Review of the manuscript:

Development of crystal orientation fabric, microstructures and deformational regimes in the deep sections and overall layered structures of the Dome Fuji ice core, Antarctica

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Revised version submitted to *The Cryosphere*

This manuscript presents detailed data on fabric evolution and microstructures in the 3035 m long DF2 ice core from East Antarctica, drilled at the Dome Fuji station. In earlier work the same research group published similar data from the uppermost 2400 m of the core, but here the focus is mainly on the depth interval 2400-3035 m. An overview is, however, also given of the evolution of the above mentioned parameters throughout this deep ice core.

A major scientific effort lies behind the results presented and the data are of great importance for studies of the internal structure and deformation properties of large ice sheets. Both state-of-the-art methods and new techniques are used to measure and characterize fabric and grain structure at relatively high resolution down the core. Methods are mostly well described and sources of error are adequately adressed in the paper.

Although some assertions made by the authors will be met with criticism – in spite of improvements made from the initial version – the importance and detailed description of the data is such that the paper should be published in *The Cryosphere*. This reviewer does not have specific criticisms, but asks the authors to take into account the comments and corrections suggested below.

Saruya et al. focus on main processes believed to control the development of fabric in ice under the conditions prevailing at Dome F:

- C-axis rotation under compressive stress leading to the development of a single pole fabric
- Rotation recrystallization and subsequent splitting of a grain into 2 or more grains
- The role of simple shear in the fabric evolution
- The interplay between inclined layering (from horizontal, due to bedrock topography) and the mean direction of the single pole fabric
- The effect of impurities and grain size on c-axis rotation
- Nucleation of new grains with c-axis orientations differing from that of surrounding older grains, at relatively high temperatures in the lowest 20% of the ice sheet

A clear picture emerges on the development of c-axis orientations in the DF2 core and interesting data on a-axis orientations are presented as well.

Perhaps surprising is the fact that this paper (as well as the companion paper on the upper 80% of the ice core, Saruya et al., 2022), does not discuss the grain size development in the core in any detail. Grain growth receives fleeting mention and some insight can be gleaned from Figures 5-7 and Figure 10, but no information is given on normal grain growth rates. If the authors aim to treat this topic in another publication, this should at least be stated, since studies of crystal size and crystal orientation are closely intertwined.

This reviewer has access to two reviews on a previously submitted version of this manuscript, as well as to the replies given by the authors. It seems to me that the authors have made a major effort in responding to the major criticisms offered by the two reviewers, both of whom are leading experts in this field. Examples:

Reviewer 1 criticised the authors´ emphasis on grain boundary sliding (GBS) in the earlier version, stating that the evidence for this deformation mechanism in the core was very limited. The authors have responded to this by significantly toning down the potential occurrence of GBS in the revised version.

Reviewer 1 is critical of the authors´ interpretation of small grains on the boundary between two larger grains as evidence for nucleation of new grains (sometimes referred to as dynamic or migration recrystallization) – see Figure 7. It also seems like Reviewer 2 does not support the authors´ interpretations on this issue. Author responses are detailed and they defend their view by pointing out that observed c-axis fabric changes at depth support the assertion that new grains are being nucleated.

It may be added here that it is surprising how little discussion there is in the paper on the effect of higher temperatures near the bed on grain size development. Section 4.4 mentions very large crystals below 2950 m depth (blue curve in Figure 5), but there is no further interpretation. Grain size curves between DF2 and EDC are compared in Figure 10, but a comparison with the Vostok core – where very large crystals were observed in the lowest part of the meteoric ice – would have been particularly interesting here.

Even though the authors have made efforts to shorten the text (following reviewer advice), the paper is still very long and the text is often repetitive. Actually, the repetitions are at times helpful for the reader, who gets a bit lost at times in the details being discussed, and is thankful for a recap! The Conclusions section (2.5 pages) presents a very good overview of main results and interpretations, in a better way than the bulk of the text.

The English language of the paper still needs improvement and this reviewer typed down suggestions as he read the paper through. Hopefully these suggestions can be of help in the final revision process.

Specific comments:

Comments/questions directed to the authors are blue-coloured for clarity. Note that the terms grain and crystal are used synonymously by this reviewer. Numbers like L20 refer to line numbers in the manuscript version:

egusphere-2023-3146-manuscript-version2.pdf

L20

To examine the distribution and texture of the *c*- and *a*-axes...

→

To examine the orientation distribution of the c- and a-axes...

