Helmholtz Young Investigator Group
Deformation mechanisms for ice sheet dynamics

Dominant processes for microstructure evolution in polar ice

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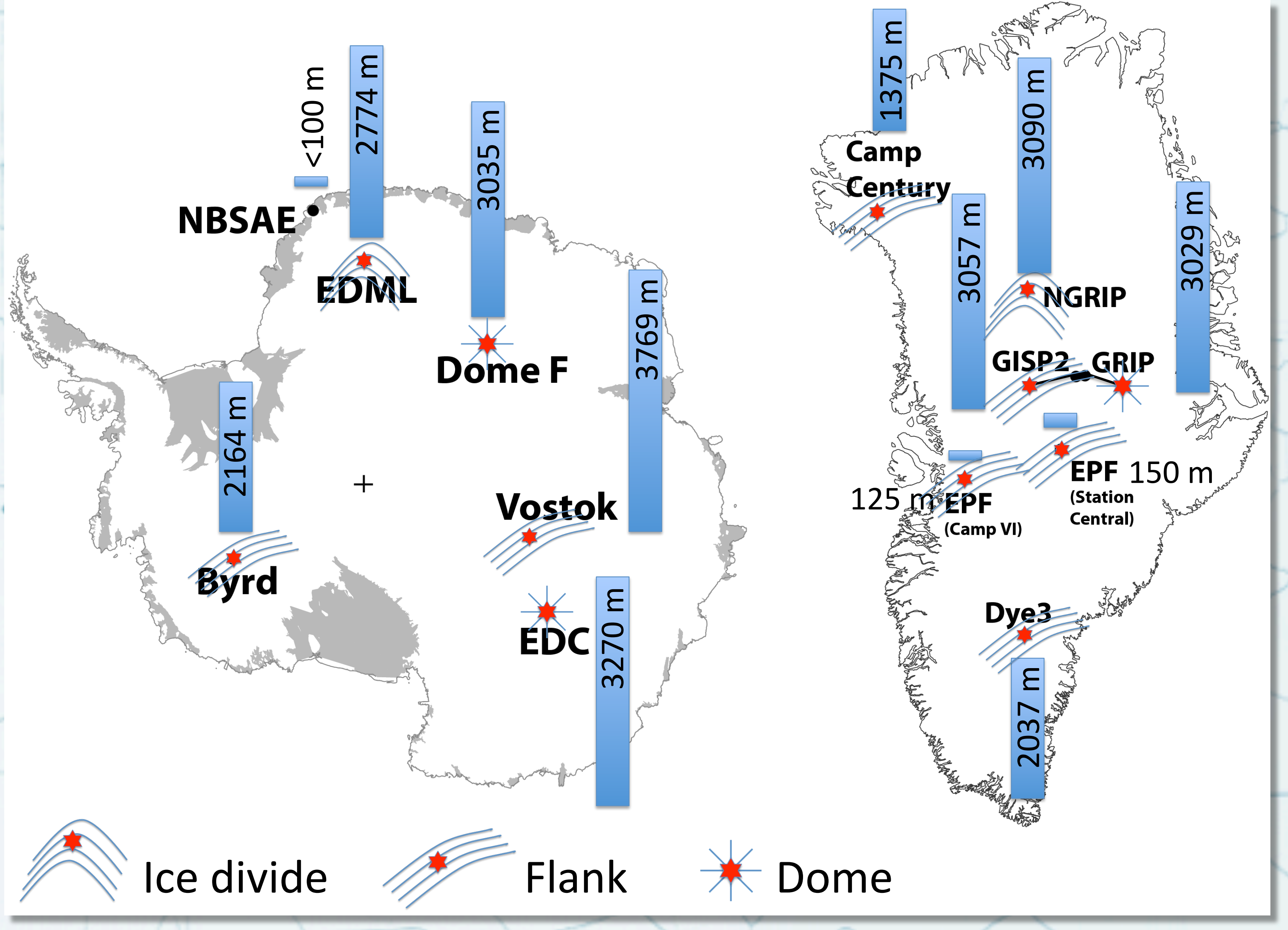
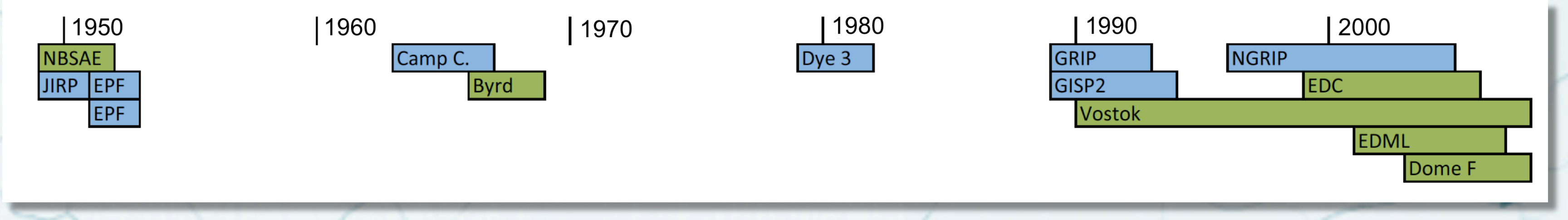
Introduction

