

Response to Reviewer 1, Dr Nicolas Stoll

We thank reviewer 1, Dr Nicolas Stoll for his thoughtful and helpful reviews of our paper. The comments have helped us to clarify many important points. This document outlines point-by-point responses to the reviewer. *The reviewer's comments are in blue type*; our responses are in black type; *extracts from the revised manuscript are in italics*.

R.1.1 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*.

We thank the reviewer for his affirmation of our work. We agree with the reviewer that the motivation to conduct experiments at 0°C should be explained in more detail. We will add additional statements in the Introduction section to clarify this paper's motivation.

General comments

R.1.2 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 (1.72-78), 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)?

We thank the reviewer for providing suggestions on clarifying the motivations. In the modified manuscript, we will add additional statements to clarify our motivations, which include (1) assess the grain growth mechanisms in natural ice at 0°C, (2) assess the impact of hot-water drilling on the modification of ice microstructure, and (3) use ice as an analogue to understand the annealing of minerals at their melting temperatures.

R.1.3 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.

We thank the reviewer for pointing out our writing mistakes. We will correct these mistakes accordingly (detailed are provided in the replies to the specific comments).

R1.4 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.

We will provide photographs of the annealing experiments in the supplementary materials.

Specific comments

R1.5 l. 22: natural ice is characterized

Corrected.

R1.6 l. 23: I think you mean “grain boundaries are pinned by bubbles”

Apologize for our vague writing. We have corrected it.

R1.7 l. 23: l. 26: in the grain interior

Corrected.

R1.8 l. 27: It is not totally clear what you mean by one stage, maybe add half a sentence to describe it.

We agree with the reviewer that the description of “one stage” is unclear. We have removed this sentence in the modified manuscript.

R1.9 l. 30: the wording is unprecise, “ice grain growth” or “growing of the ice crystals” might be better.

We agree with the reviewer. We have modified the sentence to *We suggest the bubble-pinning, which inhibits grain growth,...*

R1.10 l. 31: I would like to read one last sentence in the abstract briefly describing what your results mean.

We have added a new statement to describe the meaning of our findings to natural ice:

The observed abnormal grain growth with a weakening of CPO intensity in our annealed samples, in good agreement with the weak CPO in the shallow part of the Priestley ice core, suggests that abnormal grain growth could be common in the shallow part of the Priestley glacier.

R1.11 l. 44: delete “statistics”

Corrected.

R1.12 l. 56: add “comparably impurity-rich”; ice is still a very pure material.

Corrected.

R1.13 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.

We thank the reviewer for pointing out that some more recent references should be added. We have added Stoll et al. (2021) as a new reference.

R1.14 l. 62: For recent microstructural results from a deep ice core maybe add Stoll et al., 2021b.

We have added Stoll et al. (2021).

R1.15 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).

We thank the reviewer for his suggestion. However, we respectfully argue that this paragraph has already clearly stated the complication of factors that affect ice grain growth (as agreed by the reviewer) and we also suggest sufficient citations have been provided.

R1.16 l. 67: maybe replace original with host.

We respectfully suggest keeping the description of “original grains” as it is commonly used for describing nucleation processes in rock and ice deformation literature (e.g., Fan et al., 2021; Halfpenny et al., 2006).

R1.17 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

Previous studies have used entire ice cores acquired from hot water drilling for microstructural studies (e.g., Jackson, 1999; Jackson & Kamb, 1997). We agree with the reviewer that our previous statement is not robust enough. Therefore, we have modified the statement to *For example, during hot-water drilling, the circulation of pressurized hot water, which is used to produce and maintain the opening of boreholes, can lead to an increase in the ice-core temperature*

R1.18 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.

We apologise for our misleading statements. Therefore, we have modified the statement to *Moreover, the back-flowing of subglacial water into the borehole, which might happen during the drilling of deep ice cores*

R1.19 l. 83: Merge both sentences: ..kinetics to better understand grain growth in natural ice”.

We have merged the sentences as suggested.

R1.20 l. 92: space between of25.4

Corrected.

R1.21 l. 96: replace eliminated with discard/vanish/exude or something similar

Corrected.

R1.22 l. 98: ice slabs are used

Corrected.

R1.23 l. 99: thickness of ice slabs

Corrected.

R1.24 l. 100: is there a more specific name than Antarctic ice core no 30.?

The core number used in this paper remains consistent with the original report (Thomas et al., 2021) and we currently don't have a specific name for it.

R1.25 l. 100: is there a more specific name than Antarctic ice core no 30.?

The core number used in this paper remains consistent with the original report (Thomas et al., 2021) and we currently don't have a specific name for it.

R1.26 l. 104: Fig. number missing

We apologize for this mistake. The figure number has been corrected.

R1.27 Fig. 1: 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).

We have corrected the labelling to Priestley ice.