(„texture" refers more to grain size and shape)

L22

detailed crystal grain orientations

→

detailed crystal orientations

L24

as eigenvalues

→

as eigenvalues of the orientation tensor

L28

Below 1800 m in the UP80%, layers with varying dusty impurities

→

Below 1800 m in the UP80%, layers with varying concentrations of dusty impurities

L38-39

What are c-axis layers ??

L53-54

whereas shearing on alternate slip systems is significantly more difficult, nearly a hundredfold

→ (suggestion)

whereas nearly a hundred times greater (shear) stress must be applied to induce deformation along other slip systems within the crystals

L57-58

The study of anisotropic ice deformation has been conducted historically. They were done through theoretical research

→

Anisotropic ice deformation has been studied theoretically

L59
and through laboratory experiments
→
and in laboratory experiments

L61-62
These laboratory-based studies are characterized by experimental setting of strain rate by more than several orders of magnitude, and under temperature close to melting point,
→
The experimental setting in these laboratory-based studies is characterized by strain rates that are several orders of magnitude higher than *in situ* strain rates in ice sheets, and at temperatures close to the melting point,

L62-64
Therefore, these laboratory-based knowledge can be a valuable reference mainly for such conditions.
→
The laboratory results are thus, strictly speaking, not directly applicable to ice-sheet conditions.

L64
play another essential role. Examples of Antarctic deep ice core include
→
play an essential role. Examples of Antarctic deep ice cores include

L68-69
Examples of Greenland ice sheet include
→
Examples from the Greenland ice sheet include

L70
and among others
→
and other cores

L72-74
For instance, during the internal deformation of the ice sheet, the flow forms preferred orientations of crystal axes, at the same time, the ice flow is modulated based on them.
→
For instance, the internal deformation of an ice sheet leads to the development of preferred orientations of the ice crystals, which in turn influence the flow of the ice sheet.

L83-84
dome regions in central area of the ice sheets

→
dome regions in the central parts of ice sheets

L95
was presented by
→
was described by

L94
and it is suitable to investigate
→
and such a setting is suitable to investigate

L98
deepmost → deepest

L104-105
composition of the deepest 1% thickness (3000–3035 m).
→
Composition of the deepest 1% of the ice sheet/ice core (3000-3035 m).

L105-106
These properties were found to retain the basic layered structure of ice core signals except in the deepest few meters.
Not certain what this sentence means – was the size and concentration of air hydrates and the oxygen isotope ratio typical for the meteoric ice above (except in the deepest few meters) ?

L108
sampled at every 11 m depth. → sampled at 11 m depth intervals.

L111-113
Dynamic recrystallization within ice sheet has been widely investigated historically, as reviewed in papers or textbooks (e.g., Poirier 1985; Humphreys and Haterly 2004; Faria et al., 2014a, b) or individual papers (e.g., De La Chapelle et al. 1998; Weikusat et al. 2009, Kipfstuhl et al. 2009, Montagnat et al. 2012, 2014; Stoll et al., 2021a).
→ (suggest change to)
Studies on dynamic recrystallization in ice sheets have been reported by e.g. Poirier 1985; De La Chapelle et al. 1998; Humphreys and Haterly 2004; Weikusat et al. 2009; Kipfstuhl et al. 2009; Montagnat et al. 2012, 2014; Faria et al., 2014a and Stoll et al., 2021a.

L113-114
Exploring deep ice rheology and crystal properties, dynamic recrystallization is one of main focuses in this paper.

➔ (suggestion)

In this paper, we take advantage of the unique opportunity that the Dome F ice core offers to study the role of dynamic recrystallization in the formation of textures and fabrics in the deeper parts of the East Antarctic ice sheet.

L115

What does „Advancing ice sheet dynamics“ mean here? Would it not be more suitable to shorten the title of this section to: The development and role of crystal orientation fabrics

L117

„layer structures of the c-axis fabric“ is not very clear wording.

L131

variations in the deformational history of the vertical compression.

→

variations in the deformational history of an ice-sheet region where vertical compression is the dominant stress regime.

L135

across wide area of ice sheets. → across wide areas of ice sheets.

L141-143

Following this previous study, research focusing on the lowermost (deepest) approximately 20% thickness zone (ranging from about 2400 m to the deepest ice at 3035 m) remains to be done, to examine textural data for the entire thickness of the ice sheet.

→ (suggestion)

Following this previous study, research has focused on the lowermost (deepest) approximately 20% of the DF core (depth interval 2400-3035 m), to complete the picture of textural and fabric evolution in the entire ice sheet column.

L147

We compare textural data by these methods with various data analyzed from the ice core.

→

We compare textural data obtained with these methods with various data sets from studies of the ice core.

