Response to Reviewer 2, Prof. Christopher J. L. Wilson

We thank reviewer 2, Prof. Christopher J. L. Wilson 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; our responses are in black; *extracts from the manuscript are in italics.*

R.2.1 This preprint by Fan et al. suggests grain growth in natural ice is much slower than synthetic ice and is based on two sets of experiments. The authors successfully obtain high-resolution EBSD data that provide insights into microstructural and CPO changes. The paper is generally well written, but suffers from some inconsistencies and repetitions and some minor rearrangement, shortening and streamlining of the text is required. There are far too many one sentence paragraphs or subsections in this manuscript that do not let the reader to obtain a good sense of flow. If substantial modifications are undertaken then it would be suitable for The Cryosphere.

We thank the reviewer for his affirmation of our work. We agree with the reviewer that the rearrangement and shortening of the text is necessary. We have modified the manuscript by following the reviewer's comments.

Response to specific comments for the author's consideration

R.2.2 This papers introduction (lines 33-44) contains general statements on the mechanical behaviour of ice which are not relevant to their annealing story. I would suggest it would be better to highlight why there is a need to better understand grain growth in ice and formulate the aims of the paper more clearly.

We agree with the reviewer that lines 33-44 are less relevant to the focus of this paper. We have removed them. Moreover, we rephrased this paragraph so that one of our motivations, which is understanding grain growth is important for modelling ice-sheet dynamics, has been emphasized.

R.2.3 In the Abstract and also in introduction it would be good to point out that these are both short- and long-term annealing experiments. In the text it would also be an idea to say how these compare with the time frame summarized in the plot (Fig. 13) in Wilson et al (2014).

We thank the reviewer for suggesting that we should (1) specify the scale of annealing time, and (2) compare it with previous studies.

We have modified a statement in the abstract *To understand better grain-growth processes and kinetics, we compared microstructural data from synthetic and natural ice samples that were annealed at ice-solidus temperature (0ºC) to successfully long durations (from a few hours to 33 days).*

We have added a new statement in the introduction *The annealing time, which expands from a few hours to 33 days, is consistent with previous studies (Wilson et al., 2014; Azuma et al., 2012).*

R.2.4 Annealing times are used inconsistently throughout the manuscript. Days are used in Fig. 2; Hours in Figs. 4 & 5; Seconds in Fig. 7; Hours in Figs 8, 9. On some of the plots it may be worth having two timescale bars included. Hours used on lines 404, and months on line 474.

We apologize for this inconsistency. We have followed the reviewer's comments and modified the figures and text accordingly to address such inconsistency.

1. The time unit of "month" has been replaced by "days" in the text.

2. In Fig. 2(c), we use the unit of both hours and days in the x-axis.

3. In Fig. 7, we use the unit of both seconds and hours in the x-axis. This is because we would like to keep the unit of k (mm^2s^{-1}) consistent with previous studies (e.g., Azuma et al., 2012).

R.2.5 The results section is very disjointed and in need of some consolidation. E.g. Why not combine sections 3.2.1 and 3.2.2; 3.3.1 and 3.3.3 and the subheading "3.3.2 Bubbles" could be better identified.

Thank you for the suggestion. We have (1) merged Sects. 3.2.1 and 3.2.2, (2) merged Sects. 3.3.1 and 3.3.3 as the new Sect. 3.3.1.

R.2.6 There is no proper introduction to the Discussion' section (4). It would be good if there is a summary that sets the scene for the following subsections. In fact much of section 4.1.1 could be removed as many of the equations have little bearing on the discussion in section 4.1.2.

We apologize for a lack of introduction at the beginning of Sect. 4. We have added the following paragraph:

The microstructural evolution is fundamentally different between synthetic and Priestley ice during annealing (Sect. 3.2, 3.3). To explore ice-grain growth mechanisms, we start by comparing the evolution of ice-grain size between synthetic and Priestley ice (Sect. 4.1). After that, we focus on interpreting the microstructural-evolution data from Priestley ice to understand (1) the role of bubbles in the inhibition of ice-grain growth (Sect. 4.2), and (2) mechanisms that control the activation of abnormal grain growth and how does abnormal grain growth modify the grain size and CPO in natural ice (Sect. 4.3).