R1.28 l. 110: Cold laboratory

The name of our lab is the “Ice Lab”. Therefore, we would like to keep the expression of “Ice Lab”.

R1.29 l. 115: the bins

We only have one chilly bin. Therefore, we would like to keep the expression of “the chilly bin”.

R1.30 l. 118: hamper/impact

Thank you for the suggestion. We have modified the statement to ... *as the contamination of silicon oil on the sample surface will hamper the collection of electron backscatter diffraction (EBSD) data.*

R1.31 l. 124: There might be more precise words than recharging and maintained. Once can be deleted.

Thank you for the suggestion. We have modified the statement to *During experiments, we stabilised the temperature of silicon oil at ~0°C by refilling the water-ice bath every seven days.*

R1.32 l. 142: Maybe add dewar flask/bottle for readers not acquainted with laboratory terms.

Thank you for the suggestion. We have modified the statement to ... *a liquid nitrogen dewar tank.*

R1.33 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?

Thank you for pointing out these mistakes. We have specified that the grain size is the measurement of the area-equivalent diameter in the text. We have also added this information in Table 1 in the modified manuscript. We apologize for the wrongly recorded number of grains for samples 12_P_A, 12_P_B, 13_P_A, and 13_P_B. This mistake has been corrected in the modified manuscript. We have also modified the expression of "thin section" to "thin slice".

R1.34 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.

We have modified Fig. 2b so that the small plot is clearly labelled as *a zoomed-in view of a sealed aluminium vessel.*

R1.35 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.

We have modified Fig. 2b so that the small plot is clearly labelled as *a zoomed-in view of a sealed aluminium vessel.*

R1.36 l. 155: space at 5mm

Corrected.

R1.37 l. 169: Describe briefly how you prepared the slices, did you microtome the surface?

We have added a new statement to explain the sample-polish procedure: *We acquired a polished sample surface by hand lapping on grit papers with grit sizes of 80, 240, 600, 1200 and 2400 at -40°C.*

R1.38 Fig. 3: Put the scale in panel a and e.

Corrected.

R1.39 l. 213: CPO already introduced, the same applies for SPO later in the text.

We have corrected this mistake for the whole manuscript.

R1.40 l. 217: Briefly introduce the M-index and add “the”.

We have added “the” to the front of the “M-index”. The M-index is a standard method for quantifying CPO strength. We suggest that our original text has already provided a brief and clear explanation of the M-index.

R1.41 l. 219: ...bubbles, as done for calculating grain sizes.

Corrected.

R1.42 l. 222: delete “will”

Corrected.

R1.43 l. 226-229: Is this needed? You explain the different aspects in more detail, I think you don't need this introduction.

We agree with the reviewer. We have removed this paragraph.

R1.44 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.

Detailed temperature records have been provided in Figs. 2(c) and 2(d).

R1.45 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

We agree with the reviewer. We have corrected this mistake.

R1.46 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 ...

We have corrected this mistake.

R1.47 Fig. 4c): The x-axis could be designed more accessible with e.g. 10^x

Corrected.

R1.48 l. 261: small ice grains, otherwise you need something to compare it with

We have modified this sentence to *The starting material of Priestley ice is characterised by small ice grains with less irregular grain boundaries interlocking with large ice grains with more irregular grain boundaries*

R1.49 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

This sentence describes Fig. 5(a). Therefore, it is necessary to describe what we see from the figure (Fig. 5(a)). The CPO has been described in Sect. 3.3.3.

R1.50 l. 269: 12-18 times larger than that of/ 12-18 times the value of the median ice grain size

Corrected.

R1.51 276: Delete the part about abnormal bubbles if you don't discuss it later

Corrected.

R1.52 l. 277: space and(d)

Corrected.

R1.53 l. 278: SPO introduced already

Corrected.

R1.54 l. 279: the last part belongs into the discussion section

We have removed this part.

R1.55 l. 281: increases with time

Corrected.

R1.56 Fig.5c) The x-axis could be designed more accessible with e.g. 10^x

Corrected.

R1.57 Is there any meaning to the black-white bars below c and e? The caption could be shortened by referring to Fig. 4.

The black-white bar separates the analyses of ice and bubbles. In the modified manuscript, we have changed the black-white bar to a solid thick line to avoid confusion. Priestly ice contains bubbles, which are illustrated as black blobs. These features, which do not exist in synthetic ice, need to be mentioned for Priestley ice. Therefore, we would suggest keeping the caption (which is not long) for clarification.

R1.58 l. 294: CPO patterns are generally...

Corrected.

R1.59 Fig. 6 caption: delete point, only pole figure. Thomas et al. (2021), similar with Bons and others and Azuma and others -> consistency in referencing

Corrected.

R1.60 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.

We use seconds (s) for time and millimetres (mm) for grain size so that the unit for parameters (e.g., k) remain consistent with previous studies (e.g., Azuma et al., 2012).