The microstructure of polycrystalline polar ice is affected by many recrystallization processes, which can occur simultaneously as well as in succession. The size and shape of individual grains, the orientation of c-axes and the occurrence of sub-grain boundaries are all influenced by a number of agents, including stress, strain, impurity content, and temperature within the ice. To interpret the structures found in ice core data with respect to the generating deformation mechanisms, it is necessary to better understand the feedback between microstructure and rheology of the ice. A better knowledge of ice rheology is also required for improving macroscopic ice flow models and producing realistic projections of the mass balance of ice sheets.

Historical background



The analysis of microstructural data of deep ice cores within the last decades contributed significantly to the understanding of recrystallization processes. The review paper by Faria et al. (in preparation) revisits some historic results.
Below: time line of ice core drilling activities shown in map. Green bars indicate Antarctic campaigns, blue bars indicate Greenland campaigns.



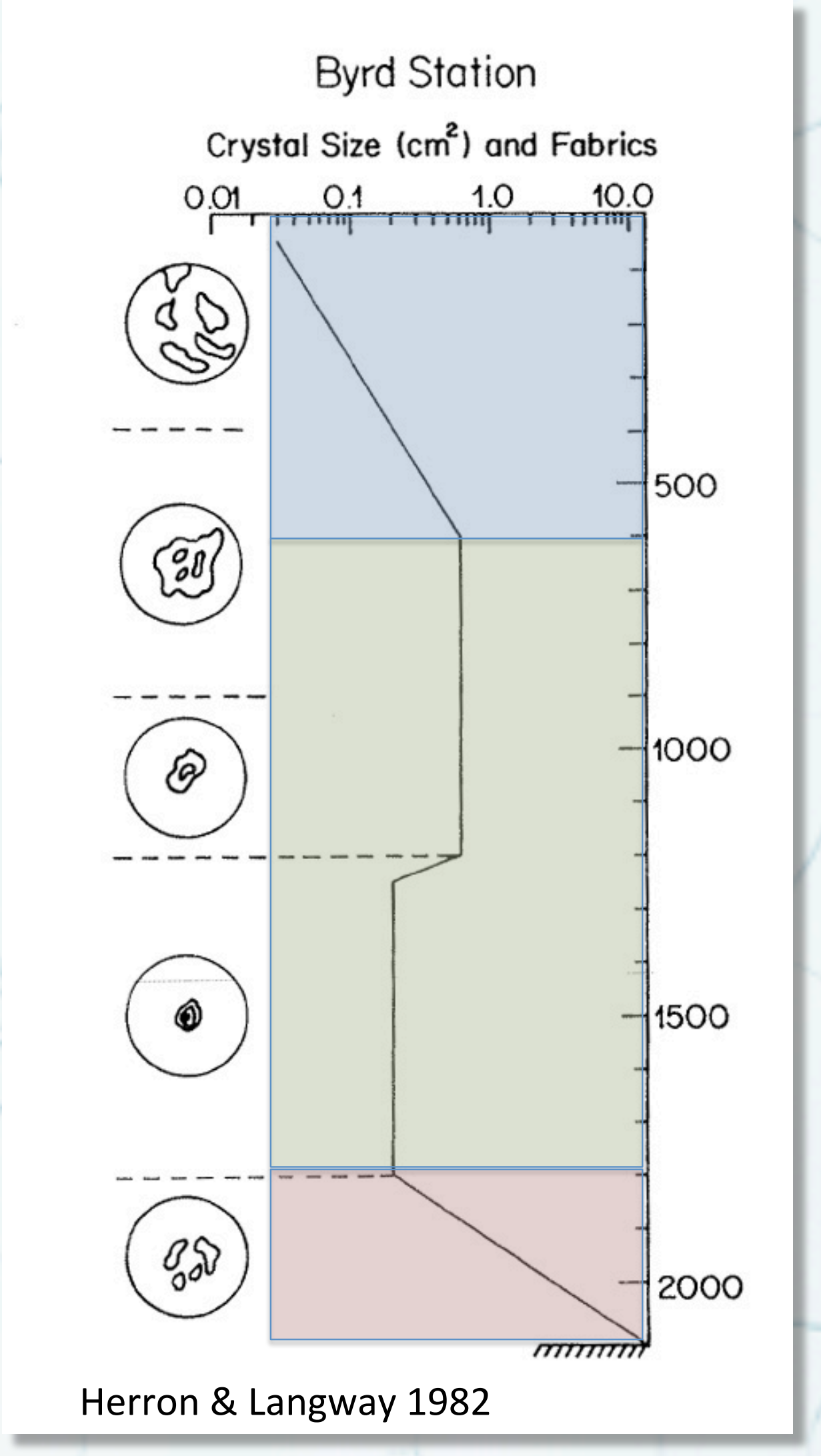
Recrystallization regimes

The analysis of grain sizes and c-axis orientation distributions with depth of the Byrd deep ice core, Antarctica, suggested that microstructural evolution could be characterized by three main depth ranges of the ice core, defined by their predominant recrystallization regimes. A generalization of these results gave rise to the tripartite paradigm of polar ice microstructure ("three-stage model"):

(1)Normal Grain Growth (**NGG**): steady increase of the average grain size with age/depth, foam-like structure.

(2)NGG is balanced by rotation recrystallization or "polygonisation" (**RRX**), splitting of grains along sub-grain boundaries, leading to a stationary average grain size.

