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Texture of the Upper 1000 m in the GRIP and NorthGRIP Ice Cores

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Abstract: In this study we discuss new and published profiles of c-axis fabric and size distributions of a large number of crystals in the upper 1000 m of the Greenland GRIP and NorthGRIP ice cores as obtained with an automatic c-axis fabric analyzer. We show that in both cores the fabric is strongly anisotropic already just below the firn (about 110 m depth) with a degree of orientation around 30%. We determine the mean crystal area profiles which are somewhat contrasting to earlier findings based on manual measurements. The crystal size distributions are compared to a simple 1D model which takes into account crystal growth and polygonization (rotation recrystallization). The model suggests that the crystal size distribution develops into a Bessel type distribution that differs from the commonly applied log normal distribution. Finally, we combine the fabric and microstructure results to determine the sub-grain boundaries in the GRIP samples. Both the size distribution model and the sub-grain study suggest that polygonization is significant already below the firn and that the physical processes governing the conventionally adapted 'normal grain growth' and 'polygonization' regimes are identical. The new measurements provide a dataset for ice sheet models that take into account the anisotropy of the Greenland ice sheet.

Key words: ice core, ice crystal, texture, fabric, Greenland

1. Introduction

There is a great interest in knowing the present and future mass balance of the Greenland and Antarctic ice sheets. The long-term development of the ice sheets can be modeled by advanced flow models [1, 2]. To accurately model the ice flow, knowledge of the anisotropy within the ice sheet is needed and recent ice flow models take this anisotropy into account [3-5]. Therefore, there is an increasing demand for high-quality measurements of ice crystal texture in ice cores. We here define texture as both the c-axis distribution (fabric) and the grain boundary network (microstructure) of the crystals.

On the experimental side, new automatic instrumentation has recently made it possible to perform measurements of ice crystal texture in thin sections with very good statistics [6-8]. The new instruments may allow analysis of up to several thousands of crystals in a single thin section of ice as compared to typically a couple of hundreds by conventional manual techniques. A further advance of the new instruments and the digitalization of the measurements is that it enables to combine the fabric and the microstructure measurements whereby sub-grain boundary studies can be carried out with good statistics.

Several texture studies have been performed for the Greenland ice cores over the last decade. A manually obtained profile of GRIP textures was obtained by [9] and a similar analysis was carried out for the GISP2 ice core [10]. A detailed study of ice crystals around Greenland Interstadial 3 was presented by [11] and [12] made an analysis of folds and other features in the deeper part of the GISP2 core.

All texture studies of the more recent NorthGRIP ice core [13] have been carried out using the new generation of automatic analyzers. [14] presented a continuous fabric profile for NorthGRIP, whereas [15] made a high-resolution texture study of the past 5 kyr. A Holocene case study of seasonal variability in crystal properties was presented by [16], and recently [17] assessed the influence of polygonization (rotation recrystallization) in the NorthGRIP ice core over the past 5 kyr.

In this work we present a new texture profile of the upper 1000 m of the GRIP ice core which we discuss in the context of published texture profiles from the GRIP, NorthGRIP, and GISP2 ice cores. The data set is relevant for the interpretation of the Greenland ice rheology in the upper part of the ice sheet and for anisotropic ice flow models that incorporate ice fabric.

2. Methods and results

Nine vertical samples, 20 cm long, 10 cm wide and 0.7 cm thick, were obtained from the GRIP ice core, evenly distributed in the depth interval 110-1000 m. The late Holocene accumulation at GRIP is 23 cm, so each sample covers approximately one annual layer. From each of the samples, two 10 x 10 cm^2 vertical thin sections were prepared using standard techniques. The orientation of the vertical sections with respect to the core axis is not known, but as GRIP is situated at a dome we assume axial symmetry with respect to the core axis. The ice crystal texture was determined using an automatic crystal analyzer in Copenhagen using procedures described in [15] and [8]. The precision in the c-axis orientation determination is better than 1^o whereas the accuracy is around 5^o.

