REPLY TO REVIEWER 1

Review of Bierman et al., "Scientific history, sampling approach….Camp Century…."

Responses to reviewer comments are in italic below

I enjoyed reading this manuscript. It's an informative paper and provides some important background and context for the ongoing, and potentially future, analyses of the Camp Century subglacial sediment core. It is a little unusual in that significant parts of it are in a narrative style but I think in this case it is entirely justified. For the samples to be most useful their origin and handling need to be absolutely clear and the authors have done a significant service in doing the 'detective work' to track down much of this information. This information will be useful to anyone wanting to work on the material, and I suspect this paper will be their first port of call before starting, and indeed I would expect Figure 8 to be widely cited and reproduced.

Thank you for considering and appreciating the need to document the core and its provenance and handling.

The primary analyses reported (mainly summarised Fig 8) are useful in and of themselves for understand the material and its origins and so there is a clear and original research contribution as well as the documenting of process and history.

The paper is original and within scope of The Cryosphere. Methods are appropriate and results are appropriately discussed with excellent use/citation of previous literature. The abstract is a good summary of the paper. The paper makes a contribution to our understanding of sub-glacial sediment form a near-unique physical archive, and is of broad relevance.

I have provided minor edits on the attached pdf but the text is generally clearly structured, well-written and figures and tables are to a high standard.

Other more discursive queries and comments below:

Line 69 – all of the other four sections in this paragraph explain the purpose of the section, except the first one. So could add clause after 'sub-glacial sediment ', along lines: "..in order to provide clear context and documented handling information for ongoing and future analyses"

This is a good suggestion and we have adopted the proposed wording.

Table 2:

- Formatting probably needs grid lines to line up entries/rows more clearly. At present some of the relationships between entries in different columns are ambiguous without going to Fig 4. (this also applies to Table 3)
- Line 150 - What subtraction error are you referring to? I can see what look like a number of differences between values in Column 3 and Column 4.
- In the table what is the meaning of the apparent reversal in depth of core (column 4) in core tube 1058? Depths in tube 1057 reach 1373.5 and then a sequence of 1374.69 and 1371.92 (i.e. a reversal) before 1373 in tube 1059

We adopted the suggestion to use grid lines for clarity if allowed by the editors – this will need to be checked when the table is laid out in proof. The apparent reversal referred to by reviewer is present in figure 4 and likely is the result of transcription/subtraction errors to which we refer in the ms and about which the reviewer comments. We have clarified the text in response to this comment.

Table 3:

- Please define all the institutional acronyms (final column) in the caption.
- Count 25 – thermal state reads 'Frozen and'. And what ?
- This table could be improved by ordering rows by the sub-sample a,b etc. This would also have benefit of more closely tying it to text and Fig 6.

We defined all acronyms and removed the "and" which was a typo. We disagree about reordering the table believing it is more clear to sort by analysis as is currently done.

Length of core and post-depositional changes

- Line 393 –. The statement on difference of core length between 3.55 and 3.44m is left unexplained or perhaps implicitly might be seen as suggesting an earlier mis-measurement. But I was struck that the difference is only ~3% and visual comparison of the 1972 and 2021 photos suggests that there has been substantial changes to the segments: for example there is much more surface relief, larger surface grooves etc on several of the segments when photographed more recently. I think this raises the possibility that as well as partial thawing noted in the text that there may have been other long-term

changes perhaps caused by sublimation-induced drying out and shrinkage. If so this could explain the 3% difference in length without a measurement error.

This is an interesting and important thought and we added it as a possibility to the paper.

Figure 8

The missing sections (e.g. 1063-3) are displayed in the stratigraphic log with an assigned brown colour when they should be blank.

We made this change.

Magnetostratigraphy

I note that 6 samples were judged to have been stored upside down. Given the comment on development of a viscous remnance during storage (line 472), it would be helpful to see a comment if there is any difference/anomalies in the magnetic measurements for those samples.

We addressed these two comments together:

The 3 samples that may represent genuine reversed polarity internals are 1061-D1, 1061-D3, and 1062-3*, where * indicates samples that were stored upside down. Other samples display negative inclinations at just one AF level, which is likely noise (for example 1063-8), or the trend appears to be shallowing and would likely shift to positive inclination if higher AF demagnetization levels had been applied (for example 1063-4). The following patterns are the basis for suggesting potentially robust reversed polarity:*

- *Sample 1061-D1 shows a near vertical inclination at the NRM step (0 mT), then swings to negative values following AF demagnetization. This is consistent with a viscous overprint in the vertical direction, which could represent either a drilling overprint or a storage overprint, which is removed at the 10 mT AF demagnetization level.*
- *Sample 1062-3* shows shallow positive inclination at the 0 mT level, which becomes progressively more negative at the 10 mT and 20 mT steps. This similarly suggests removal of an overprint in the same sense as 1061-D1.*
- *Sample 1061-D3* displays consistently negative inclinations at the 0, 10, and 20 mT AF levels, suggesting no overprint.*

There is no systematic behavior in the AF demagnetization behavior of the 5 samples that were stored upside down (a 6th sample stored upside down was a pilot sample in Christ et al., 2021 and was not sampled for paleomagnetic work). We observe steepening and shallowing of the inclination in these samples as well as noisy behavior. There are no systematic differences between the samples stored upside down and the rest of the sample set.

