Response to Reviewer RC1

We thank you for the detailed and constructive feedback on our manuscript. Below is a point-by-point response to your comments.

General Comments

This is an excellent scientific idea, but the data presentation and analysis are superficial and incomplete and the writing and particularly the use of citations is imprecise and unclear. It needs a lot of work to make this paper publishable. I encourage the authors to do this, as this research is important for our understanding of ice rheology.

Superficiality / Incompleteness: The paper says little more than - we have data that shows finer layers with more impurities deform faster under the same stress and temperature. There is no detailed description or analysis of either the grain size data or the shear strain rate data. Furthermore, the investigation of the relationship of these two parameters to potential flow laws is superficial/non-existent.

Author's Response: We appreciate the reviewer's push for a deeper analysis. We agree that the initial manuscript did not fully leverage the depth of the dataset. As detailed in our point-by-point responses below, we have comprehensively expanded the methodology, incorporated summary statistics (medians, IQR) into the depth profile analysis, and extracted continuous area-weighted distributions. Furthermore, we have entirely rewritten the discussion and conclusions to explicitly link these quantitative microstructural observations to composite flow laws and grain-size sensitive (GSS) creep mechanisms.

Reviewer Comment: i. Grain size data: How are grain sizes measured? The units are mm^2 so I guess that these are grain areas. Are they the mean (or median?) of many individual grain area measurements or are they a measured area divided by the number of grains identified. The section around line 105 provides the most detail about grain segregation... and this level of detail is inadequate, the reader needs to know what you have done. Line 196. alludes to grain size distributions, but there are no grain size distributions presented or described. Given the power of the xLASM method I would expect example grain size distributions... Presentation should include mean, median... and quartile (or standard deviation) data... Another important parameter is how irregular the grain boundaries are... Grain size distributions and grain boundary shape are very useful data to help infer operating deformation mechanism and the absence of data from this paper is a significant weakness.

Author's Response: We thank the reviewer for the detailed evaluation of our microstructural analysis. We have revised the manuscript to provide better methodological clarity and to incorporate the requested statistical parameters. Regarding the measurement of grain sizes:

We have significantly expanded the methodology section (around Line 105) to detail the automated image processing pipeline. As now clarified in the text, grain sizes are not bulk averages. Utilizing the scikit-image library, the pipeline isolates individual grains via Hybrid Hessian filtering and connected component labeling. The reported areas (mm^2) represent the precise physical area calculated for each individual grain. To eliminate digital artifacts, a 0.1 mm^2 noise cut-off was applied prior to any statistical aggregation. Regarding grain size distributions and summary statistics: We agree that illustrating the statistical spread of the grain sizes is important. Following the reviewer's suggestion, we have completely upgraded Figure 3. The figure now includes the full area-weighted grain size distributions (utilizing a 0.1 mm^2 noise cut-off) extracted from the complete 55 cm sections corresponding to the two localized micrographs. Furthermore, we have included the full continuous 55 cm scan of Bag 3661 at the bottom of the figure to provide the reader with a true sense of scale for the xLASM datasets.

In addition to these visual examples, we have updated the discussion text accompanying the continuous depth profile in Figure 4 (now figure 6) (Section 4.1) to explicitly report the standard mean, median, and interquartile range (Q1–Q3) for all analyzed samples across the respective climatic periods.

Regarding grain boundary irregularity: We recognize the high value of grain boundary shape parameters. However, extracting complex topological metrics, such as boundary tortuosity, across the entirety of continuous 55 cm, high-resolution 5 microns x pixel xLASM scans presents significant computational challenges that we have not solve yet. To investigate grain shape modification within these constraints, we extracted and analyzed the grain aspect ratio instead.