We would like to politely suggest keeping section 4.1.1 and equations included in this section. Because Eqs. (1)–(5) are co-dependent, and they are essential for the audience to understand how did we calculate the value of *n* and *k*, which are the key for discussion in the Sect. 4.1.2.

R.2.7 The section on evaluating the bubbles in the Priestley ice (4.2) needs to be considerably shortened and unnecessary referencing needs to be scaled back.

We agree with the reviewer. The following statements from the original manuscript have been removed so that this section only focuses on discussing bubbles:

(2) Insoluble and soluble impurities. Natural ice contains insoluble impurities, such as $CaSiO_3$ and SiO_2, and soluble impurities, such as ions produced from dissolved salts (Baker et al., 2003; Faria et al., 2010; Gow, 1968; Gow & Williamson, 1971; Stoll et al., 2021; Svensson et al., 2005; Weikusat et al., 2017). *The methods applied in this study do not enable us to locate impurities within grains and/or at grain boundaries. In contrast, the synthetic ice was produced from ultra-pure water (Sect. 2.1); therefore, the content of insoluble and soluble impurities should be negligible.*

(3) Geometrically necessary dislocation (GND) density. The Priestley ice develops intragranular boundaries (Fig. 5(b); Sect. 3.3.1), indicating a relatively high GND density. In contrast, the synthetic ice has few intragranular boundaries (Fig. 4(b); Sect. 3.2.1), indicating a relatively low GND density.

Previous studies suggest grain boundary can modify the surface tension of air bubbles; consequently, bubbles can be dragged by grain boundaries and move via water-molecule transportation (Azuma et al., 2012). We did not directly observe the movement of air bubbles in this study. This is because our data are "snapshots" of ice and bubble microstructures. Understanding the kinematics of bubble movement requires additional input from in-situ annealing experiments, where bubble positions can be continuously monitored.

We added a short statement to clarify why other possible parameters such as impurities, CPO, and strain energy are not discussed.

In the following paragraphs, we will focus on evaluating the impact of bubbles on the inhibition of ice grain growth. Evaluating the impact of impurities, CPO, and strain energy on the grain growth of ice would require additional data input and extensive modelling that are beyond the scope of this paper.

R.2.8 he section 4.3 could also be significantly shortened and the discussion and referencing of previous work (e.g. lines 430-435) is out of place and could be deleted.

We agree with the reviewer. We have removed lines 430–435.

R.2.9 Nowhere in this manuscript has there been a discussion of strain energy and its role as a contributor to grain boundary migration.

We thank the reviewer for pointing out that there is a lack of discussion of strain energy in the current manuscript. We have attempted to explore the role of dislocation density on the abnormal grain growth in Sect. 4.3 using our EBSD data. However, to further understand the role of strain energy on grain growth we would need to (1) add annealing experiments on experimentally deformed samples, and (2) add modelling that can evaluate the hypothesis derived from experiments. We are currently conducting ELLE modelling using deformed and undeformed samples as inputs. One of the motivations of this modelling project is to evaluate the role of strain energy on grain growth. Therefore, evaluating the role of strain energy on grain growth is out of the scope of this paper and it will be thoroughly discussed in our future papers.

R.2.10 Overall, this paper presents some high-quality experimental data. However, conclusions are too focused on the Priestley glacier and do not suggest the significance of this work and how it compares with Azuma's research and how it could be applied to other ice sheets or glaciers.

We thank the reviewer for affirming our work. We agree with the reviewer that two improvements are required in the section of conclusion: (1) suggest the significance of our work to the natural ice system, (2) emphasize the comparison of our work with Azuma's work.

To address the first point, we have implemented the following changes to the statements:

Abnormal grain growth introduces an additional grain-growth process to normal grain growth. Together, bubble pinning and abnormal grain growth govern the grain size change in natural ice samples.

Consequently, we speculate that grain growth in natural ice might comprise more than one stage and it should correspond to more than one set of grain-growth parameters.

Abnormal grain growth is observed in annealed natural ice samples.

Annealed natural ice samples that contain abnormally large grains exhibit a weaker CPO intensity compared with other annealed samples without abnormal grain growth.

