Author's response to reviews:

Cosmogenic nuclide exposure age scatter in McMurdo Sound, Antarctica records Pleistocene glacial history and processes

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Responses to comments are show in *italic font.* Changes made in the text are shown in *red italic font.* Line numbers all refer to the clean, non-track changes version of the revised manuscript.

Response to editor comments:

Dear Authors,

Thanks for submitting the revised manuscript along with the detailed responses to the critical comments suggested by two expert reviewers.
As you know, the two reviewers provided two important comments such as nucleogenic (or inherited) 3He production and Interpretation of MIS-8 Ross Sea Drift.
I found the first concern is now clearly corrected and explained in the revision. The second concern was well defended but needs more explanation in the revised manuscript.
Specifically, any influence on the interpretation of the apparent ages by "surface erosion (actually weathering) rate of the sampled boulder surface. Definitely it should yield older ages. I know the correction for erosion rate is not straightforward but the readers would expect at least the possible explanation.

Response: *We have addressed this in the discussion section about the Upper Discovery deposit. Specifically, we explain that the particular granite boulder that was sampled had a cavernous weathering pit indicating that this sample was weathering leading to a loss of the cosmogenic ^{10}Be inventory. When a Antarctica specific erosion rate of 0.13 mm/kyr is applied to this granite sample, the erosion-corrected age is (147 ka). When a dolerite specific erosion rate is applied (0.19 mm/kyr), the dolerite exposure ages of the same deposit are still much older (226 – 356 ka). We are hesitant to calibrate the ^{10}Be exposure age of this single boulder based on an erosion rate that is apparently much higher than the regional average.*

In the clean version of the revised manuscript we have added the following (lines 404-410):

"Even if lithology-specific boulder erosion rates for granite (13 mm kyr^{-1}) and dolerite (19 mm kyr^{-1}) (Marrero et al., 2018) in Antarctica are considered, the difference between the exposure ages of the granite boulder (147 ka) and the dolerite boulders (~226-356 ka) is too much to be explained by the difference in erosion rates between lithologies. This suggests that this particular granite boulder was weathering much faster than regional average rates or it may have been affected by post-depositional movement. Additional exposure age constraints from the Upper Discovery deposit as well as other higher elevation Pre-LGM glacial sediments in the McMurdo Sound region will further test if a glacial high-stand occurred during MIS 8."

Other minor comments and technical corrections are well modified.

I would add some minor comments/corrections below, which I would like you to incorporate the final version of the manuscript.
- Fig. 2, "Trans Antarctic Mountains": Could you upside down it just like other characters?

Response: *Fixed as you suggested*

- The revision still does not provide “production rate of 3He and 10Be”. Which number did you use, global or local (Antarctic)? Please provide specific number (e.g. 4.3 atoms/gyr).

Response: *We added these details in the methods section: global ^{3}He production rate (120 ± 9.4 atom g^{-1} yr^{-1}) (Goehring et al., 2010) [line 185] and global ^{10}Be production rate (4.15 atoms g^{-1} yr^{-1}) (Martin et al., 2017) [line 198].*

- Local LGM: The present study suggests a local LGM occurred at 19.6-12.3 ka, based on 14 ages of fossil algae embedded in Ross Sea Drift. I think the present conclusion assumes that the dated RSD is the terminal or latero-frontal moraine which marks the most extensive position of the glacier system. Considering the extensive characteristic of glacier ice during LGM (simply glaciation peak), the ice may have been a unified body particularly in the low elevations where the RSD is found.
Is there any possibility that the RSD can be a recessional or retarded lateral moraine? It is interesting that the local LGM at Terra Nova Bay (only ~100 km north) occurred during “MIS 4”, not during MIS 2 (Rhee et al., QSR, 2019. Timing of the local last glacial maximum in Terra Nova Bay, Antarctica defined by cosmogenic dating).

Response: *The timing of the local LGM in McMurdo Sound is based on 237 calibrated radiocarbon ages from the maximum limit of Ross Sea drift on the volcanic islands and peninsulas of McMurdo Sound (Christ & Bierman, 2020) as well as headland moraines in the ice-free valleys of the Royal Society Range (Hall et al., 2015; Jackson et al., 2018; Hall et al., 2001). The lower elevations of Ross Sea drift could indeed be part of a recessional moraine deposited as the grounded ice sheet thinned and retreated. In this manuscript we are only examining exposure age samples that were collected from the maximum limit of the ice sheet, so we think that our interpretations remain consistent with the glacial geomorphology of the area. The timing of the local LGM from radiocarbon ages of glacio-fluvial and glaciolucustrine deposits along the former ice margin agree well with glacial marine sediment age constraints that show the transition from grounded ice to either a floating ice shelf or seasonally open marine conditions after 8 ka just north of Ross Island.*

Thanks for directing me towards Rhee’s 2019 paper.