Sample No.	Depth (m)	Age (yr b2k)	Number of crystals	Degree of orientation (%)	Mean crystal area (mm^2)	Eigenvalues a_1	a_2	a_3
202	110.65	396	4078	34.2	3.61	0.53	0.24	0.23
400	219.75	895	1965	33.8	5.16	0.53	0.24	0.23
611	335.60	1454	1793	37.3	5.31	0.55	0.23	0.22
808	443.95	1995	1467	45.1	6.58	0.60	0.21	0.19
996	547.55	2548	1307	47.9	7.10	0.61	0.20	0.19
1208	664.25	3221	1188	48.1	7.48	0.61	0.22	0.18
1395	766.80	3826	1331	54.4	7.48	0.65	0.19	0.16
1610	885.35	4602	1428	56.3	6.91	0.66	0.17	0.16
1819	1000.00	5420	1471	57.4	6.85	0.67	0.18	0.15

Table 1: Properties and results of the GRIP samples. The sample age is given in 'b2k' (= years before 2000 AD). The 'eigenvalues' are those of the second-order orientation tensor.

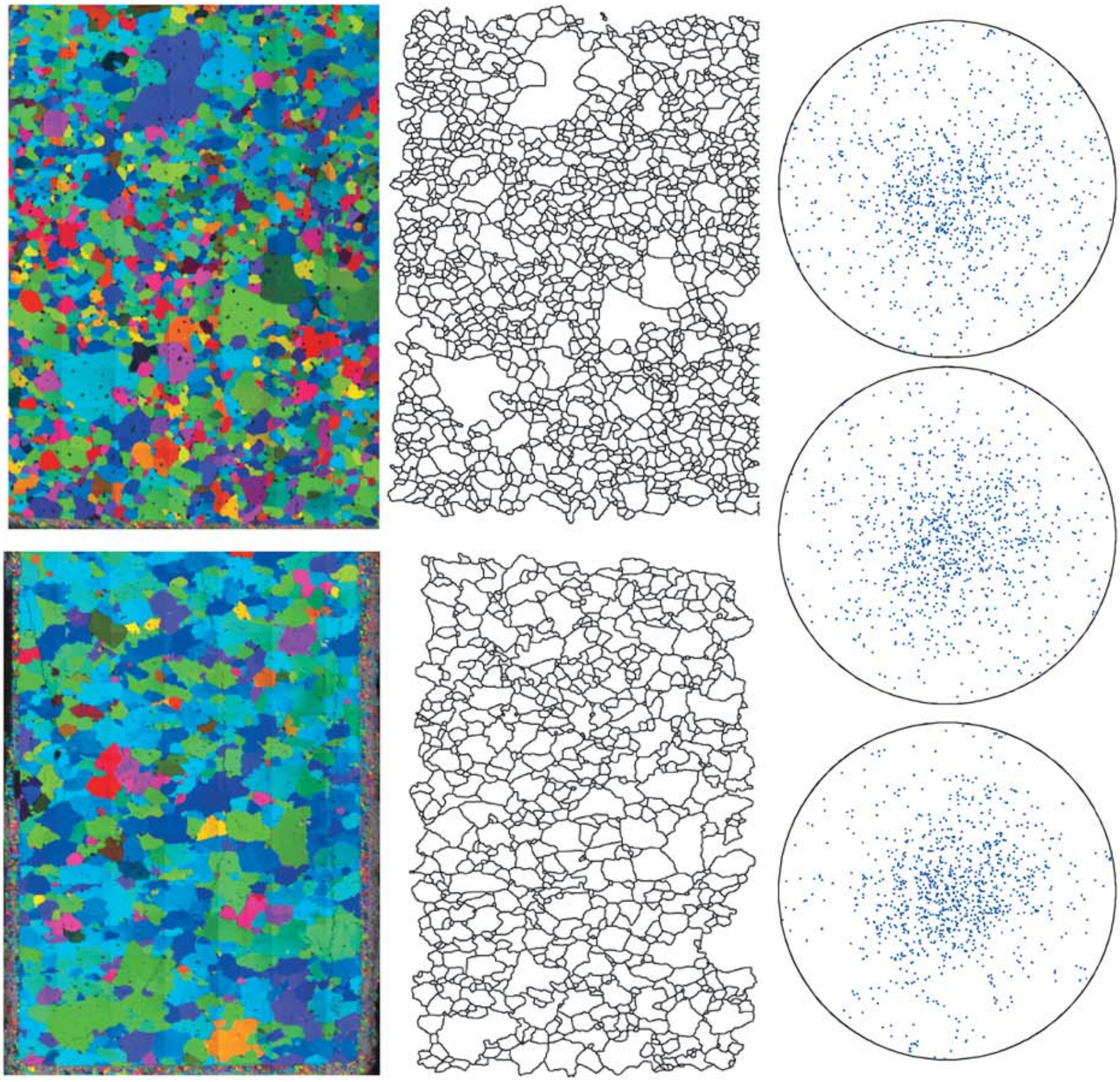

Figure 1: Examples of GRIP samples. Left: 10 cm long vertical thin sections from 111 m (top) and 1000 m (bottom) depth with artificial color coding representing the c-axis orientation. Center: Corresponding microstructure. Right: Top-view fabric diagrams of samples from 111 m (top), 548 m (center), and 1000 m (bottom) depth showing the gradual clustering of c-axes (N=1000).