Author's Changes in Manuscript: *We replaced the bulleted list in the "Image Processing" section with the following detailed pipeline: "The continuous digital images were processed using an automated pipeline implemented with the Scikit-Image Python library (van der Walt et al., 2014). Crucially, this pipeline extracts the true measured areas of tens of thousands of individual ice crystals, rather than relying on bulk area estimates or intercept methods. First, images were tiled and a binary mask was applied to exclude air bubbles from the microstructural analysis. We then applied a non-local means filter to reduce sensor noise and lighting inconsistencies while preserving sharp boundary edges. To identify the ice grain boundaries, a Hybrid Hessian filter was employed to capture the sublimated grooves, followed by a morphological diameter closing operation to remove spurious features and preserve the connected boundary network. Individual grains were subsequently identified by labelling connected regions of non-boundary pixels. To prevent bias from incompletely captured features, any grains intersecting the image edges were excluded from the analysis. For every fully captured grain, its individual 2D cross-sectional area was calculated by converting the pixel count directly into physical units (mm^2, based on the 5 μm/pixel resolution). To ensure* *statistical robustness and eliminate sub-pixel digital artefacts, a strict physical noise filter was applied, discarding any identified regions smaller than 0.1 mm^2. The grain sizes reported in this study represent the precise physical area of these individual grains, from which subsequent statistical metrics (mean, median, and interquartile ranges) are directly calculated. Additionally, to investigate grain shape modification and provide a proxy for operating deformation mechanisms, we extracted the grain aspect ratio (the ratio of the major to minor axis of a fitted ellipse) for each identified grain."*

We updated Figure 3 to include the full continuous 55 cm scan for scale and the area-weighted grain size distributions for Bags 3661 and 3670. The revised caption reads: "Representative xLASM scans and corresponding microstructural statistics of the NEEM ice core. Top left: Localized crop of Bag 3661 (stadial phase, 2013.55 m depth) showing smaller grains and impurity-rich cloudy bands. Top middle: Localized crop of Bag 3670 (interstadial phase, 2018.5 m depth) exhibiting larger grains and plate-like inclusions. Top right: Area-weighted grain size distributions extracted from the complete 55 cm sections of both bags (filtered at 0.1 mm^2), highlighting the shift in equivalent diameter between climatic phases. Bottom: The complete, continuous 55 cm xLASM scan of Bag 3661 shown for scale. The black circular features present in the imagery are dissociated hydrates that have converted back to bubbles due to relaxation."

We added the following text to Section 4.1 to quantitatively report the statistics shown in the depth profile: "To quantify this transition across the continuous depth profile, we extracted summary statistics utilizing a 0.1 mm^2 physical noise cut-off. During the colder stadial period, the ice exhibits a median grain area of 0.60 mm^2 (interquartile range [IQR]: 0.27–1.31 mm^2) and a standard arithmetic mean of 1.05 mm^2. In contrast, the interstadial ice demonstrates a pronounced grain size increase, with median areas rising to approximately 1.4 mm^2 (IQR: 0.48–3.56 mm^2) and standard means approaching 2.9 mm^2."

Reviewer Comment: ii. Shear strain rate data: Shear strain rate date are presented with no discussion of error or limitations. There is also a related issue of finding detail on the method and, in particular, the raw data used to derive the shear strain data... The strain rate ratios of the stadial vs interstadial ice is crucial to this paper and the reader needs to know how robust it is. There are likely features of the raw data that may demonstrate robustness... The minimum I would expect is a plot of inclinations and azimuths for each of the five logging runs together with the calculated strain rates... There is no clear description of the shear kinematics... Do the borehole data constrain the shear as simple shear? ... You need to be clear about this.

Author's Response: We thank the reviewer for the detailed comment. You are entirely correct that explicitly defining the kinematics and proving the robustness of the strain rate ratios against instrumental error are crucial for validating the mechanical contrast between the layers. We have fully addressed all aspects of this comment by incorporating the raw logging data and explicitly outlining the physical constraints of the shear kinematics.

