Referee comment to Fan et al. “Grain growth of natural and synthetic ice at 0°C”

Fan et al. provide an interesting and well-structured manuscript regarding the differences in grain growth of natural and synthetic ice. Despite being investigated for several decades, grain growth of ice crystals remains a topic with many open questions. This is mainly due to the challenges in observing grain growth in situ, i.e. in glaciers or ice sheets, and in setting-up laboratory experiments with boundary conditions similar to natural conditions (time, strain). The presented manuscript compares synthetic ice samples with natural samples from Antarctica and discusses the differences in the microstructure observed during the experimental time frame.

The manuscript is well-written, provides good figures, and the experiments have been carried out thoroughly. The topic is of interest for the community and the data gathering and analysis is well done as far as I can evaluate it. However, the motivation, and especially the decision to conduct experiments at 0°C, should be explained in more detail. I am not an expert in annealing studies and 0°C are usually avoided at all costs in microstructural ice core research. With some work on the issues mentioned below, I am sure that the manuscript can be published after minor revisions in *The Cryosphere*.

General comments:

1. I agree that crystal grain growth in ice is far from understood and that temperature certainly plays a role. However, the motivation of the manuscript remains a little unclear to me. You present examples (l.72-78), but these are merely very specific cases. Mechanical drilling is preferred over hot-water drilling for the majority of ice cores, especially for deep ice cores, and subglacial water inflow into a borehole is scarce and does not impact the already drilled ice, thus a maximum of a few meters. The vast majority of natural ice samples are well preserved for microstructure analysis or are discarded right away. Hence, I would encourage you to elaborate a bit more on the perks of the new insights regarding grain growth at 0°C (e.g. maybe that hot-water drilling could be used more frequently)?

2. The language is overall fine, but more (small) mistakes occur towards the end of the manuscript. I try to mention them below, but another spelling check would be beneficial.

3. I would be interested in a real photograph of the annealing experiment. Fig. 2 gives a good overview, but a photograph in the Appendix would be useful.

Specific comments:

l. 22: natural ice is characterized
l. 23: I think you mean “grain boundaries are pinned by bubbles”
l. 26: in the grain interior
l. 27: It is not totally clear what you mean by one stage, maybe add half a sentence to describe it.
l. 30: the wording is unprecise, “ice grain growth” or “growing of the ice crystals” might be better
l. 31: I would like to read one last sentence in the abstract briefly describing what your results mean
l. 44: delete “statistics”
l. 56: add “comparably impurity-rich”; ice is still a very pure material.
l. 57: Weikusat et al., 2017b deals only very briefly with impurities and does not investigate them; for more recent work refer to e.g. Bohleber et al., 2023, Stoll et al., 2022, 2023.
l . 62: For recent microstructural results from a deep ice core maybe add Stoll et al., 2021b.
l. 64: The sentence is certainly true, but it is important to add that several processes are not understood yet. Especially the relationship between grain growth, fabric/deformation, and impurities/bubbles remains unclear. Zener pinning has, to my knowledge, only been observed very rarely in ice and the presented evidence raises some doubts. You could cite Stoll et al., 2021a and references within for a recent review and overview of the topic without going into to details here (since it is not the scope of this manuscript).