Table 1 provides the sample information along with the number of crystals identified in each sample, the mean crystal areas, the degree of orientation, and the eigenvalues of the second-order orientation tensor [8]. Sample ages are according to [18]. More than 1000 crystals have been identified in each sample. Figure 1 shows examples of thin sections and corresponding c-axis diagrams (Schmidt plots). The samples are shown with artificial colors indicating the orientation of individual crystals.

3. Fabric evolution

The c-axis fabric can be described by several different parameters. In this study, we apply the non-area-weighted 'degree of orientation', R, which has been widely used in previous Greenland fabric studies and which is suitable to describe the fabric at locations with core axial symmetry (e.g. [8]).

Several studies have reported on the fabric in the upper part of the Greenland ice cores. Based on manual measurements of GRIP thin sections [9] reported that the fabric just below the firn is random (R < 20%) and that the fabric strength increases rapidly to R > 45% below 400 m depth.

The first results from the NorthGRIP ice core were obtained with an automatic instrument and showed a close-to-random NorthGRIP fabric in the upper 800 m of the core [14]. Those results were, however, erroneous and [16] applied different samples and a different instrument to show that, indeed, the fabric in the topmost part of NorthGRIP is not random. The NorthGRIP R-value increases gradually from 29 % at 116 m depth to 50 % at around 800 m depth. This finding was confirmed by repeated measurements using the instrument applied in [14], so that there is now consensus about the NorthGRIP fabric.

Because of the somewhat contrasting fabric results from the GRIP and the NorthGRIP ice cores we decided to analyze the new GRIP data set that is presented here. For this dataset we determine a clearly non-random fabric for the depth interval 111-400 m with R-values in the range of 33-37 % (Figure 2). We, therefore, have a discrepancy with the work of [9] for this interval. In contrast, there is a surprisingly good agreement between the two data sets for depths greater than 400 m. The good agreement is observed despite the facts that 1) the samples for the present study were taken more than 10 years after those of [9], 2) the samples are not taken from exactly the same depths, 3) the measurements were made using very different techniques (manual versus automatic), and 4) the statistical basis is very different (roughly 10 times more crystals per sample in the present study). The close agreement of the two studies suggests that they are both accurate. Above 400 m depth some of the discrepancy may be explained by the relatively low number of crystals applied in the study of [9]. [15] showed that the R-value exhibits quite important variability of up to 20 % (absolute) at a centimetre scale. Therefore, if the measurements by [9] are obtained from a relatively small depth interval, the measured R-value may differ significantly from a more averaged value.

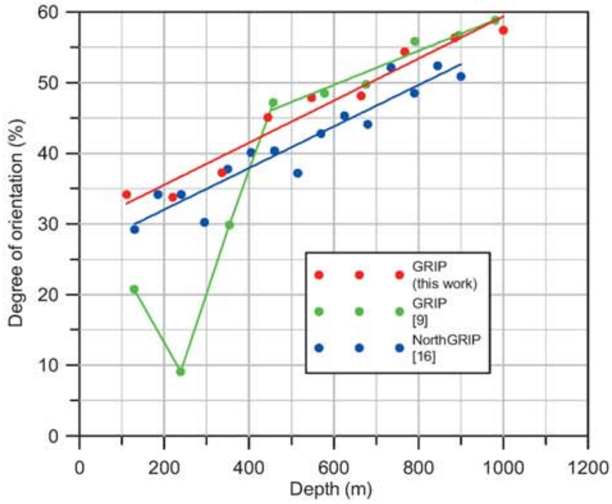

Figure 2: Development of the degree of orientation of c-axes with depth for GRIP and NorthGRIP. Points represent measurements and lines are (piecewise) linear fits to the data points.