I recommend “Publish after some minor revisions".

Associate Editor,
Yeong Bae Seong.

Thanks so much Dr. Seong. You may not remember this, but I collected my very first cosmogenic nuclide sample with you on a small ice-free bedrock surface on the Danco Coast in the Antarctic Peninsula while we were aboard the ARAON in spring of 2013. Thanks for being my first teacher in cosmogenic nuclide field methods nearly a decade ago!

AUTHOR RESPONSE TO REVIEWER COMMENT #1

Cosmogenic nuclide exposure age scatter in McMurdo Sound, Antarctica records Pleistocene glacial history and processes

Andrew J. Christ, Paul R. Bierman, Jennifer L. Lamp, Joerg M. Schaefer, and Gisela Winckler

Author responses are recorded in italics below reviewer comments.

General Comments:

In this paper, Christ et al. present a new surface-exposure dataset from the McMurdo Sound region of the Ross Sea in Antarctica. Although the high prevalence of inherited cosmogenic nuclides in local sediments makes surface-exposure dating in the region a challenge, here the authors use a nearby radiocarbon chronology to benchmark their data and to enable direct comparison of their apparent exposure ages with the timing of the local Last Glacial Maximum (LGM). They also recalculate exposure ages from previously published studies to enable a synoptic view of regional exposure ages and inheritance.

Their results indicate that although inheritance is indeed pervasive in the sampled glacial sediments, the ultimate pattern of exposure-age scatter is in part dictated by lithology and associated transport history. For example, clasts derived from subglacial sources appear to best reflect the timing of local deglaciation. In contrast, clasts sourced from areas above glacial trimlines produce exposure ages suggestive of possible nuclide inheritance. Following this analysis, Christ et al. assess potential longer-term (pre-LGM) patterns of glaciation in McMurdo Sound. They suggest that the pre-LGM Discovery drift unit was deposited during MIS8, highlighting the utility of surface-exposure dating to investigate surface processes and landscape evolution through time.

This paper illustrates an excellent application of larger exposure-age datasets. It is well written and well presented, and I appreciate their thoughtful discussion of how different sediment sources with unique histories may impact surface-exposure chronologies. There are a few areas where I think the authors need to add additional detail or justification for their methods and interpretations. I also have one larger comment centred on their discussion of 3He ages from local dolerite. I detail these comments below, as well as a few technical comments/corrections.

Response to general comments*: Thank you very much for your well-stated summary of work and thoughtful comments. We will address your general comments about our methods and interpretations, and specific comments about* $^{3}He_{pyroxene}$ *ages below.*

Specific Comments:

The authors note that Ross Sea drift pyroxene 3He ages predate nearby quartz 10Be ages by 14-32 kyr (line 384). They assign this offset to differing mechanisms of clast transport and deposition and suggest that the age offset may be explained by 'inherited' cosmogenic 3He. Previous studies show that Ferrar Dolerite pyroxenes contain non-zero amounts of non-cosmogenic 3He (see Ackert, 2000; Margerison et al., 2005; Kaplan et al., 2017; Balter-Kennedy et al., 2020). This amount is generally around 5-7 x 10^6 at/g, and so significant over the timescales of interest here. In particular, this amount could account for some or all of the apparent offset between the Ross Sea drift 10Be and 3He ages. This could lessen the need for a depositional mechanism in this case. If the authors have a 'shielded' piece of Ferrar Dolerite on hand from their field site they could measure this non-cosmogenic amount directly. Alternatively, they could assume a non-cosmogenic concentration roughly in line with that measured elsewhere. Or if they have reason to think that non-cosmogenic 3He is not present within their samples they should make that clear within their discussion and interpretations. In any case, I would encourage the authors to discuss this point within their text.