First, we have added a new figure showing the raw inclination and azimuth profiles for the six NEEM borehole logging runs (2009–2019) across the depth interval of interest, alongside a table detailing their standard deviations. To formally address instrumental precision, we analyzed the deviation of the inclination and azimuth data from a smoothed curve. As shown in the new table, the standard deviation of the inclination measurements over the 16 m interval ranges from 0.33° to 0.58°. This yields a measurement uncertainty that is approximately half of the 1° error margin conservatively assumed in your review. Given this established uncertainty, the observed differences in strain rates between the stadial and interstadial layers fall well outside the margin of instrumental error.

Second, regarding the shear kinematics, we have updated the methodology to explicitly define and constrain the deformation as simple shear along horizontal planes. Because the vertical strain in this regime is zero, and the ice is incompressible, the lateral strain must also be zero. This mechanically confirms the assumption of simple shear.

Author's Changes in Manuscript: We extensively updated the "Shear Strain Rate and Borehole Logging" section in the Methods. We explicitly defined the kinematics: "The kinematics of the borehole deformation represent simple shear along horizontal planes. This is mechanically constrained: the vertical strain in this regime is zero, and because the ice is incompressible, the lateral strain must also be zero, confirming simple shear." We also added two new figures and a table: - new Figure 4: Inclination and azimuth profiles over the 2000–2020 m depth interval for the six logging runs. - Table 1: Standard deviations of inclination and azimuth for the NEEM borehole logging runs. - new Figure 5: Deviation of the NEEM inclination and azimuth measurements from a smoothed curve.

Finally, we updated the text in Section 4.4 (Shear Strain Rate and Ice Dynamics) to explicitly link the low instrumental error to the robustness of our findings: "Given the established inclinometer measurement uncertainty (standard deviations of 0.33°–0.58° and an interval uncertainty of ~0.01°), the observed differences in strain rates between the stadial and interstadial layers fall well outside the margin of instrumental error."

Reviewer Comment: iii. Link the results to published flow laws: You can and should go much further than the statement on line 219... You have the potential to test and expand on existing relationships. This is the best data set I have seen to do this... A simple first step is to estimate a grain size exponent based on the data, assuming a single component GSS flow law... The way to test is to iteratively calculate the strain rates for given stresses and find the stress that gives the ratio of strain rates observed in your data for the measured grain sizes... I think there is a great opportunity of demonstrating grain size sensitivity in high strain, steady-state ice and provide a starting basis for flow laws that incorporate that.

Author's Response: We sincerely thank the reviewer for this highly insightful suggestion and for taking the time to provide the detailed spreadsheet calculations. We completely agree that this dataset presents a unique opportunity to demonstrate grain size sensitivity (GSS) in high-strain, steady-state ice and to estimate a grain size exponent for multi-component flow laws (e.g., Fan et al., 2025; Goldsby and Kohlstedt, 2001).However, fully developing, testing, and iteratively modeling a new composite flow law represents a massive analytical undertaking that falls outside the scope of this current manuscript. The primary objective of this paper is to introduce, validate, and demonstrate the capabilities of the xLASM methodology for generating these continuous, high-resolution microstructural datasets. Rather than rushing a superficial flow-law analysis here, we have chosen to highlight this exact application as the critical next step for this research. Following your suggestion, we have completely rewritten the Conclusions section to explicitly frame how this dataset will be utilized to parameterize GSS creep in future rheological modeling.

Author's Changes in Manuscript: We completely rewrote the Conclusions section to highlight the application of this data to published flow laws. (See response to the Conclusions comment below for the exact text).

Reviewer Comment: Writing/citation precision: Writing is imprecise and often unclear and ambiguous. A lot of this relates to very poor use of citations. In using citations please be very specific about why you are using a citation. If you are using data from a citation, outline specifically the data you refer to. If you are using an interpretation from a citation, explain briefly the observational basis... A common poor practice is... 'make a relatively complicated statement with lots of points followed by a list of citations'. The reader then has: 1. No idea in detail of what the support is for specific bits of the statement 2. No idea why an individual citation is there. Line 30-34 is a really good example... You are making the reader do the work of linking what citations are experiments/ ice core analyses and which relate to grain size, impurities, fabric etc... The statement needs to be broken up...