We added the following text to end of section 4.4:

"The majority of our samples display positive inclinations, consistent with normal polarity, with the possibility of 3 reversed polarity or excursion intervals in Units 1 and 2 recorded in samples 1061-D1, 1062-3, and 1061-D3. Although the AF demagnetization data are limited, these samples display inclinations that become progressively more negative at higher AF levels, consistent with removal of vertically downward overprint, or inclinations that remain moderately negative at all AF demagnetization levels."

Other analyses

Is there a reason why there is no analytical pathway for microbiology (cf. micro-paleontology). Subglacial biology is of course an area of huge interest and the omission was notable. Was this due to a judgement that the lack of a sterile handling chain over 50 years rules out meaningful or robust analyses on these core samples ? Or another reason? A sentence or two on this might be helpful.

There is a microbiology pathway in table 3 (11,12,15) and in figure 8 (microfossils and pollen) and we are making such analyses including environmental DNA. We clarified this during revision.

Data from Christ et al., 2021 and 2023

Line 537 introduces an age constraint that has not been previously discussed. Given the usefulness and likely reproduction of Figure 8 is it worth adding an annotation to figure or comment in caption on likely age ranges of top and bottom (pilot) samples, taken from Christ et al.

Good suggestion, we implemented in revision.

Future availability of samples

Given the statement in Line 70 on approach to sample distribution I was expecting something explicit towards end about availability of material. Had the authors considered including something, perhaps in code/data availability, on how other

groups might get hold of some of these materials, especially if they can suggest collaborative/novel analyses? Who would they speak to ? Who decides on what happens to the material ? And if not are all these analyses already planned to be undertaken by the institutions noted in final column of Table 3?

This is a useful addition to the ms and we thank the reviewer for suggesting it. We added text explaining that the archive half of the core remains in Copenhagen and will be accessible for those wishing to do further analyses upon application to the ice core facility there and a plan for collaboration with Danish scientists. Similarly, material presently in the US will be sent to the US Ice core facility for preservation and future distribution under similar protocols after current NSF funding ends, that is approval of a sample request proposal and collaboration with US scientists.

All of the analyzed in Table 3 have been or will be completed as part of the NSF-funded project.

We have reviewed the comments made on the PDF by the reviewer. All are minor wording clarification suggestions or inclusion of other hypotheses that we have accepted while revising the ms.

Mike Bentley

22/2/24

REPLY TO REVIEWER 2

The manuscript conveys the scientific history and describe the sampling approach of the Camp Century subglacial sediment core, some sixty years after the core was retrieved. The objective is to provide fundamental observations and provide a core stratigraphy for subsequent analytical work performed on subsamples.

The manuscript is well written, well structured, and with a great level of detail to provide an important backbone for any coming analysis. The authors have done an excellent job in setting up a stratigraphy and strategizing the sampling for future studies. The scientific history of coring endeavors is a great addition, that made reading the manuscript more exciting. From these points, I think the manuscript is ready for publication.

We appreciate the reviewer's enthusiasm for the manuscript.

I have only one minor comment, which regards the readership: The authors are careful to interpret the stratigraphy to only a certain extent and do not provide these interpretations on the Figure 8 (which by the way could do with larger font sizes).

The reviewer is correct. We chose in this ms not to present data/interpretations beyond that gathered during the core cutting and sample allocation process. Although we are now as a team generating such data, their presentation and interpretation will require a series of more focused papers in this same special volume. We thus have remained modest in our interpretations. We will propose to the editors that figure 8 be laid out as a full page in landscape orientation which will make the fonts larger than the current review ms.

Probably for a reason, although I do find the manuscript a little too much of a "cliffhanger" in terms of the next steps with this material. As it is now, the manuscript is seemingly intended for those researchers, who will get to work on the material.

This was not our intent but it is good to know this is how the reviewer perceived the ms. Our intent is to provide fundamental information about the core for a wide variety of readers far into the future, some of whom will be working on the core but many of whom will just want to know about the sub-ice sediment that was never fully described in earlier publications.

I find it a shame, that the authors do not outline some research questions and engage a broader community.