Response: *Thank you for pointing out the need for a nucleogenic* $^{3}He_{pyx}$ *correction. In the submitted version of the manuscript we did not apply this correction. Unfortunately, we did not collect "shielded" Ferrar Dolerite samples to directly measure the non-cosmogenic* ^{3}He *contribution at our field site. We recalculated the dolerite exposure* *ages using the correction of 3.3E+06 atoms/g reported by Balter-Kennedy et al. (2020), as well as the 5E6 to 7E6 at/g correction that you suggest. These corrections decrease the $^{3}He_{pyx}$ exposure ages of dolerite samples in Ross Sea drift by ~12.6 kyr (3.3E6 at/g correction), 19 kyr (5E6 at/g correction), and ~26 kyr (7E6 at/g correction). See the table below for a comparison of the non-correct and corrected ages (using the LSDn scaling scheme) below. Regardless of the correction, nearly all of the exposure ages of dolerite in Ross Sea drift are older than the timing of the local LGM, indicating that our original observation about inherited nuclide inventories in dolerite clasts remains valid. This sensitivity test suggests that the 7E6 at/g correction is likely too much for these samples, as it produces an apparent exposure age that appears modern (ACX-13-08: 161 yrs). This would be the only sample in the entire dataset (regardless of lithology or nuclide) to generate such a young age. The 5E6 at/g correction produces an apparent exposure age for this sample that is plausible but still too young (7.7 ka). The 3.3E6 at/g correction produces an exposure age (14.3 ka) that corresponds to the timing of the local LGM in McMurdo Sound. In the manuscript. We will report exposure ages using the 3.3E6 at/g nucleogenic correction reported by Balter-Kennedy et al., 2020 as this is the most up-to-date value used in the Antarctic cosmogenic nuclide community and produces exposure ages that are more plausible than higher correction values.*

In the revised manuscript we will include the information about the $^{3}He_{pyx}$ nucleogenic correction in the methods section and cite the papers (Ackert, 2000; Balter-Kennedy et al., 2020; Kaplan et al., 2017) you have kindly supplied.

Sample name	No nucleogenic correction	3.3E6 at/g nucleogenic correction		5E6 at/g nucleogenic correction		7E6 at/g nucleogenic correction	
	Age (yr)	Age (yr)	Difference	Age (yr)	Difference	Age (yr)	Difference
ACX_13_008	26,978	14,300	-12,678	7,752	-19,226	161	-26,817
ACX_13_009	44,503	31,938	-12,565	25,407	-19,096	17,722	-26,781
ACX_13_012	42,320	29,565	-12,755	23,014	-19,306	15,307	-27,013
ACX_13_048	255,752	245,901	-9,851	240,827	-14,925	234,857	-20,895
ACX_13_052	239,440	229,235	-10,205	224,133	-15,307	218,130	-21,310
ACX_13_061	357,598	347,931	-9,667	341,487	-16,111	335,043	-22,555
ACX_13_068	242,780	232,358	-10,422	226,990	-15,790	220,674	-22,106
ACX_14_005	376,717	361,628	-15,089	353,854	-22,863	344,709	-32,008
ACX_14_015	52,310	35,999	-16,311	27,519	-24,791	17,543	-34,767

Changes in text: Line 179-181: We subtracted a non-nucleogenic ^{3}He correction of 3.3 x 10^{6} atoms g^{-1} (Balter-Kennedy et al., 2020) to all ^{3}He measurements, as this is the most up-to-date correction measurement and higher correction values (5 - 7 x 10^{6} atoms g^{-1}) generate some exposure ages that produce modern exposure ages that are unreasonably young.

The authors use the "LSDn" scaling scheme for their exposure age calculations. While I see no problem with this they should include a few lines to justify this choice. Why is "LSDn" preferable for this location or time period versus an alternative scheme? If the authors chose an alternative scheme, would their interpretations change? For example, would samples still fall within the proposed MIS8 window using an alternative scaling scheme such as "St"? Or would younger samples still correlate with radiocarbon ages of Ross Sea drift? As the "LSDn" scheme can produce higher production rates relative to alternative schemes such as "St" or "Lm", justifying their choice of scheme here is key.

Response: *Thanks for bringing attention to this, we recognize that we should have clarified our decision about the scaling scheme. We employed the LSDn scaling scheme, which is time dependent, because the compiled dataset spans a wide timescale over the past 500 kyr. As you have suggested, we applied the LSDn, Lm ,and St scaling schemes for sensitivity testing on the exposure age dataset. Regardless of the scaling scheme applied, we still observe the same trends according to nuclide and lithology. The LSDn scheme indeed produces younger exposure* *ages than St or Lm, but the difference is usually less than 1 kyr for samples with exposure ages <50 ka. None of the samples younger than 20 ka in McMurdo Sound have differences greater than 880 yr; this means our interpretations about the exposure age scatter relative to the radiocarbon constrained timing of the local LGM are not affected. The exposure age difference between scaling schemes becomes greater for older samples, but again does not affect our interpretations even for samples from Mount Discovery that correspond to MIS 8. As we revise the paper, we will include these details about the scaling scheme sensitivity testing.*

Change in text: Line 184-189: "We employed the LSDn scaling scheme, which is time dependent, because the compiled dataset spans a wide timescale over the past 500 kyr. We note that exposure ages using the St or Lm scaling schemes generate slightly older exposure ages, but do not change observed patterns in the wider dataset."