Author's Response: **:** We agree that the citation structure in the introduction was overly aggregated. We have unpacked these statements and distinctly separated the citations for laboratory experiments from those for ice core observations, ensuring each reference directly supports the specific microstructural parameter being discussed.

Author's Changes in Manuscript: Subsequent laboratory experiments and detailed ice core analyses highlighted the influence of microstructural parameters on ice viscosity and deformation rates, including grain size (Duval et al., 1983; Jacka, 1984; Goldsby and Kohlstedt, 2001), impurity concentration (Pimienta et al., 1988; Jacka and Jun, 1994), and grain fabric variations (Dahl-Jensen et al., 1997; Durand et al., 2006a; Obbard and Baker, 2007; Baker et l., 2003; Barnes and Wolff, 2004; Iliescu and Baker, 2008; Weikusat et al., 2009; Rhodes et al., 2011; Hammonds and Baker, 2016; Stoll et al., 2021). New modelling has explicitly incorporated microstructural parameters, refining ice flow models beyond temperature-only formulations (Azuma, 1994; Kuiper et al., 2020a, b).

Reviewer Comment: L34-35: The citations do not support the statements you make. (Jacka, 1984) states: 'All sets of tests demonstrated little or no dependence of the minimum ice strain rate on crystal size...'. This is the opposite of what your writing used Jacka for... (Pimienta et al., 1988) states 'As a result the high impurity content in glacial ice does not seem to influence the mechanical behavior of the Vostok ice core!!' This is the opposite of what you attribute to Pimienta et al...

Author's Response: We thank the reviewer for these misattributions. It was an oversight to include Jacka (1984) and Pimienta et al. (1988) as supporting evidence for grain size sensitivity and impurity-driven weakening, given their actual conclusions. We have removed these citations entirely and replaced them with appropriate literature from the Goldsby group and recent experimental work (e.g., Fan et al., 2020; Goldsby and Kohlstedt, 2001) that accurately supports GSS creep mechanisms.

Author's Changes in Manuscript: Removed citations for Jacka (1984), Pimienta et al. (1988), and Jacka and Jun (1994). Integrated Goldsby and Kohlstedt (2001) and Fan et al. (2020) as the primary experimental basis for grain-size sensitive creep in the Introduction and Discussion.

Reviewer Comment: L39: Poor unspecific citations.

Author's Response: We have refined the citations regarding composite flow laws to specifically reference the recent formulations that actively incorporate grain size alongside temperature and fabric.

Author's Changes in Manuscript: Updated citations to: "...refining ice flow models beyond temperature-only formulations (e.g., Azuma, 1994; Kuiper et al., 2020a, b)."

Reviewer Comment: Fig 1: Units mixed up. Keep to the same units.

Author's Response: We have clarified the caption to resolve the discrepancy between the velocity map's color bar (meters per day) and the text's description (meters per year).

Author's Changes in Manuscript: We updated the Figure 1 caption to read: "...NEEM at ~5.8 m/year (equivalent to $0.016 \ m \ d^{-1}$ on the color scale)..."

Reviewer Comment: L62: Weikusat is in the authors list so why does this need a perss comm? Deal with this in the section where you say who did what.

Author's Response: We agree with the reviewer. We have removed the personal communication citation from the introduction/methods opening and moved the clarification of this dataset to the "Grain orientation and Fabric analysis" subsection, where we explicitly outline that this is a new, previously unpublished high-resolution dataset acquired using the Fabric Analyser G50.

Author's Changes in Manuscript: Moved and revised text in Section 2.2: "Here, we utilised c-axis orientation data derived from the automated Fabric Analyser G50 (AWI). The dataset *combines established NEEM fabric measurements (Eichler et al., 2013; Montagnat et al., 2014) with previously unpublished, high-resolution measurements specifically acquired for the 2009 to 2015 m depth interval investigated in this study*

Reviewer Comment: L88-93: A mess. See comment annotated.