To summarize, the fabric is not random in the upper, central part of the Greenland ice sheet below the firn. A similar conclusion can be drawn from several recent studies in Antarctic ice cores, such as EPICA Dome C (Durand et al., this issue) and Dome F [19], although the sub-firn degree of orientation generally is lower at those colder locations.

4. Mean crystal size evolution

Crystal sizes can be described in a variety of ways. For example, by a 1D crystal size, which, in turn, can be crystal width, height, or radius of a best-fit circle, or by the 2D crystal area as it appears in the thin section, which again represents a cross-section of the full 3D crystal. Many manual crystal studies have determined crystal sizes by the linear intercept method in which the number of crystals intercepting a line across the sample is counted (e.g. [9, 10]).

Figures 3 and 4 compare respectively crystal area and 1D crystal size profiles for the GRIP, NorthGRIP, and GISP2 ice cores. Some important differences can be noticed for the GRIP crystal sizes/areas obtained in this study and those presented by [9]. In Figure 3, the crystal areas of [9] are generally larger than those of this study. Part of this discrepancy can be attributed to the different measurement techniques applied in the two studies. Whereas this study presents the measured crystal areas of vertical thin sections, the crystal areas determined by [9] are based on horizontal linear intercept measurements that are converted to areas by assuming circular crystals. Because the crystals are horizontally elongated, the crystal areas based solely on horizontal sizes will be larger than those obtained from vertical thin sections.

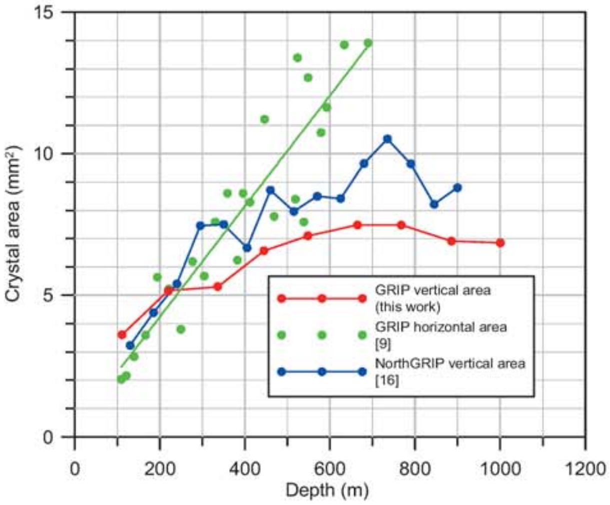

Figure 3: The mean crystal areas for the GRIP and NorthGRIP cores on a depth scale. The GRIP areas from this study and those from NorthGRIP are obtained from vertical thin sections. The GRIP areas by [9] are calculated from horizontal crystal diameters assuming circular cross sections and the straight line is a linear fit to those data points.

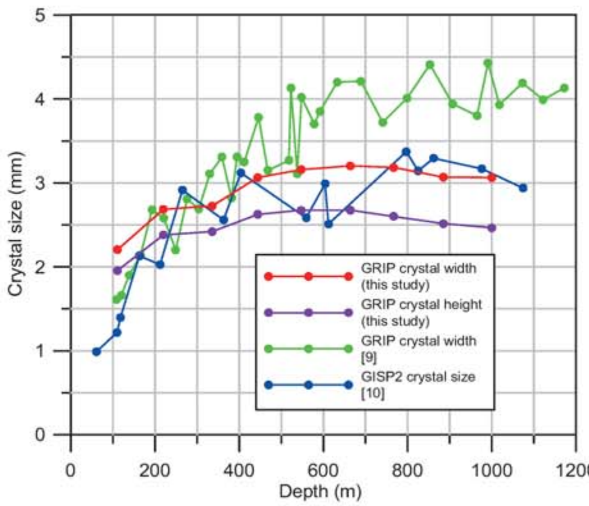

Figure 4: The mean crystal size evolution for the GRIP and GISP2 cores on a depth scale. The GRIP crystal sizes from this study and those from NorthGRIP are deduced from the crystal microstructure, whereas the GRIP areas by [9] and the GISP2 crystal sizes are obtained by the linear intercept method.

The same difference is reflected in figure 4, where the most important discrepancy is a 30% difference in the mean crystal width below 600 m depth between this study and that of [9]. It is not clear what causes this important difference. The GISP2 measurements of [10], that are also based on the linear intercept method, appear to match well with the present study, except for the youngest samples.