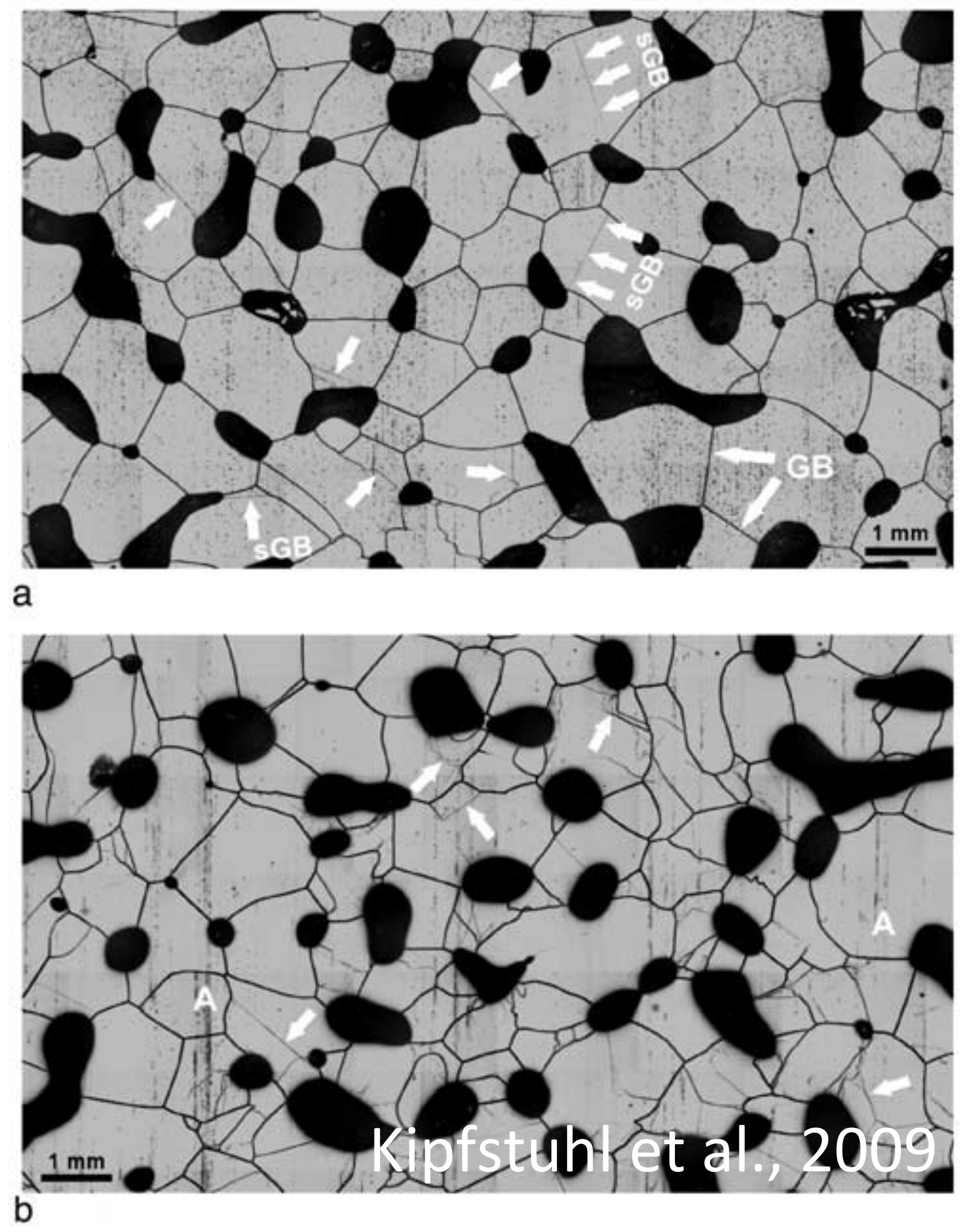
(3)Strain-induced boundary migration (**SIBM**) including nucleation of new grains, resulting in larger average grain sizes and a bulk anisotropy often characterized by multiple maxima in the c-axis orientation distribution.



