Response to Reviewer RC2

General Comments

This manuscript has the potential to have a very strong impact for the community. To reach that potential, I feel it needs significant expansion in several areas, described below.

Although the manuscript reports many microstructural metrics and compares them to additional datasets typically associated with paleoclimate, at its heart, the contribution seems to explore the relationship between microstructure and rheology. Ice rheology is of critical importance for a range of cryospheric interpretations and predictions, including sea-level rise, continental ice volume, ocean circulation, and many others. So the topic is of high value. As presently structured, the manuscript provides a significant amount of tantalizing data and suggestive relationships, but lacks the robust analysis to give high confidence to the interpretations. The manuscript also has the opportunity to consider the impact of the microstructure findings on paleoclimate studies. To meet these needs, I expect a fairly thorough rewriting of the document is in order. As such, I won't provide a line-by-line set of comments here, but will rather focus on the areas where I see the most benefit of expansion.

Author's Response: We thank you for recognizing the potential impact of our dataset and for providing feedback. We completely agree that the initial manuscript presented suggestive relationships that required a much more robust and uniform analysis to firmly support our interpretations. As detailed in our specific responses below, we have extensively rewritten the methodology, applied uniform statistical analyses across the continuous depth profile, and significantly expanded the discussion to firmly set our findings within the context of composite flow laws and rheology.

(1) Full presentation of the methods. First, I suggest making it much clearer in the text what datasets were collected as part of this study and what datasets were taken from previously published work. For the latter, a short methods overview is sufficient, as the reader can learn the details from the other source. For the former, a much more extensive description of the methods would benefit the reader greatly. In particular, the grain size analysis is non-trivial and I didn't see any reference to an assessment of the validity or uncertainty associated with the Scikit-Image library. Several figures demonstrating how the automated calculations match manual measurements (or references to papers that do include those comparisons) will provide confidence in the data quality. The modeling is not described at all and is also non-trivial. It should be described much more fully if the authors would like to include reference to it in the Discussion.

Author's Response: We appreciate you highlighting the need for clearer methodological boundaries. We have thoroughly revised the Methods section to explicitly distinguish between previously published datasets (such as the stable isotopes from Gkinis et al., 2021, and CFA impurities from Erhardt et al., 2022) and the new, high-resolution microstructural data generated specifically for this study. To ensure reproducibility of our new data, we completely

rewrote the "Image Processing" section. It now details the exact automated pipeline used, including tiling, non-local means filtering, the application of a Hybrid Hessian filter to capture sublimated boundary grooves, and the physical noise cut-offs applied to extract 2D cross-sectional areas.

Author's Changes in Manuscript: We reorganized and expanded Sections 2.1 through 2.4 to clearly state data origins and provide short overviews of the methods used for previously published data. We extensively rewrote the "Image Processing" paragraph in Section 2.1 to detail the Scikit-Image algorithmic steps utilized to extract the grain boundaries.

(2) Full presentation of the data. I suggest the authors provide all the data generated in this study in supplementary material or linked to a repository. The previously published data are presumably in a repository and should be linked as well. It is possible that I missed those references, but I didn't see any supplementary files.

Author's Response: We agree that making the data and analytical tools accessible important. The Python scripts and processing of the data is already available in Zenodo. All raw xLASM images and processed data have been compiled and we will be hosted at Pangaea.

(3) Multivariate correlation statistical analysis. These data appear strong candidates for a much more robust analysis of correlation among the different metrics. Some reference was made to statistical tests, but the more uniformly the tests are applied, the more confidence given to the interpretations. In addition, I suggest rather than analyzing selected paired datasets, a more comprehensive approach would provide significantly more insight.

Author's Response: We thank you for the suggestion. We incorporated summary statistics (medians, interquartile ranges, standard arithmetic means) to quantify the microstructural shift between the climatic phases.

Author's Changes in Manuscript: We added continuous depth profile summary statistics in Section 4.1 (Grain size and abrupt events). We also updated Section 4.3 (Impurity effects) to explicitly detail our use of Spearman's rank correlation coefficient to evaluate the monotonic relationships between the various impurity concentrations and grain size.

(4) Implications. The Discussion section could be expanded significantly to provide the authors' perspectives on how their findings relate to rheology and paleoclimate interpretations. I am particularly curious to hear how the strain rate variation extrapolates to affect paleoclimate information above and below the transition. For rheology, a broad body of literature has examined the question of influencing factors. The new data contribute to that discussion, and for the contribution to have the most impact, a much more nuanced look is required at the factors involved vis a vis the data themselves. This analysis will rely heavily on the more detailed data presentation and statistical analysis referenced above.

Author's Response: We are very grateful for this feedback, which prompted us to significantly deepen our discussion of the broader implications. For rheology, we have rewritten the text to

explicitly link our quantitative microstructural observations to recent composite flow laws (e.g., Goldsby and Kohlstedt, 2001; Fan et al., 2020). We now note that by applying our continuously measured fine and coarse median grain sizes under estimated NEEM shear stresses, these models accurately predict the empirical borehole strain rate ratio (~1.6) observed across the transition, strongly validating grain size-sensitive (GSS) creep mechanisms. Regarding paleoclimate, we added context explaining how these rheological variations imply that impurity-rich stadial layers undergo enhanced, localized thinning compared to adjacent interstadial ice. Recognizing this strain rate variation is an important consideration for refining depth-age models, interpreting layer thicknesses, and accurately reconstructing paleoclimate chronologies across abrupt transitions.

Author's Changes in Manuscript: We extensively rewrote Section 4.4 (Shear Strain Rate and Ice Dynamics) and Section 5 (Conclusion) to explicitly incorporate composite flow law analysis and the resulting implications for multi-component flow models.

To summarize, the data included here could add valuable information to the ice dynamics field. A more robust treatment of the methods, data, and implications will increase the impact of this work significantly.

Thank you again for the feedback on our manuscript. To increase the impact and robustness of this work, we have thoroughly implemented the methodological and analytical improvements requested. This includes a more rigorous presentation of the image processing pipeline, a more comprehensive statistical treatment of our multivariate datasets, and a substantially expanded discussion that anchors our microstructural observations directly within the context of ice rheology.