R1.61 l. 344: Fig. 7 does not compare, it displays the data which is a comparison. Rephrase.

We use modified the sentence to *Figure 7(b) displays a comparison between the modelling result and measurements...*

R1.62 l. 347-355: Challenging to read as you refer to sections not read yet. Maybe rephrase or switch order.

We assume the reviewer refers to the sentence *We suggest that grain-growth inhibition in natural ice is controlled by both reduction of grain boundary mobility and driving force (as discussed in Sect. 4.2) and processes that are different from normal grain growth (as discussed in Sect. 4.3).*

We would like to politely suggest that this sentence is only a transitional sentence that links to the following discussions in sections 4.2 and 4.3. To reduce the confusion, we have modified the sentence to *We suggest that grain-growth inhibition in natural ice is controlled by both reduction of grain boundary mobility and driving force (as discussed in the following Sect. 4.2) and processes that are different from normal grain growth (as discussed in the following Sect. 4.3).*

R1.63 l. 367: by the microstructure

Corrected.

R1.64 l. 372: We compare the following microstructural differences...:
Delete "these microstructural differences include"

Corrected.

R1.65 l. 375: Can you quantify "many more" with your data?

We have modified this sentence for clarification. *The Priestley ice is bubble rich as revealed by the SE image (Fig. 5(a)). In contrast, the synthetic ice does not contain visible bubbles (Fig. 4(a)).*

R1.66 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 shorten this paragraph and mention that impurities 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

We thank the reviewer for his thoughtful comments. We have (1) added Stoll et al. (2021) as a reference, and (2) removed statements on preliminary data of impurities in Priestley ice.

R1.67 l. 386: strong CPO pattern – which one?

We have modified the statement to *The starting material of the Priestley ice has a strong CPO whilst the synthetic has a CPO that is close to random.*

R1.68 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.

We have modified the statement to *We separately calculated the density (i.e., number per unit area) of bubbles.*

R1.69 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”

We apologize for the misleading statement. We have modified the sentence to *... the bubble density remains similar for bubbles at different locations...*

R1.70 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

We have corrected this mistake. Please refer to R1.68.

R1.71 l. 405: To me, the density does not remain stable in 8d) for the first 400 hours.

We have modified this sentence to *The bubble density remains relatively stable before ~400 hours...*

R1.72 l. 407: density of bubbles evokes material density thoughts, stick to bubble density

This statement describes the density of bubbles at different locations.

R1.73 l. 421: give examples of previous studies or use the singular. Grain boundaries can modify.

We have modified this statement to *Azuma et al. (2012) suggest grain boundaries can...*

R1.74 l. 422: Simply say that the applied methods cannot investigate bubble movement, that's totally fine and does not have to be defended

We have modified this paragraph to simplify the statement.

R1.75 l. 427: delete much and directly name the size difference

Corrected.

R1.76 l. 430: replace production with “development” or “attribute abnormal grain growth with” -> the sentence can be shortened

Corrected.

R1.77 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

We have modified the statement to *...the occurrence of abnormal grain growth usually correlates with initially slow grain growth and some grain boundaries with different characteristics...*

Grain growth of ice matrix -> ice grain growth

R1.78 l. 441: Mention this is the methods already

This statement was not mentioned in the Methods and we suggest it is necessary to keep it here for clarity.

R1.79 Fig. 9a) Think about using a perceptually uniform colour scheme than jet/rainbow, see e.g. Crameri et al. (2020) for details

Corrected.

R1.80 l. 465 annealed samples...ice core data suggest that abnormal....

Corrected.

R1.81 l. 466: “An annealing” or “annealing experiments of ice samples”

Corrected.

R1.82 l. 467: Better “strengthening” than “enhancement”

Corrected.

R1.83 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, some 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

Thank you for the suggestions. We have modified the figure accordingly.

R1.84 l. 476: define “sampling”, does it include drilling, core handling, first processing etc?

Corrected.

R1.85 l. 477: clarify bubbles at ice grain boundaries (all, most, few)

Corrected.

R1.86 l. 479: grain boundary. Abnormal grain growth is an additional process

Corrected.

R1.87 l. 480: avoid generalizations: grain size change in our (natural) samples/ in the depth range investigated

Corrected.

R1.88 l. 481: Number density of bubble

Corrected.

R1.89 l. 486: ...contrast can drive abnormal grain growth...

Corrected.

R1.90 l. 487: inhibits grain boundary migration of ice grains / in the ice matrix

Corrected.

R1.91 l. 490: CPO usually gets stronger with depth, is this relevant for your comparison?

We suggest the abnormally weak CPO at the shallow part of Priestley ice is tightly correlated with abnormal grain growth. Therefore, we suggest this statement is relevant to this paper.

References

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