Related to the above, although the authors note their chosen scaling scheme I was unable to find any discussion of the nuclide production rates used for exposure age calculations. As they use the online calculator [hess.ess.washington.edu] I assume this means that they utilise the standard/default 'global' production rates provided, but this should be clarified.

Response: *You are correct that we mistakenly omitted explaining the production rate used in our calculations. We used the global production rates supplied by the online calculator. We will clarify this in the revised manuscript.*

In addition, what atmospheric model is used for exposure-age calculation? I presume they used the Antarctic 'ANT' standard of Stone (2000), but it is best to list all calculation parameters to ensure reproducibility.

Response: *Yes – thanks for calling attention to this. We did use the ANT standard of Stone 2000. We will include this detail in the revised manuscript.*

Change in text line 181-185 relevant to the two comments above:" ^{3}He in pyroxene ($^3He_{pyx}$) exposure ages were calculated using Version 3 of the online exposure age calculator hosted by the University of Washington (https://hess.ess.washington.edu/) (Balco et al., 2008) assuming density of 2.9 g·cm^{-3}, corrected for shielding and thickness, the Antarctica-specific atmospheric model (ANT) (Stone, 2000), the global ^{3}He production rate (120 ± 9.4 atom g^{-1} yr^{-1}) (Goehring et al., 2010), and used the LSDn scaling scheme (Lifton et al., 2014)."

Figure 5 is an excellent visual synopsis of the data, but would it be possible to indicate which samples come from each lithology? Perhaps using additional colours or shapes? As lithology is such a central component of the overall discussion I think including this element would be very useful for the reader.

Response: *Great suggestion – we will change the symbology to different shapes to show different lithologies. We revised Figure 5 to show target nuclide and lithology as different symbol shapes and used different colored symbols for Ross Sea drift (yellow), pre-LGM deposits (orange), and the Upper Discovery deposit (purple). See new figure below.*