To address the second point, we have added new statements:

Annealing experiments at 0°C were conducted on synthetic, ultra-pure water ice samples, and natural, Priestley ice samples. The grain size of synthetic samples increases with annealing time, with a grain-growth exponent, n, of 2–3, consistent with Azuma et al. (2012).

The grain-growth rate in natural ice samples is much slower than predictions using grain-growth parameters derived from bubble-free synthetic ice (e.g., this study; Azuma et al. (2012)).

Response to editorial comments keyed to line numbers

R.2.11 55- It would be good to see some specific references to papers that demonstration how dust and dissolved salts effect the ice microstructure.

We apologize for the lack of citation. We have added references that address the effect of dust and dissolved salts on ice microstructure, including Faria et al. (2014) and Stoll et al. (2021).

R.2.12 105- I have difficulty relating text statements referring to the ice flow plane with Fig. 1a? Why isn't the flow plane clearly identified in the figure? In the natural ice was there any suggestion of a grain shape alignment parallel to the flow plane?

The flow plane could not be clearly identified during the sample cutting in this study. Therefore, we did not mark the flow plane in Fig. 1(a). After the collection and processing of EBSD data, we could reveal grain shape and CPO, which can be used to identify the flow plane (Thomas et al., 2021).

R.2.13 Table 1. - I feel the caption could be expanded to better identify what S_M_A P_B etc sand for and shorten the text between lines 155-158.

We have added a caption for Table 1 to explain the meaning of sample numbers:

[2] *The first number refers to the number of ice slab cut from ice cores. The "S" refers to synthetic ice; "M" refers to the medium grain size of synthetic ice; "P" refers to Priestley ice; "A" and "B" refers to thin slices subsampled from each ice slab.*

We would suggest to keep lines 155-158 so that the meaning of "ice slab" and "ice slice" can be clarified.

R.2.14 162 - The sentence "For a few….. (Table 1" could be removed as this is already said on line 145 at bottom of Table..

We have removed this statement.

R.2.15 185 & 195 - Is it necessary to have (SE) in the text and caption. It would be better to write it out in full.

Corrected.

R.2.16 213 – Why write out CPO in full again when it was used on lines 44, 46, 60 etc.

Apologize, we have corrected this mistake.

R.2.17 221 – Why repeat the spelling out of SPO when this was undertaken on line 219? Again it is repeated on line 279, 289 (in caption) and elsewhere in the paper, e.g. line 360.

Apologize, we have corrected this mistake.

R.2.18 225 – 235 – These two sections should be removed from here as they repeat material that should be in the methods section. This will then require renumbering and possibly renaming the following sections.

We have removed the introduction for the Sect. Result. We merged the section of temperature fluctuation to the section method.

R.2.19 243 – delete 'experiment'.

Corrected.

R.2.20 278 – SPO problem.

Corrected.

R.2.21 279 – Remove unnecessary parenthesis.

Corrected.

R.2.22 306 – Why is it really necessary to have subsections 4.1 and 4.1.1 ? you need to reorganize subheadings.

We would like to politely suggest keeping subsections 4.1.1 and 4.1.2. This is because section 4.1 discusses the grain size evolution in synthetic and natural ice. For the clarity, it would be great to separately discuss synthetic ice and natural ice. We understand that the subheadings are unnecessarily long and we have shortened them to "*4.1.1 Synthetic ice*" and "*4.1.2 Priestley ice*".

R.2.23 310-331 – Except for the first paragraph, the rest of this section does not contribute anything to this highly descriptive paper. The parameters n, k and t0 are not really defined. There are equations, which are really not used and their relevance is unclear. Why not explain these parameters in the figure caption to Fig. 7?

Please refer to R.2.6 for the response.

R.2.24 318 – change 'and others' to et al.

Corrected.

R.2.25 339-340 – Why not combine these two paragraphs and shorten them in the light of writing a new introduction to the "Discussion" section.

We have added an introduction to the Sect. Discussion. For details, please refer to R.2.6.

R.2.26 Fig. 7b – The significance of this figure and the rate constant, k, needs to be better clarified in a new introduction to the "Discussion". Or this figure could be removed.

The significance of Fig. 7(b) has been discussed in Sect. 4.1.2 as it is a key part for us to explore the k value at a fixed n value for Priestley ice. We would like to politely suggest keeping this figure as it is a key part of our discussion.