5. Crystal size distribution

The evolution of the crystal size distribution gives a much more detailed picture of the crystal dynamics than the averaged mean crystal size. Traditionally, the crystal size distribution has been compared to a log normal distribution that fits the distribution quite well, e.g. [9, 11], although there is no physical argument why the distribution should be log normal. [20] introduced a simple 1D model for crystal growth and polygonization that quite successfully captures the NorthGRIP crystal size distribution evolution in the upper 1000 m.

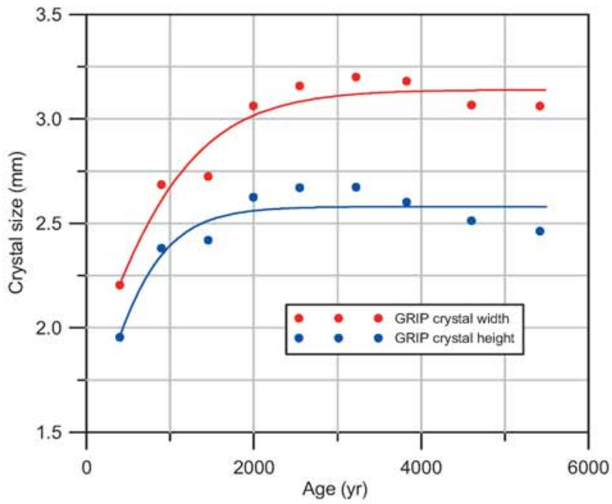

Figure 5: The mean horizontal and vertical crystal size evolutions for GRIP (points, this study) compared to the model (curves) of [20].

In the model, crystal growth is accounted for by a parabolic coarsening in the form of a diffusion-like term, that corresponds to the often applied normal grain growth for the mean crystal size. Polygonization is introduced in the model by assuming a constant crystal fractionation per unit length and time, i.e. large crystals have a greater probability of splitting than smaller crystals. As for the measurements, the model reaches a constant mean crystal size at the time where crystal growth is counterbalanced by polygonization (Figure 5). Both grain growth and polygonization processes will also depend on factors such as temperature and impurity content of the ice, but because those factors are rather constant in the Greenland Holocene ice they can be ignored in this case.

Examples of GRIP 1D crystal size distributions from this study are given in Figure 6. We compare the distributions to a log normal distribution and to the steady state solution of the model by [20]. For the younger samples, the distribution is quite well matched by the log normal, but for the deeper samples the model fit is best in particular for the larger crystals. Because the model simulates the entire crystal size distributions rather than just the mean crystal size, the comparison to data is quite rigorous. The rather good agreement between model and measurements suggests that the model does include important physical processes for the grain size evolution, although the model is very simple and ignores other important properties such as strain.

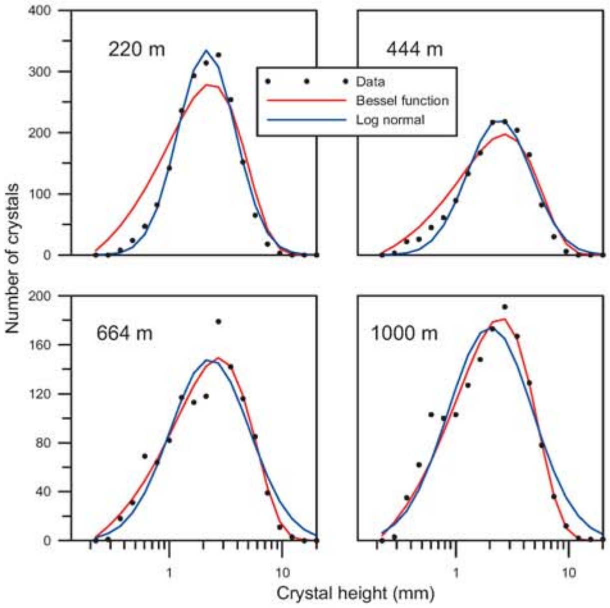

Figure 6: Distributions of GRIP vertical crystal sizes (points, this study) compared to a log normal distribution and to the stationary solution of the model that contains a Bessel function (curves).

6. Normal grain growth and polygonization

Several ice crystal studies conclude that the crystal size/area profiles in the upper part of the ice sheet can be separated in two regimes (e.g [9, 21, 22]):

1) A normal grain growth regime initiating just below the firn where the mean crystal area increases linearly according to the normal grain growth law.