Herron & Langway 1982

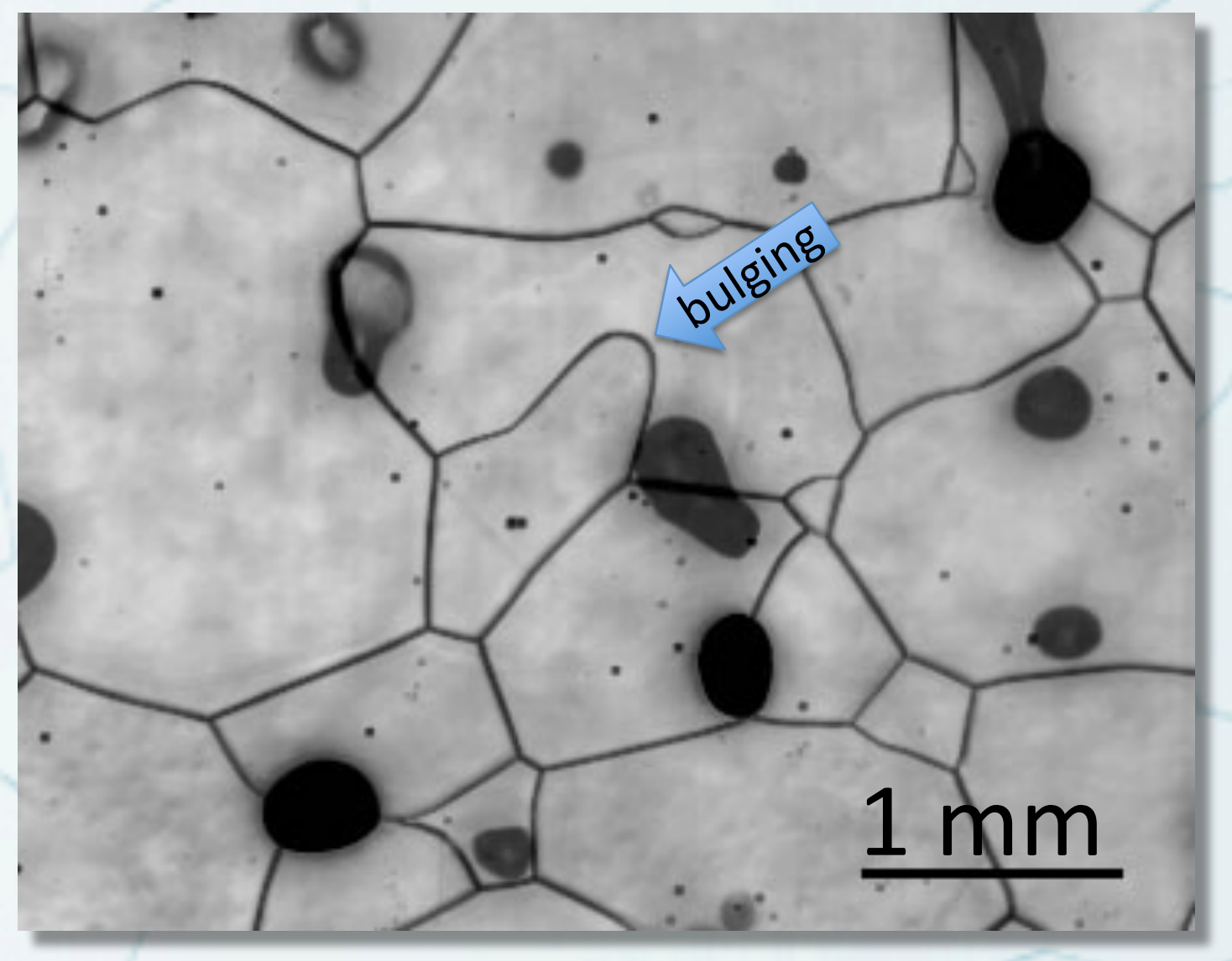
New data - new ideas

Some information from ice cores reported in the literature and recent studies show that this three-stage model is not always valid (see review Faria et al. in preparation). Data from the EDML ice core indicate that here dynamic recrystallization is equally present at all depths starting from firn depth on. This has been observed in studies on subgrain boundary occurrence and grain shape analysis as well as classical grain size curves (Kipfstuhl et al. 2009; Weikusat et al., 2009). The images to the right show the microstructure of polar firn from the EDML ice core in 60 m (a) and 80 m (b) depth. The upper shows the expected NGG fabric, whereas the lower shows bulging grain boundaries and subgrain boundaries.