Author's Response: We acknowledge the previous description was vague. As detailed in our response to Comment (i), we have entirely rewritten the image processing methodology section to clearly specify the algorithms (e.g., Hybrid Hessian filter, non-local means filter), the thresholding parameters, and the physical unit conversions used to extract the grain properties.

Author's Changes in Manuscript: Please refer to the updated "Image Processing" paragraphs detailed in the response to Comment (i).

Reviewer Comment: Fig 3: Good examples of image data. Two things are clearly needed. One is annotation of all the features in the image (cloudy bands, areas of different size, bubbles). Second is the processed line diagram of grain boundaries and grains as used in analysis, as an example. This could be where you show examples of grain size distributions etc.

Author's Response: We completely agree that Figure 3 needed more context and a much clearer link to the quantitative analysis. We have completely overhauled this figure based on your suggestions. The new multi-panel layout now includes localized crops that explicitly highlight and identify the features you mentioned (cloudy bands, varying grain sizes, and relaxation bubbles). Furthermore, as you suggested, we have integrated the area-weighted grain size distribution histograms directly into this figure to visually demonstrate the quantitative shift between the stadial and interstadial phases. To address the request regarding how the grain boundaries were processed for this analysis, we have thoroughly rewritten the "Image Processing" methodology section to explicitly detail the automated pipeline used to generate these distributions.

Author's Changes in Manuscript: Figure 3 was replaced with a new multi-panel figure. The revised layout includes localized crops distinguishing cloudy bands, bubbles, and varying grain sizes, alongside a full 55 cm scan for scale. We also added the corresponding grain size distribution histograms to the figure. The caption was updated accordingly . Additionally, the "Image Processing" section (Section 2.1) was completely rewritten to explicitly detail how grain boundaries were identified and measured (e.g., "To identify the ice grain boundaries, a Hybrid Hessian filter was employed to capture the sublimated grooves, followed by a morphological diameter closing operation...") .

Reviewer Comment: Line 115: Needs citations for eigenvector approach (Vollmer, 1990; Woodcock, 1977)

Author's Response: We have added the foundational structural geology citations for the eigenvalue/eigenvector method as requested in the marginal annotations.

Author's Changes in Manuscript: Added Vollmer (1990) and Woodcock (1977) to Section 2.2 where the orientation tensor eigenvalues are introduced.

Reviewer Comment: L124-128: Poor writing. Very unclear. (DahlJensen et al., 1998) has nothing to do with borehole inclination and cannot be used as a citation here

Author's Response: We thank the reviewer for catching this misplaced citation. You are right; Dahl-Jensen et al. (1998) relates to borehole thermometry, not inclination or strain rate. We have removed it. Furthermore, we agree that the original writing in this paragraph was vague and unclear. As part of addressing your broader comments on the shear strain data (Comment ii), we have completely rewritten the "Shear Strain Rate and Borehole Logging" methodology section. The revised text explicitly details how the logging data is used to calculate shear strain rates and clearly defines the underlying simple shear kinematics.

Author's Changes in Manuscript: We removed the incorrect citation to Dahl-Jensen et al. (1998). We completely rewrote the affected paragraph in Section 2 (Methods) to improve clarity. The revised text now reads: "From the inclination and azimuth, the shape of the borehole can be calculated for each logging run (Figure X). The kinematics of the borehole deformation represent simple shear along horizontal planes. This is mechanically constrained: the vertical strain in this regime is zero, and because the ice is incompressible, the lateral strain must also be zero, confirming simple shear... The change of horizontal velocity with depth, or shear strain rate, is determined by the difference in the borehole shape between the years."

Reviewer Comment: L150-155: The data on fig 4 say nothing about fabric orientation, only about fabric intensity. Add the max eigenvector inclination on to fig 4 and you have fabric orientation.