l. 67: maybe replace original with host
l. 74: The entire ice core or “just” the outer rim? As mentioned above, hot-water ice cores are not primarily used for microstructural analysis as far as I know.
l. 76 ff: Backflow of water is luckily not usual, but occurs in special occasions, such as the EPICA drilling, and is tried to be avoided. Furthermore, there are many problems if such backflow and refreezing occurs, the impacted ice will certainly not be used for “normal” microstructural analysis. Mentioning this rare occasion as a major objective is thus not very strong. Similarly, natural samples are usually well preserved or discarded before analysis.
Rephrase it to “can occur” to avoid drawing a misleading image here and rethink the justification of your objectives, I am sure there are better fitting options to address.
l. 83: Merge both sentences: ..kinetics to better understand grain growth in natural ice”.
l. 92: space between of25.4
l. 96: replace eliminated with discard/vanish/exude or something similar
l. 98: ice slabs are used
l. 99: thickness of ice slabs
l. 100: is there a more specific name than Antarctic ice core no 30.?
l. 104: Fig. number missing
Fig. 1: Change to Thickness. I think it would be helpful to clearly define your natural ice samples once and then just refer to it, thus either natural or Priestley ice (I would suggest the latter).
l. 110: Cold laboratory
l. 115: the bins
l. 118: hamper/impact
l. 124: There might be more precise words than recharging and maintained. Once can be deleted.
l. 142: Maybe add dewar flask/bottle for readers not acquainted with laboratory terms.
Table 1: Clarify the parameter for grain size, is it diameter?
I am confused by sample 12 and 13, the ice grain numbers don´t add up as they do in the other samples. If they are not available it´s fine, but in sample 15 N/A does not have an impact on the total number. Please clarify.
*You usually refer to a “thin slice”, here to a “thin section” – stick with one term or do they differ?
Fig. 2b): The small plot is a bit confusing. Maybe you can think of a clearer way to present it, if this information is crucial.
l. 155: space at 5mm
l. 169: Describe briefly how you prepared the slices, did you microtome the surface?
Fig. 3: Put the scale in panel a and e.
l. 213: CPO already introduced, the same applies for SPO later in the text.
l. 217: Briefly introduce the M-index and add “the”.
l. 219: …bubbles, as done for calculating grain sizes.
l. 222: delete “will”
l. 226-229: Is this needed? You explain the different aspects in more detail, I think you don´t need this introduction.
l. 231-235: I think it´s important to have a temperature record to evaluate the experiments, but a designated subsection might not be needed. Maybe you find a way to implement it in the other sections; if not leave it like it is.
Section 3.2: medium is a relative term (as long as you don´t define it), I am not sure if the grain size has to be in the title
l. 249: delete to. I think the use of “c-axis CPOs” is redundant, CPOs usually refer to the c-axis if not stated otherwise. You don´t show a-axes data here, so rephrase to e.g. “…and c-axis patterns are characterized by …
Fig. 4c): The x-axis could be designed more accessible with e.g. 10^x
l. 261: small ice grains, otherwise you need something to compare it with
l. 268: I suggest to clearly state the crystal orientations instead of the colours, which is confusing to readers not used to CPOs and the colour legend
l. 269: 12-18 times larger than that of/ 12-18 times the value of the median ice grain size
276: Delete the part about abnormal bubbles if you don´t discuss it later
l. 277: space and(d)
l. 278: SPO introduced already

l. 279: the last part belongs into the discussion section
l. 281: increases with time
Fig.5c) The x-axis could be designed more accessible with e.g. 10^x
Is there any meaning to the black-white bars below c and e? The caption could be shortened by referring to Fig. 4.
l. 294: CPO patterns are generally…
Fig. 6 caption: delete point, only pole figure. Thomas et al. (2021), similar with Bons and others and Azuma and others -> consistency in referencing
Fig. 7 Annealing time in s is tricky, try to stick to time formats already used (hours preferably). The same goes for grain size, so far you used microns. Solid circles are
l. 344: Fig. 7 does not compare, it displays the data which is a comparison. Rephrase.
l. 347-355: Challenging to read as you refer to sections not read yet. Maybe rephrase or switch order.
l. 367: by the microstructure
l. 372: We compare the following microstructural differences…:
Delete “these microstructural differences include”
l. 375: Can you quantify “many more” with your data?
l. 379: Weikusat et al., 2017b deals only very briefly with impurities and does not investigate them; for more recent work refer to e.g. Bohleber et al., 2023, Stoll et al., 2022, 2023. For readability it would be good to stick with soluble or dissolved impurities.
The discussion of impurities in your samples is tricky, since no data is published (yet). All natural ice contains impurities, this is thus not a necessary statement. I think you can shoren this paragraph and mention that impurtiies play a role (even though the details are unclear, see Stoll et al., 2021a), but you can´t discuss this point due to missing data (which is totally fine, investigating impurities would be another major approach). This is partially done in later sentences, could be easy to combine there
l. 386: strong CPO pattern – which one?
l. 395: To avoid confusion, clearly define that you are talking about the number to area ratio as density, and did not measure the density of the bubble.
l. 397: bubble density remains similar for all bubbles? Clarify that you talk about different (location) type of bubbles and maybe name them instead of using “all bubbles”
Fig. 8: You use bubble density in the text, but not on the respective y-axis. Explain it in the text/caption and then use it accordingly.
l. 405: To me, the density does not remain stable in 8d) for the first 400 hours.
l. 407: density of bubbles evokes material density thoughts, stick to bubble density
l. 410: long complicated sentences, try to break it up
l. 421: give examples of previous studies or use the singular. Grain boundaries can modify.
l. 422: Simply say that the applied methods cannot investigate bubble movement, that´s totally fine and does not have to be defended
l. 427: delete much and directly name the size difference
l. 430: replace production with “development” or “attribute abnormal grain growth with” -> the sentence can be shortened
l. 433: What is non-film material?
l. 434: This is confusing. Grains are not really surrounded by grain boundaries, but contain planar defects/dislocations separating the material inhibiting different orientations. Give examples of these characteristics. Grain growth of the ice matrix is redundant and not 100% correct, better say ice grain growth
l. 441: Mention this is the methods already
Fig. 9a) Think about using a perceptually uniform colour sheme than jet/rainbow, see e.g. Crameri et al. (2020) for details
l. 465 annealed samples…ice core data suggest that abnormal….
l. 466: “An annealing” or “annealing experiments of ice samples”
l. 467: Better “strengthening” than “enhancement”
Fig. 10: I like the idea of a schematic drawing to communicate the main conclusion of the large amount of data. However, I suggest to emphasize the difference between both options (e.g. by writing on the arrows). The example of minimized normal grain growth looks exactly the same as the