L148-149 (twice)

crystal orientation fabric → the crystal orientation fabric

L153

that correspond to ages of more than 1 million years

→

covering snow deposition over more than 1 million years

L155
extends → extend

L157
knowledge of englacial layers under various ice conditions.
→ (suggestion)
knowledge of the physical properties and the deformation history in different regions of the East Antarctic ice sheet.

L167-168
In terms of the c-axis fabric, Azuma et al. (1999, 2000) reported that at DF1 the c-axis fabric exhibited the elongated single pole fabric as the dome undergoes deviatoric strain depending on orientations.
→
This is not very clearly worded – what does „depending on orientations" mean here ? Are the authors referring to the mean c-axis orientation being perpendicular to the bedrock slope (line 172) ?

L191
signals of dynamic recrystallization
→
signs of dynamic recrystallization

L195
The principle of...have been described
→
The principles of...have been described
Or
The principle of...has been described

L219-220
deviating from the vertical (hereinafter, inclination angle) in the same direction of the maximum layer slope.
→ (suggestion)
deviating from the vertical (hereafter, inclination angle) in the same direction as the normal to the maximum layer slope.

L266-267
Data from both cases....in agreement
→
Data from both cases....are in agreement

L302 (check also L304 and L306)
generally have periodicity of 60 degrees

→(suggestion)
generally display maxima at 60 degree intervals
(„periodicity“ normally refers to regular variation with time)

L314-315, this sentence needs improvement/rewriting to become intelligible:
„It is also very important to note that the SDρ is well synchronized with the grain size (Figure 5e), which implies underlining Physics.“

L323-324 (Fig. 4 caption)
The vertical orientation aligns with the core axis.
According to Fig. 5 the borehole is inclined 3-6° in the depth interval being considered so the core axis hardly represents the vertical.

L351-360
The authors outline grain sizes in the entire core, mentioning that individual grains become „extremely large“ below 2950. No figures are given, though, and Fig. 10e seems to indicate grain size peaks exceeding the maximum value given on the vertical axis of that diagram. The limited size of thin sections is, of course, an issue at these great depths, but it would be good if the authors could at least mention maximum grain sizes inferred from the study.

L361-364
Supporting references are needed for the statement that the c-axis (mean) angle will not coincide with the normal to the shear plane.

L381-382 – these two sentences need English-language improvement.

L382
These features were unique in the impurity-rich depths
→
These features were present in the impurity-rich layers

L386
tend to be distributed as more straight lines
→
are often displayed as straight lines

L388-389
However, some features of impurity-rich layers observed in panels (a) and (c) are persistently present in (e). That is, flattened grains have slanting features.
→ (suggestion)
However, some features of impurity-rich layers observed in panels (a) and (c) are persistently present in (e), where flattened grains display slanting features.

L391-394 – improve English language

L419
reported that → reported

L435-436
We suggest that the steady grain sizes in the impurity-rich layers established themselves after these layers had reached deeper depths.
→
We suggest that the steady grain sizes in the impurity-rich layers were attained when these layers had reached greater depths.

L484-485
The conditions of ice sheets in Antarctica, in terms of temperature and stress, are located on a boundary zone between dislocation and diffusional creep on the deformation mechanism map
→ (suggested rewording)
Due to prevailing temperature and stress conditions, the ice within the Antarctic ice sheet(s) is located in a boundary zone between dislocation and diffusional creep on the deformation mechanism map.

L486
When ice is under temperatures → When ice is at temperatures

L497-504
This description of Fig. 5 has already been given earlier on.

L506-507
the consistency of the inclination angles in the visual layers and the c-axes cluster depends on glacial/interglacial periods.
→
The consistency between the inclination angles of the (normal to) the visual layers and the c-axis cluster is affected by varying conditions between ice deposited during glacial and interglacial periods.

L525-533
Are there any results from surface-based GPS-measurements, that could confirm the assumption that ice flow has occurred towards the center of the trough?
And since there is a trough there, wouldn´t the internal layers of ice sitting in the trough also be convex-shaped in the absence of basal mass loss due to melting?

L546 – improvement in wording required:
the all the c-axes thus the c-axes cluster rotates

L547
total amount of inclinations
→
total inclination

L558
are plotted in entire depths figure (Figure 10).
→
are plotted for the entire depth of the core in Figure 10.

L566-567
dust particles located → dust particles are located

L568
„Production of dislocation is one of the possibilities.“
Does this mean that the presence of microparticles leads to dislocation production? Please clarify!

L570-572
Item (ii) – it is unclear how the content of this sentence relates to the issue mentioned in L569, that microparticles may act as a sink of dislocations like grain boundaries.

