-axes measurements (right). Pictures show same part of a section in each case. C-axes orientations are encoded in colours distributed in a Schmidt-diagram (see Legend). C-axes measurements have been conducted with an automated fabric analyzer system (Wilson et al. 2003).

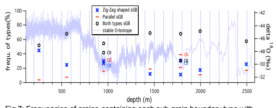


Fig.7: Frequencies of grains containing each sub-grain boundary type with depth (left axis). Right axis shows stable oxygen isotope record (Oerter 2004 pers. comm.) for reference. (CB=cloudy band).

Typically both types occur together in the same grain. A predominance of grains showing only (zigzag) twist boundaries over grains with tilt boundaries only in the shallowest part of the core might be due to the first random and than slowly aligning c-axes distributions. But interpretation of this features is not yet available. In most depth ranges both types occur similarly often.

Sub-grain boundary sites in the grain

sGB within the grains are not distributed homogenously but often appear localized accumulated along GB especially at sites where a protruding prominent geometry of GB can bee seen (Fig.9) (Hamann et al. 2004). During this investigation approximately 20 to 40% of all grains per sample have been marked to show these geometry effects on sGB locations in the grain.

Possible causes of this effect might be:

•complicated resolved shear stress at these outstanding sites due to different orientations of GB-planes as GB are not straight, which leads to higher strain in the vicinity and higher production of dislocations. Additionally might edges of GB serve as sources for dislocations.

•high accumulation of moving dislocations at GB edges, which act as barriers. In these two cases the prominent geometry of the GB would cause the site of sGB-formation.

•pinning of a moving GB by a sGB holding it at a spot. In this case the sGB would cause the protruding geometry of GB as GB bulge out.

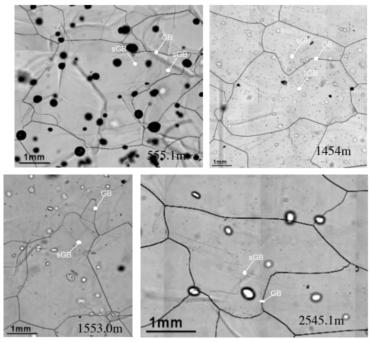


Fig.9: Examples for typical sGB sites within the grain from different depths.

Acknowledgements

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References

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