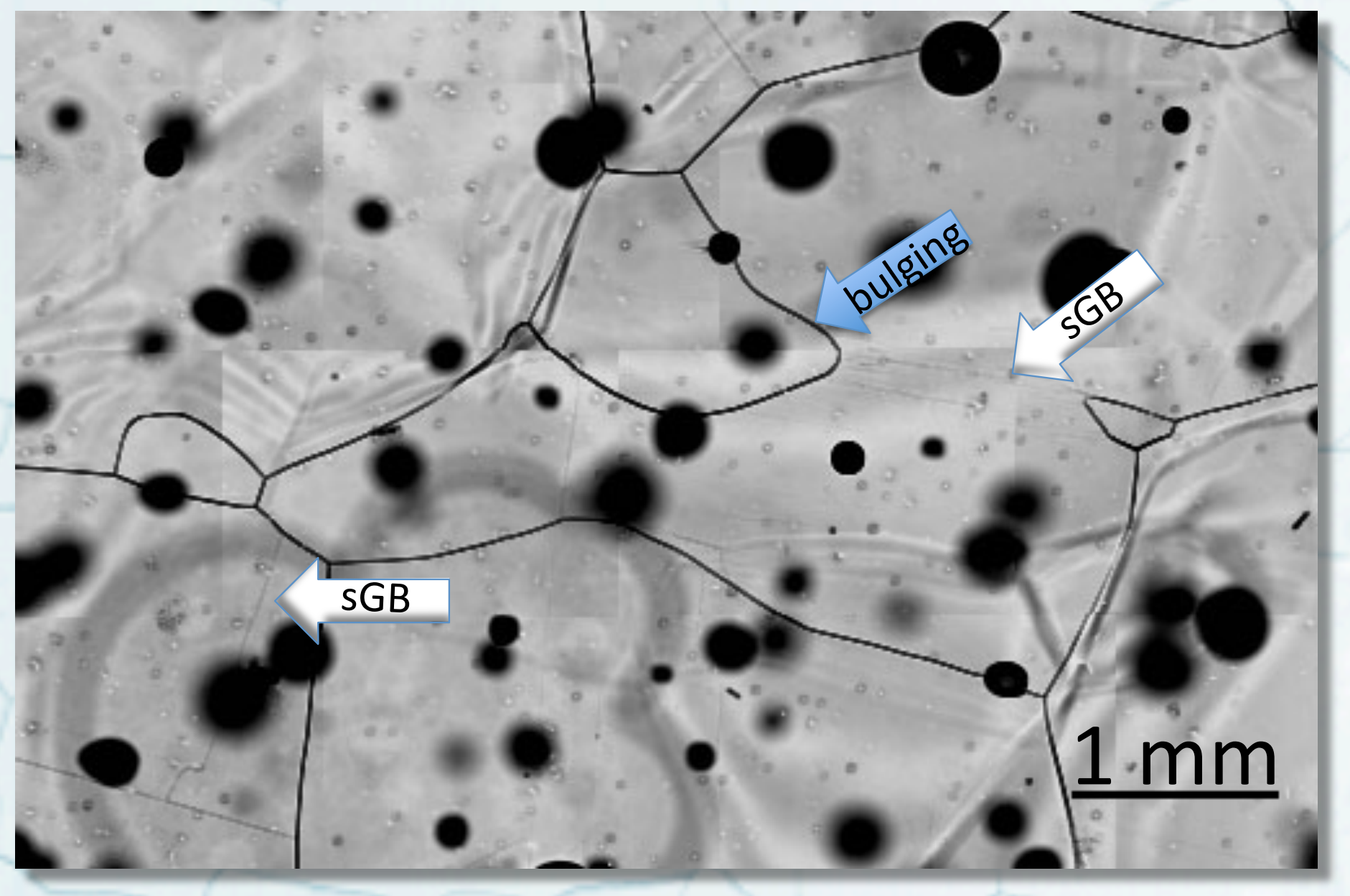
Kipfstuhl et al., 2009

Evidence for dynamic recrystallization



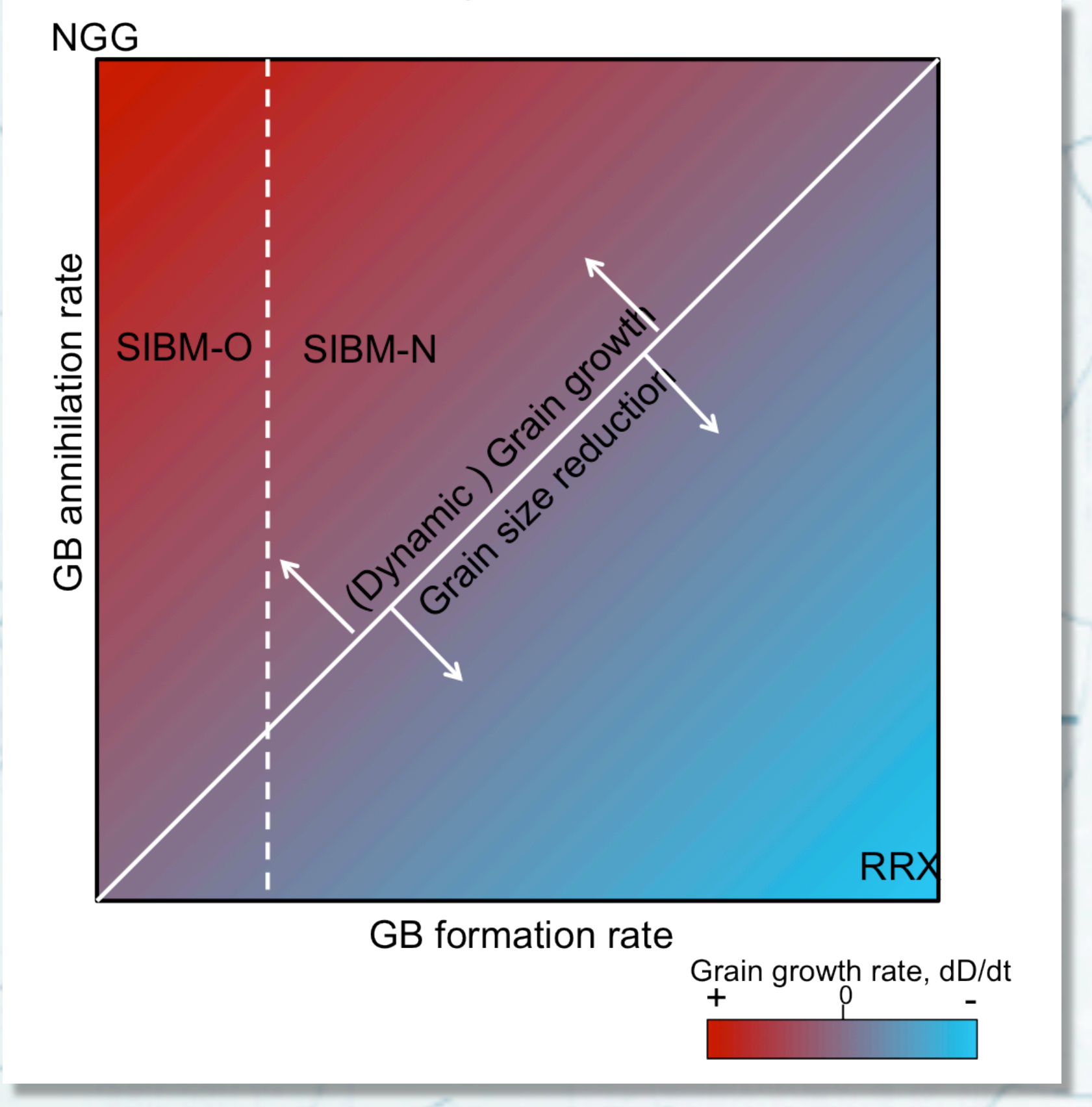
Further evidence for dynamic recrystallization in upper part of the ice core of Dome Fuji.
The image from 175 m depth shows a bulging grain boundary, suggesting strain induce boundary migratio being active here.

Another example from EDML, in 304 m depth: Again the bulging of grain boundaries as well as subgrain boundaries in the middle of a large grain can be detected, indicating RRX as well as SIMB.



New Recrystallization diagram

How best visualize the different recrystallization regimes and the weighted influence of the individual processes? Here we show the