This is an excellent suggestion and when revising the ms, we included just such a set of research questions with the goal of engaging the broader community.

Researching ancient Greenland – using tiny bits of sediment – is quite buzzworthy. Therefore, I would propose a resume of what was found in Christ et al. 2024, in the section 'initial interpretation and paleoenvironment' along with an outline of the most pending research questions that these two papers have now led to (also in context of what is known from other similar type studies).

We have followed the reviewer's suggestion and done this in revision – presenting the findings of Christ et al. 2023 (not 2024) and outlining the most pertinent research questions that sub-ice material can address.

Summarizing what we think we know now, and what is still uncertain, perhaps aided by conceptual figures, would engage a broader readership and could thereby pave the road for novel approaches (both analytical and modeling) that were not initially considered by the authors.

We have, in responding to the comment above, addressed this comment. With half a dozen other papers now in preparation and more to come, we need to limit the reach of this paper so that future authors, most of whom are students, have full ownership of their data.

REPLY TO REVIEWER 3

This paper presents an overview of the scientific history of the Camp Century sub-glacial sediment that was drilled in northwestern Greenland from 1960-1966 CE. It also presents detailed descriptions of the sampling approach, a physical characterization of the sediments, and some scientific data (e.g. paleomagnetic data, pH, and conductivity). In this sense, the paper represents a mix between historical accounts and scientific results. However, I believe this approach is fully justified, and I enjoyed reading the historical accounts of the drilling projects at Camp Century in northwestern Greenland. It is important to document how this rather unique sedimentary archive was retrieved, handled, and stored. The paper is very well written, and the topic is suitable for the journal. Below, I provide a few suggestions and comments that I hope the authors will consider.

Thank you for your thoughts on our work.

General recommendations

The paper provides a detailed description of the sampling approach that was applied to the material available from cores drilled between 1960-1966 CE. Now that the authors have the benefit of hindsight, I wonder if they have any recommendations concerning the processes that preceded their involvement with this material, such as the initial sample treatment, documentation, and storage. This kind of advice could prove useful for future efforts to recover sediment cores beneath ice sheets.

This is a very interesting idea that we had not considered. Thank you for this valuable suggestion. We have added this to our discussion in the paper including the following:

1. *Preserving sediment without light exposure allows it to be dated by luminescence (done at Camp Century, EastGrip, NEEM, but not at GISP2 and Dye3). Documentation (such as percent recovery during drilling) is also important.*
2. *Maintaining detailed and accurate records of transport/storage conditions from time of collection, avoiding contamination impacting future analyses, and considering ways to minimize pest accessibility in collection/storage/transport is key (e.g., a modern carpet beetle made its way into the Camp Century samples over the last 50+ years).*
3. *For biomarkers, drilling and sampling in a way that avoids contaminating both the lipids (considering the use a drilling fluid that doesn't contain hydrocarbons) and the DNA/RNA (i.e., collect in sterile containers, using sterile sampling equipment) – realizing of course limitations of the polar environment although such work has been pioneered in sub-ice Antarctic lakes.*

4. *Perform bulk density measurements – even roughly (by weighting and measuring volume) – will useful at an early stage of the core processing (even feasible in the field, ideally before core cutting).*
5. *We will stress that Camp Century has taught us the importance documenting all post-coring sampling activities and the value of sustained funding and support for ice core storage facilities that make it possible for future researchers to come back to a core many decades later.*

Paleomagnetic data

Upon reading the paper, I felt it would have been appropriate to show the pmag data discussed in section 4.4 on a figure (and not just in table S5). For instance, the NRM (or 20 mT) data could be displayed on a panel in figure 8, but it is also clear that it isn't straightforward to interpret the data, mainly because the inclinations are scattered (the declinations are bound to scatter at this location). On that note, I think it would be useful if the authors could comment on the high degree of scatter – are there any trends related to the type of material or stratigraphic unit? Although the samples may not be equally susceptible to acquiring a viscous overprint, I would not expect this pattern if the NRM is dominated by a viscous overprint from storage at NBI. It would also be informative to know if the scatter tends to decrease after demagnetization, even though demagnetization at 20 mT may not be sufficient to reveal any patterns. Finally, it would be good to know if the pmag data associated with the six core segments that were stratigraphically inverted during storage stand out, or differ, from the remaining data, as would be expected if the viscous overprint was acquired during storage.

I realize that a detailed discussion of the pmag data may be outside the scope of this paper, so I will let the authors decide on how to deal with this.