starting material, som slight modifications would be good to avoid the interpretation that nothing at all is happening.
Conclusions: Use full sentences, the numbering is not necessary. Mention where Priestley ice is from
l. 476: define “sampling”, does it include drilling, core handling, first processing etc?
l. 477: clarify bubbles at ice grain boundaries (all, most, few)
l. 479: grain boundary. Abnormal grain growth is an additional process
l. 480: avoid generalizations: grain size change in our (natural) samples/ in the depth range investigated
l. 481: Number density of bubbles
l. 486: …constrast can drive abnormal grain growth…
l. 487: inhibits grain boundary migration of ice grains / in the ice matrix
l. 490: CPO usually gets stronger with depth, is this relevant for your comparison?

Literature

Crameri, F., Shephard, G.E. & Heron, P.J. The misuse of colour in science communication.*Nat Commun* **11**, 5444 (2020). https://doi.org/10.1038/s41467-020-19160-7

Stoll N, Eichler J, Hörhold M, Shigeyama W and Weikusat I (2021a) A Review of the Microstructural Location of Impurities in Polar Ice and Their Impacts on Deformation. Front. Earth Sci. 8:615613. doi: 10.3389/feart.2020.615613

Stoll, N., Eichler, J., Hörhold, M., Erhardt, T., Jensen, C., and Weikusat, I.: Microstructure, micro-inclusions, and mineralogy along the EGRIP ice core – Part 1: Localisation of inclusions and deformation patterns, The Cryosphere, 15, 5717–5737, https://doi.org/10.5194/tc-15-5717-2021, 2021b.

Stoll, N., Hörhold, M., Erhardt, T., Eichler, J., Jensen, C., and Weikusat, I.: Microstructure, micro-inclusions, and mineralogy along the EGRIP (East Greenland Ice Core Project) ice core – Part 2: Implications for palaeo-mineralogy, The Cryosphere, 16, 667–688, https://doi.org/10.5194/tc-16-667-2022, 2022.

Bohleber, P., Stoll, N., Rittner, M., Roman, M., Weikusat, I., & Barbante, C. (2023). Geochemical characterization of insoluble particle clusters in ice cores using two-dimensional impurity imaging. *Geochemistry, Geophysics, Geosystems*, 24, e2022GC010595. https://doi.org/10.1029/2022GC010595

Stoll, N., Westhoff, J., Bohleber, P., Svensson, A., Dahl-Jensen, D., Barbante, C., and Weikusat, I.: Chemical and visual characterisation of EGRIP glacial ice and cloudy bands within, The Cryosphere Discuss. [preprint], https://doi.org/10.5194/tc-2022-250, in review, 2023.