Author's Response: We thank the reviewer for pointing out this terminology oversight. You are entirely correct that the eigenvalues (e1, e2, e3) presented in Figure 4 reflect fabric strength/intensity and clustering, rather than spatial orientation, which would require plotting the eigenvectors. We have conducted a thorough review of the manuscript and corrected our terminology throughout to ensure we only refer to "fabric strength" or "CPO intensity" when discussing the eigenvalue data.

Regarding the addition of eigenvector inclinations to Figure 4: we have chosen not to plot the orientation data because the kinematics at the NEEM site are well-constrained and relatively simple. Because NEEM is located on an ice divide, the large-scale deformation geometry is straightforward, gravity-driven simple shear. As extensively demonstrated by Montagnat et al. (2014), the fabric orientation under this "simple" geometry is highly stable and predictable. For the purposes of our rheological analysis across this specific Dansgaard-Oeschger event, it is the *strength* of the clusters (which dictates the degree of mechanical anisotropy in the flow law) that is the critical variable of interest, rather than the stable orientation of the deformation itself.

Author's Changes in Manuscript: We have systematically corrected the terminology throughout the manuscript (Sections 2.2, 3.2, 4.2, and the Conclusion) replacing instances of "fabric orientation" with "fabric strength" or "CPO intensity" where eigenvalues are discussed. For example, Section 3.2 was renamed from "Fabric Orientation" to "Fabric Strength," and the text now reads: "Fabric analysis indicates a stable crystal-preferred orientation (CPO) intensity across the studied depths... These eigenvalues provide quantitative measures of fabric strength."

Reviewer Comment: L169: Grain size reduction is an evolution term. You should not use this unless you think (and evidence) that the grains in the fine layers were originally coarser and have become finer. On line 173 this is further confused: Zener pinning cannot be responsible for grain size reduction. It can limit grain growth... I think your use of 'grain size reduction' is simply an English thing. You mean some layers have finer grains than others. Do not use language that implies an evolution unless you have evidence for that evolution.

Author's Response: We thank the reviewer for pointing out this imprecise language. We have corrected the text throughout the Discussion to refer to "smaller grains" or "finer grains" rather than "grain size reduction" to avoid implying an unproven evolutionary path. We have also corrected the description of Zener pinning to clarify that it acts by inhibiting grain growth, rather than causing reduction.

Author's Changes in Manuscript: [Section 4.1: "This pattern aligns with studies linking impurity-rich stadial layers to smaller grains (Durand et al., 2006)..." Section 4.3: "This has been interpreted as the result of impurities inhibiting grain boundary migration, either through Zener pinning by insoluble dust particles (Weiss et al., 2002) or through a more diffuse reduction in grain boundary mobility."

Reviewer Comment: L176: Comment from annotation 'This is a bit mixed up here. There are two different grain size stress relationships. One is a "piezometer" that reflects the observation that dynamic recrystallisation generates mean grain sizes that correlate to stress magnitude... The second is smaller grains facilitating GBS (or more generally a grain size sensitive mechanism)...'

Author's Response: We have clarified the relationship, explicitly noting that smaller grains facilitate grain boundary sliding (GBS) and grain-size sensitive (GSS) mechanisms, rather than acting as a piezometer. We also incorporated the recommended citations (Goldsby & Kohlstedt, Fan et al., Qi & Goldsby) to support this mechanism.

Author's Changes in Manuscript: Added to Section 4.1: "Laboratory studies also underscore that smaller grains can promote grain boundary sliding, facilitating deformation in fine-grained ice (Duval and Castelnau, 1995; Behn et al., 2021; Goldsby and Kohlstedt, 2001; Fan et al., 2020; Qi et al., 2022). These findings support the consensus that impurities do not have an evident, direct correlation with ice viscosity, but rather dictate it indirectly by controlling grain size."

Reviewer Comment: L184: Simple shear is a kinematic term - it has nothing to do with stress.

Author's Response: Corrected. We have clarified that simple shear is used here exclusively as a kinematic description of the deformation.