Reviewer 1 had similar questions regarding any trends in the AF demagnetization data, signatures of storage diagenesis, and whether aberrant behavior was observed in the samples that were stored upside down. In response to those questions, we have added the following text to end of section 4.4:

"The majority of our samples display positive inclinations, consistent with normal polarity, with the possibility of 3 reversed polarity or excursion intervals in Units 1 and 2 recorded in samples 1061-D1, 1062-3, and 1061-D3. Although the AF demagnetization data is limited, these samples display inclinations that become progressively more negative at higher AF levels, consistent with removal of vertically downward overprint, or inclinations that remain moderately negative at all AF demagnetization levels."

Our response to reviewer 1 elaborates on the observations in the 3 samples named above that led to these interpretations. For the sake of space, we do not present a detailed treatment of the paleomagnetic data here, which we believe is controlled more so by the magnetic mineral assemblage than by the ambient magnetic field at the time of sediment deposition. We will address this in a dedicated paper on the rock-magnetic results of the Camp Century core.

Sediment/ice vs. bulk density

At the boundary between Unit 2 and Unit 3, the composition of the core material changes from ice-dominated (~80% ice) to sediment-dominated (~20% ice). This abrupt transition is not clearly reflected in the bulk density, which shows a very gradual change towards higher density. Why this gradual change in bulk density? Is it due to different sample resolutions associated with the sediment/ice versus bulk density measurements? Please comment on this.

This apparent discrepancy between density and ice content is mainly due to a sub-sampling approach to measure the ice proportion, while the bulk density was done on longer full ice cylinders, at lower resolution. Moreover, the contact between Unit 2 and 3 is not horizontal but tilted; several cobbles are also embedded in the top of unit 3. We can make the log more accurate by drawing an angular and more discontinuous contact here and will clarify this difference in the text.

Changes in conductivity and pH

Lines 482-490 describe changes in pH and conductivity (Fig. 8H). The details of this plot may not be the focus of this paper, but I'm curious about the variability in these parameters – particularly those that differ from the trend described in the text (e.g. line 485: "pH is a mirror image of the bulk density profile"). In this context, I wonder why the pH is low in the bottom and upper parts of Unit 2 (it is similar to the pH of Units 3-5), which are dominated by ice (~80% ice). Also, I wonder why the conductivity is high in the upper part of Unit 1, which is explained by a high percentage of fine grans (line 484). However, similar amounts of fine grains are found both below (e.g. 1063-5) and above (e.g. 1060-c2), where the conductivity is considerably lower. I guess the conductivity is controlled by the amount of dissolved ions, but does that correlate with grain size (I guess it might)? Any comments on this?

This comment caused us to think more about the patterns of pH and conductivity with depth and the correlation of these parameters with other measures including the percentage of fine grain material. In making such comparisons, it's important to consider unit two is predominately water and that the other four units are predominately soil; thus, the controls on pH and conductivity likely differ between the units. Regression analysis shows no significant correlation between any combination of conductivity, pH, and grain size but distinct clustering; for example, the graph to the left shows that the till (unit 1) has little variance in pH but large variance in conductivity. The former likely the result of soil buffering and the latter possibly the result of soil/water interaction and the competing processes of dilution by meteoric waters and the chemical weathering of the soil. In contrast, unit 2 (the ice) has consistently low conductivity but a wide variance in pH, likely the result of low buffering capacity and the lack of sediment grains to provide ions that would increase conductivity. In revision, we have considered these relations and revisited the text adding a graphic like the one provided here.

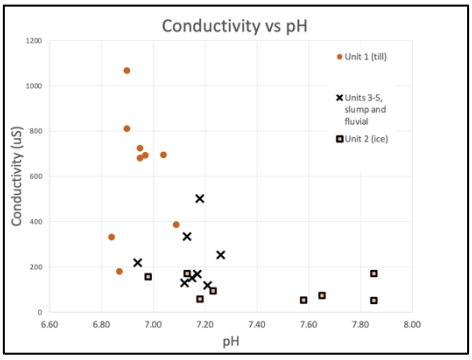

Figure 5

Nice and informative figure. However, it is not clear to me what the authors mean by "Geochronometry" in the table. Luminescence and cosmogenic nuclides are mentioned elsewhere – do you the authors have some specific dating methods in mind?

Size fractions of this materials are being used for measuring a variety of geochronologic measurements including U/Th/He and solid state measurements by ICP- LA-MA including Pb. We elaborated in the caption.

Future availability of material

It would be good to include a statement towards the end on the future availability of material – and how this process is expected to work. Also, I'm curious about what it will take to make the archive half available for analysis (who will decide this?).

This point has been noted by other reviewers and is addressed in revision. In summary, left over material in the US will be accessed per US ICF protocol and the material in Denmark will be administered by Danish protocol.

Line 569: Guess "JP Stephenson" should be "JP Steffensen".

Thank you, spelling corrected.

Line 581: “…has declares…”. Perhaps “has declared”?

Thank you, grammar corrected.