first draft of a new recrystallization diagram. Distinct recrystallization regimes can be achieved by different combinations of grain boundary formation and annihilation rates. In particular, SIBM without nucleation (SIBM-O) is dominant at the left of the diagram, with a low grain boundary formation rate, while RRX is stronger at the bottom right.



NGG coincides with the vertical axis (viz. vanishing grain boundary formation rate) when the conditions for the latter are achieved (viz. vanished stored strain energy and a steady state "foam-like" microstructure). Nucleation (seen as a combination of microscopic subgrain formation by grain-boundary bulging and RRX) occurs mostly right of the white dashed line.

References

Faria, S.H., I. Weikusat, N. Azuma: The microstructure of polar ice. J. Struct. Geol., MicroDICE Special Issue, in preparation. **Kipfstuhl**, S., Faria, S. H., Azuma, N., Freitag, J., Hamann, I., Kaufmann, P., Miller, H., Weiler, K., Wilhelms, F., 2009. Evidence of dynamic recrystallization in polar firn. J. Geophys. Res. 114, B05204. **Weikusat**, I., Kipfstuhl, S., Faria, S. H., Azuma, N., Miyamoto, A., 2009. Subgrain boundaries and related microstructural features in EDML(Antarctica) deep ice core. J. Glaciol. 55 (191), 461–472. **Herron**, S. L., **Langway**, C. C., 1982a. A comparison of ice fabrics and textures at Camp Century, Greenland and Byrd Station, Antarctica. Ann. Glaciol. 3, 118–124.