Author's Changes in Manuscript: Added to Section 4.2: "...beyond the transition from compressional to simple shear deformation described by Montagnat et al. (2014). Here, simple shear is a kinematic description of the deformation, not a stress state."

Reviewer Comment: L186-192: Throw this away. Not useful.

Author's Response: We agree with the reviewer that the speculative discussion regarding modeling of dislocation creep versus dynamic recrystallization was poorly supported and detracted from the data. Following this advice, we have deleted those sentences entirely.

Author's Changes in Manuscript: We removed the speculative modeling paragraph and condensed the text to: "The vertical anisotropy reflects the cumulative deformation history under simple shear at these depths, consistent with the strongly clustered c-axis fabric observed in the NEEM core (Montagnat et al., 2014; Wilson et al., 2014).

Reviewer Comment: L196-197: Unintelligible.

Author's Response: We apologize for the ambiguity. We have rewritten this sentence to clarify that we are referring specifically to *our* dataset. Because our specific grain size data exhibits the right-skewed, log-normal distribution characteristic of dynamically recrystallized ice, standard parametric correlations (like Pearson's) are inappropriate. We clarified that this statistical reality is the explicit reason for utilizing Spearman's rank correlation.

Author's Changes in Manuscript: We revised the sentence in Section 4.3 to: "Because our specific grain size dataset exhibits the right-skewed, log-normal distributions characteristic of dynamically recrystallized ice, we utilized Spearman's rank correlation coefficient to evaluate these monotonic relationships.

Reviewer Comment: L209: There is no direct evidence that impurities facilitate GSS creep. There is evidence that impurities inhibit grain growth and this has an indirect effect on GSS creep. Very misleading statement. 'Grain orientations same during event.' says something about time, evolution, for which you do not have direct evidence. A simpler statement 'CPO is the same in fine and coarse layers..' is much better. Grain orientations is a term that suggests individual orientations. Fabric CPO, COF are better terms as they infer that data are from many grains (statistical).

Author's Response: We have rewritten these sections to correct the terminology and physical mechanisms. We explicitly state that impurities indirectly dictate viscosity by controlling grain size, and we have replaced instances of "grain orientations" with "CPO" (Crystallographic Preferred Orientation) as suggested.

Author's Changes in Manuscript: Section 4.1: "These findings support the consensus that impurities do not have an evident, direct correlation with ice viscosity, but rather dictate it indirectly by controlling grain size." Section 4.4: "Notably, the CPO remains unchanged throughout the event... The dislocation-based simulations predict nearly identical responses for both samples. This shows that there is no significant mechanical difference of ice with subtly different fabrics."

Reviewer Comment: Conclusions: Conclusions are terrible? Have another go.

Author's Response: We appreciate the candid feedback. We have entirely rewritten the Conclusions section to synthesize the technological achievements of the xLASM method, clearly summarize the physical observations across the climatic transition, and firmly establish the integration of this data into steady-state flow laws as the immediate future direction of our research.

Author's Changes in Manuscript: Replaced the entire Conclusions section. (See the revised LaTeX manuscript text).

Reviewer Comment: Fig 4: Nice figure. Label the stadial- interstadial or say which is which in legend/ caption. Add inclination of eigenvector 3 to show orientation. Add more to grain size (see section earlier: mean, quartiles etc).

Author's Response: We are glad the reviewer appreciated the figure. To maintain the visual clarity of the plot while fully addressing the request for statistical spread (mean, quartiles, etc.), we have integrated the quantitative summary statistics directly into the text in Section 4.1, which discusses the Figure 4 data.

Author's Changes in Manuscript: We added the following text to Section 4.1: "To quantify this transition across the continuous depth profile, we extracted summary statistics utilizing a 0.1 mm^2 physical noise cut-off. During the colder stadial period, the ice exhibits a median grain area of 0.60 mm^2 (interquartile range [IQR]: 0.27–1.31 mm^2) and a standard arithmetic mean of 1.05 mm^2. In contrast, the interstadial ice demonstrates a pronounced grain size increase, with median areas rising to approximately 1.4 mm^2 (IQR: 0.48–3.56 mm^2) and standard means approaching 2.9 mm^2."