R.2.27 364 – References not in reference list. Are they necessary?

We apologize for the missing references. We have corrected this mistake.

R.2.28 365-375 Much of this discussion and references are irrelevant to the origin of bubbles, and could be deleted.

We agree with the reviewer that these discussions are not relevant to bubbles. However, we should suggest that it is also important to list other possibilities that can contribute to the reduction of grain-growth rate, such as second-phase pinning, CPO, and dislocation densities. We apologize that our idea was not introduced properly and thus caused confusion. We have thus added a statement to clarify this idea: *In the following paragraphs, we will focus on evaluating the impact of bubbles on the inhibition of ice grain growth. Evaluating the impact of impurities, CPO, and strain energy on ice-grain growth would require additional data input and extensive modelling that are beyond the scope of this paper*.

R.2.29 380-395 and to 425 – This section can be considerably condensed.

We agree with the reviewer, and we have corrected this mistake. Please refer to R.2.7 for details.

R.2.30 420 – The sentence "Further studies…natural ice" could be deleted and especially the word "elle" is not required.

We have removed this statement.

R.2.31 485-490 – This conclusion has not been supported by any data in this manuscript.

This point of conclusion is correlated with our discussion in Sect. 4.3 about dislocation densities (l 437-449 in the original manuscript). We would like to politely suggest keeping this point as it is a key part of the conclusions.

References

Azuma, N., Miyakoshi, T., Yokoyama, S., & Takata, M. (2012). Impeding effect of air bubbles on normal grain growth of ice. *Journal of Structural Geology*, *42*(C), 184–193. https://doi.org/10.1016/j.jsg.2012.05.005

Baker, I., Cullen, D., & Iliescu, D. (2003, January). The microstructural location of impurities in ice. *Canadian Journal of Physics*. https://doi.org/10.1139/p03-030

Faria, S. H., Freitag, J., & Kipfstuhl, S. (2010). Polar ice structure and the integrity of ice-core paleoclimate records. *Quaternary Science Reviews*, *29*(1–2), 338–351. https://doi.org/10.1016/j.quascirev.2009.10.016

Faria, S. H., Weikusat, I., & Azuma, N. (2014). The microstructure of polar ice. Part I: Highlights from ice core research. *Journal of Structural Geology*, *61*, 2–20. https://doi.org/10.1016/j.jsg.2013.09.010

Gow, A. J. (1968). Bubbles and Bubble Pressures in Antarctic Glacier Ice. *Journal of Glaciology*, *7*(50), 167–182. https://doi.org/10.3189/s0022143000030975

Gow, A. J., & Williamson, T. (1971). Volcanic ash in the Antarctic ice sheet and its possible climatic implications. *Earth and Planetary Science Letters*, *13*(1), 210–218. https://doi.org/10.1016/0012-821X(71)90126-9

Stoll, N., Eichler, J., Hörhold, M., Erhardt, T., Jensen, C., & Weikusat, I. (2021). Microstructure, micro-inclusions, and mineralogy along the EGRIP ice core - Part 1: Localisation of inclusions and deformation patterns. *Cryosphere*, *15*(12), 5717–5737. https://doi.org/10.5194/tc-15-5717-2021

Svensson, A., Nielsen, S. W., Kipfstuhl, S., Johnsen, S. J., Steffensen, J. P., Bigler, M., et al. (2005). Visual stratigraphy of the North Greenland Ice Core Project (NorthGRIP) ice core during the last glacial period. *Journal of Geophysical Research D: Atmospheres*, *110*(2), 1–11. https://doi.org/10.1029/2004JD005134

Thomas, R. E., Negrini, M., Prior, D. J., Mulvaney, R., Still, H., Bowman, H., et al. (2021). Microstructure and crystallographic preferred orientations of an azimuthally oriented ice core from a lateral shear margin: Priestley Glacier, Antarctica. *Frontiers in Earth Science*, *9*(November), 1–22. https://doi.org/10.3389/feart.2021.702213

Weikusat, I., Jansen, D., Binder, T., Eichler, J., Faria, S. H., Wilhelms, F., et al. (2017). Physical analysis of an Antarctic ice core-towards an integration of micro-and macrodynamics of polar ice. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *375*(2086). https://doi.org/10.1098/rsta.2015.0347