L579
In the LO20%, some thickness between 2400 m and 2650 m is
→
In the LO20%, the depth interval 2400-2650 m is

L601
from compressional axis → from the compressional axis

L602
„However, it is also noteworthy that, in Figure 5c, distribution of c-axis density approximately from 30 degrees from compressional axis (60 degrees from horizon) is always denser than 45 degrees or 60 degrees.“
Wording is not clear here. Does the sentence imply that there are more c-axes located approx. 30° from the compressional axis that there are at 45° and 60° (or in between) ?

L603-604
„It is possible that it has some underlying mechanisms in terms of nucleation recrystallization relative to the existing *c*-axis cluster.“
What does „it“ refer to here? The sentence is unclear.

L608
ice crystals will recover the c-axis orientations available for

→
ice crystals will develop c-axis orientations favourable for

L612
decreasing → decrease

L613
in the impurity-rich layer → in the impurity-rich layers

L643-644
Be more specific on why rotation recrystallization has a minimal effect on c-axis fabrics and why you assume – seemingly ad hoc – that it does not cause a-axis organization.

L714-715
the thickness of ice is approximately 10% of the original ice equivalent thickness at the time of deposition
→
the thickness of a particular ice layer is approximately 10% of the ice equivalent thickness of that layer at the time of deposition

L726
strengthening the → strengthening of the

Table 2
The ice thickness at GRIP was 3029 m (the figure 3085 m is the thickness at NGRIP).
The mean annual temperature at GRIP was -32°C during the 1990s, when the deep ice core was drilled. See Dansgaard et al. (1993). Evidence for general instability of past climate from a 250-kyr ice-core record. Nature, 1993, 364 (6434), 218-220.

L746
Based on the above discussions, we propose an overview of the layered structure of ice sheets.
To "propose an overview" sounds a bit strange.

L759-760
What is meant here by „two distinct conditions? The next sentence mentions „Four types of conditions" which adds to the confusion.

L766-767
However, these layered structures correlate directly with the vertical thinning of each layer,
Which „layered structures" and how do they „correlate directly" with the layer thinning? Are the authors referring to the effects of changing grain size, evolving fabric and variations in impurity content on the thinning rate?

L775
layers of ice c-axis fabric → ice layers with a particular c-axis fabric

L794-95
„changes in depth range“ almost sounds like a statement that depth increases with depth! The sentence is probably supposed to refer to fabric changes with increasing depth.

L807
The term „Growth of c-axis clustering“ appears several times in the paper. The authors should consider if „evolution“ or „development“ is not a more appropriate term than „growth“ in this context.

L810
The words „are observed“ need to be inserted after the word „recrystallization“, so that the sentence becomes meaningful.

L820
Possibly, crystal twinning,which share some crystal lattice points symmetrically with the neighboring crystals
→
Possibly, crystal twinning, which leads to crystals sharing some lattice points symmetrically with neighbouring crystals

L829
and layers → and the normal to the layers

L848-849
We argue that the bottom thickness of the ice sheet deeper than approximately 2600 m plays a special role in shear deformation
→
We argue that the lowermost part of of the ice column, deeper than approximately 2600 m plays a special role in shear deformation

L852-853
Ice core drilling, aiming the ancient climatic records, at locations away from the dome area carries serious risks of layer disturbances near the bottom.
→
Ice core drilling projects aiming to retrieve climate records from ancient ice may encounter layer disturbances near the bottom if the drilling sites are located away from dome summit regions.

L929
within plane → within the plane

L938 (and similarly in L922):
Here, the c-axes cluster of single pole fabric is inclined to an arbitrary horizontal orientation.
Shouldn´t this rather be (?):
Here, the plane perpendicular to the c-axes cluster of the single pole fabric is inclined to an arbitrary horizontal orientation.

Section A3
The faint and thin cloudy layers are identified when oriented vertically;
What does it mean here to be „oriented vertically? Are the cores turned and inclined until the observer looks straight down ("vertically") on the edge of the cloudy layers?

L973-974
the aspect ratio value defined as the ratio of the short and long axis of a fitted ellipse
→
the aspect ratio value defined as the ratio of the long and short axis of a fitted ellipse [i.e. long divided by short]

Table A4, column farthest to the left:
Average → Average aspect ratio

L1076-1077
Crystal orientation fabric data from the DF core and the EDC core are compared using a common age scale of the DF2021 age scale.
→ (suggestion)
Crystal orientation fabric data from the DF core and the EDC core compared using a common age scale, matching the EDC age scale with the DF2021 age scale.
Did the authors use isotope data or methane data to tie the age scales of the two cores together? If so, this should be stated.