2) A polygonization regime where the mean crystal size is in 'steady state' because the grain growth is counterbalanced by polygonization that initiates in this regime.

Recently, [17] combined NorthGRIP fabric and microstructure measurements to identify the proportion of sub-grains in the upper part of the ice core, whereby they assess the influence of polygonization. Sub-grain boundaries are defined as adjacent crystals with a c-axis misorientation of less than 10 degrees. The authors separate 'true' sub-grains caused by polygonization from 'random' low angle boundaries. The conclusion of that study is that crystal polygonization takes place already from just below the firn. The polygonization may already take place within the firn, but there are no firn measurements.

In Figure 7 we show a similar sub-grain analysis for the GRIP data as that presented for NorthGRIP by [17]. The result is very similar to that for NorthGRIP and shows that also in the GRIP ice core, polygonization occurs just below the firn. This conclusion is supported by a study of GISP2 thin sections by [7] that determine a value greater than 1 for their '1st bin' analysis at all depths indicating that polygonization is active at least throughout the Holocene.

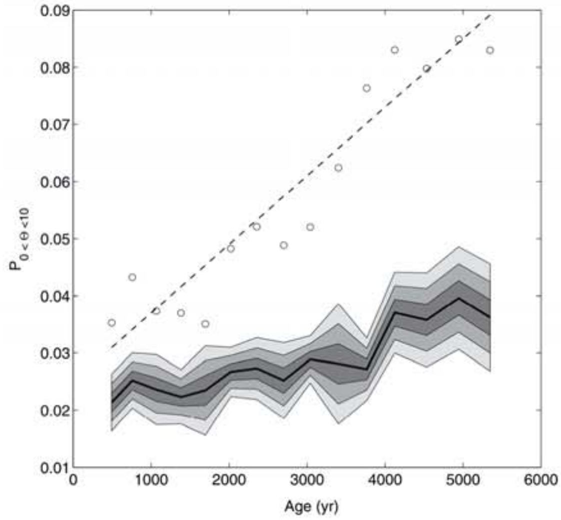

Figure 7: The proportion of sub-grain boundaries in the upper 1000 m of the GRIP ice core. The upper curve shows the relative population of low angle grain boundaries in a sample, i.e. neighbouring grains with orientations deviating less than 10°. Points are measurements and the dotted line is a linear fit. The lower envelope curve shows the same proportion, but with a shuffling of the crystal orientations within the sample that determines the 'natural background' of low-angle boundaries not caused by polygonization. The grey shading indicates the 1, 2, and 3-sigma distribution of 1000 shuffles. The difference between the two curves thus gives the accumulated effect of polygonization.

The view of a continuous competition between grain growth and polygonization already from below the firn is supported by the simple model for grain size distribution applied in the previous section (Figure 5). In the model there is no sudden change of regime from a normal grain growth to a polygonization regime. The polygonization takes place at all times with the same probability per unit length and time. Because the fractionation constant is per unit length large crystals have a greater chance of breaking than smaller crystals and, therefore, the mean crystal size approaches a constant value with age.

7. Conclusions

A new texture profile has been obtained for the upper 1000 m of the GRIP ice core. We apply this profile together with published texture profiles from the GRIP and NorthGRIP ice cores to show that the fabric in the upper part of the central Greenland ice sheet is not random. Just below the firn the degree of orientation is already around 30%.

We compare the new crystal mean area and size profiles with the corresponding published GRIP, NorthGRIP, and GISP2 profiles. Whereas we are in overall good agreement with the NorthGRIP and GISP2 crystal sizes, our data suggest that the mean crystal size in the deepest part of the profile is smaller than determined in a previous study of GRIP texture.

A comparison of the crystal size distributions with a simple 1D model suggests that grain growth and polygonization are the dominant processes for crystal sizes throughout the investigated period. The comparison also indicates that with depth the crystal sizes are better fitted by a physically justified Bessel type function than by the commonly applied log normal distribution.

In agreement with a recent study of sub-grains in the NorthGRIP ice core, we conclude that in the GRIP ice core polygonization is initiated just below the firn. This result together with the model comparison of the crystal size distributions suggest that both grain growth and polygonization are active in the so-called 'normal grain growth' and 'polygonization' regimes. This may explain why the mean crystal area profile rarely shows a well defined linear increase in the upper part of the ice sheet.

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