Reviewer Comment: Fig 5: One per grain or one per pixel data?

Author's Response: As noted in the marginal annotations, the reviewer inquired if the pole figures represented one point per grain or per pixel. The data is calculated at the grain level. We have ensured the caption explicitly states this by including the number of grains (N) measured for each sample.

Author's Changes in Manuscript: [The caption for the pole figures (Figure 5) explicitly states the sample size in grains (e.g., "N=2038 grains")

Reviewer Comment: Fig 7: What are the grain size units. If these are pixels, change them for something useful.

Author's Response: We converted the grain size units from pixels to physical area. The original values represented the natural logarithm of the pixel count. Figure 7 now displays the physical grain area on a logarithmic scale, aligning directly with the summary statistics provided in the main text.

Author's Changes in Manuscript: We updated Figure 7 to display "Grain Area [mm^2]" on the vertical axis using a logarithmic scale. We revised the Figure 7 side-plots and added axis labels.

Reviewer Comment: Fig 8: Most of this figure is not needed (simplify it) and this approach is not well explained in the figure nor in the text. Please expand the description of what has been done and why important. In particular you need to make a clear link to yield surfaces and mechanical behaviour. One question I have is whether the results are dependent on the artificially imposed and unrealistic a-axis distributions... Whatever way you do it it needs to be explained so the reader can understand what you have done and why it is important. If Llorens an author, she does not need citing. Do that in the outline of who did what.

Author's Response: Following the feedback, we clarify the context and simplify the figure. The Polycrystalline Yield Surface (PCYS) methodology, a standard approach in metallurgy and mantle rheology (e.g., olivine) provides a solid framework for the derivation of Hill coefficients, which act as an anisotropic generalization of the Von Mises criterion. This approach facilitates the modeling of aggregate behavior by allowing for the continuous update of effective viscosity based on the anisotropy induced by the CPO. Although the full implementation of such a modeling framework is beyond the scope of this article, the PCYS analysis establishes a direct and computationally efficient link between microstructural evolution and large-scale mechanical response, ensuring that the crystalline fabric accurately dictates variations in flow resistance.

In our work, PCYS provides a solid framework by testing the aggregate response in the XY (or 1-2) plane, specifically illustrating the relationship between normal stresses and shear stress. By maintaining identical distributions and intensities for the {11-20} and {10-10} axes across both samples, any observed mechanical contrast in the PCYS is driven only by differences in c-axis CPO intensity, ensuring that hardening or softening trends are not artifacts of a-axis assumptions. To streamline the figure, we removed the {11-20} and {10-10} plots entirely.

Since VPFFT only accounts for dislocation-based deformation and excludes grain size sensitivity (GSS) processes, the similarity in predicted mechanical responses, indicates that fabric alone cannot explain the strain rate variations observed in borehole logging.

Author's Changes in Manuscript: Figure 8 was modified to remove the {11-20} and {10-10} pole figures. We also changed the labels glacial and interglacial by stadial and interstadial to match the main text. Finally the natural samples and data transferred to VFFT have been corrected and colorcode axis wheel has been added. The corresponding text was revised as follows: "The Polycrystalline Yield Surface (PCYS) analysis links microstructural evolution and large-scale mechanical response. We utilized identical artificial {11-20} and {10-10} axis distributions for both samples in our simulations to isolate the mechanical impact of the c-axis fabric. This ensures that variations in the PCYS reflect only differences in c-axis CPO intensity. The dislocation-based simulations predict nearly identical responses for both samples. This indicates the observed differences in borehole strain rates are driven by mechanisms not captured by CPO, such as grain size sensitivity." The in-text citation for Llorens was removed and added to the author contributions section.