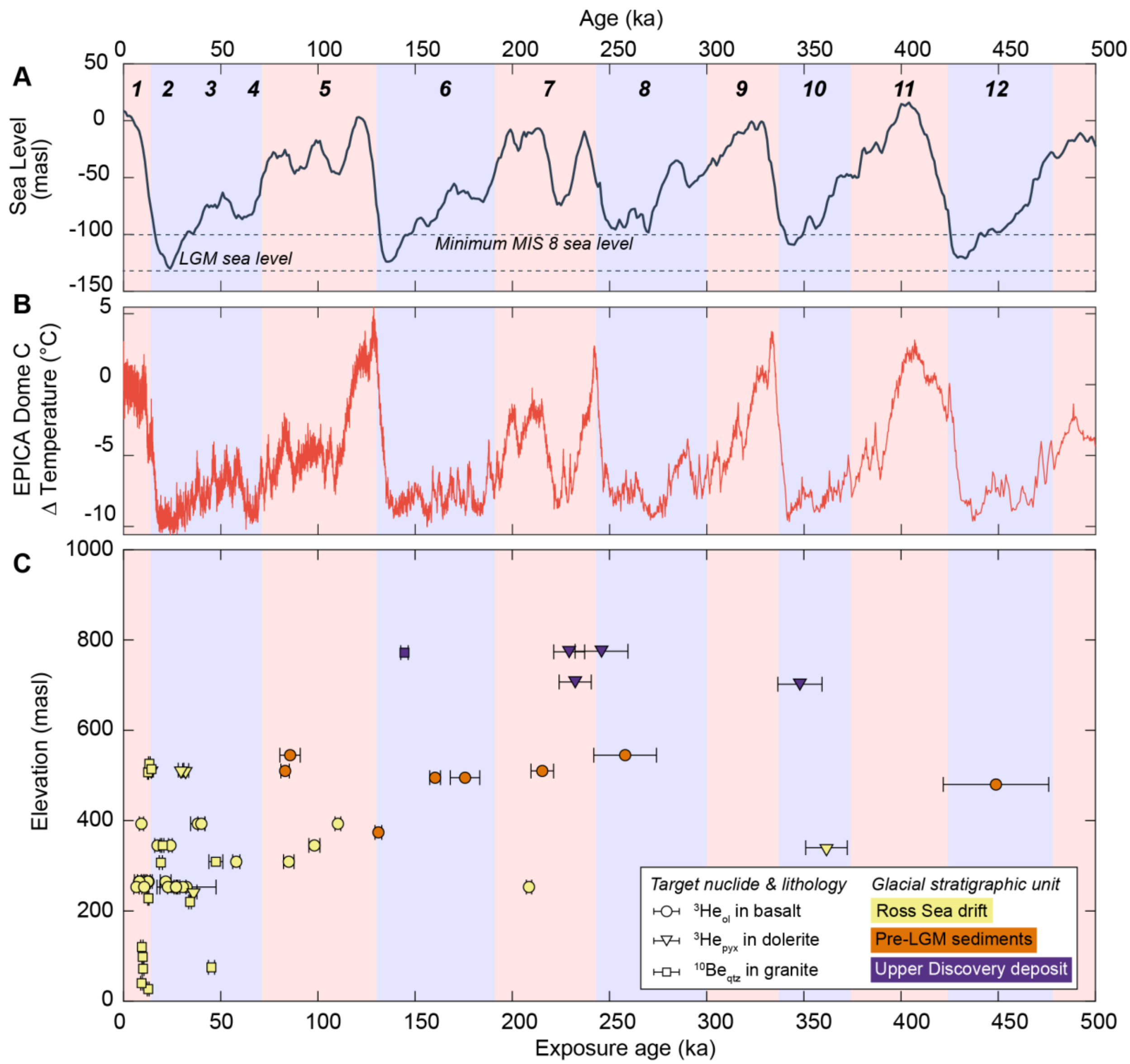


Figure 5 also highlights my concern with the second major argument of the paper, that the Discovery drift unit dates to MIS8. As the authors note, while there is no existing evidence which contradicts this hypothesis, there is also no geomorphic or geologic data elsewhere which directly supports it (beyond their three new dates). As presented, there are three 3He pyroxene samples that cluster in age near the end of MIS8. A fourth pyroxene sample is roughly 100 kyr too 'old', and the authors disregard the 'young' age of an eroding granite boulder. As the authors note, drifts often incorporate clasts with ages apparently 'old', but there is no argument made as to why these three ages should be taken as 'correct'.

To be clear, I am not suggesting that the Discovery drift is *not* MIS8 in age, but I do not think the authors have enough evidence to make the claim quite as they do. I would suggest that the authors soften their language on this point, and perhaps highlight the very exciting implications - and potential future research avenues - engendered by this possibility. The way they phrase these ideas in the conclusions section is a bit less definite, and is I think more appropriate in tone.

Response: *We agree that we can soften our tone about the MIS 8 age of the Upper Discovery Deposit given the small number of ages (n=3) that correspond to this glacial period and scatter of the other ages. We also agree with* *your suggestion to reframe this section of the discussion to highlight the implications and future research avenues that this data presents.*

Changes to text lines 408-412: "Additional exposure age constraints from the Upper Discovery deposit as well as other higher elevation Pre-LGM glacial sediments in the McMurdo Sound region will further test if a glacial high-stand occurred during MIS 8.

While our current dataset is limited by the low number of samples and exposure age scatter, maximum ice sheet expansion during the end of MIS 8 is compatible with other Pleistocene glacial records from the McMurdo Sound region."

In lines 418-19 the authors note that increased accumulation due to atmospheric warming coupled with reduced ocean forcing may provide an explanation for more extensive glaciation during MIS8. It would bolster their mechanistic argument to highlight potential parallels between this scenario and similar proposed for the LGM (such as by Hall et al., 2015, which they cite elsewhere).

Response: *Good suggestion – we will include this citation in this portion of the discussion.*

Lines 438-441: "It is possible that warmer Antarctic temperatures increased accumulation, and reduced ocean forcing supported a thicker marine ice sheet in the western Ross Sea at the end of MIS 8, similar to the mechanism proposed for the persistence of grounded ice during the last glacial termination (Hall et al., 2015)."

Technical Corrections:

In the methods section the authors note that all ages were calculated using "...Version 3 of the online exposure age calculator hosted by the University of Washington (http://hess.ess.washington.edu) (Balco et al., 2008)...". However in certain data table captions the authors state that ages were calculated using "...the CRONUS online calculator v3 with LSDn scaling scheme…". Either is fine, but these should be consistent.

Response: *Fixed throughout manuscript and tables.*

The second sentence of the caption for Figure 2 appears to be missing words?

Response: *Good catch – we will fix this.*

Line 134-135: The number of calibrated radiocarbon ages of Ross Sea drift are shown in green boxes (Christ and Bierman, 2020; Hall et al., 2015; Hall and Denton, 2000; Jackson et al., 2018).

Lines 174 and 188 - A missing word: "Updated exposure ages for all samples were calculated version 3 of the online…"

Response: *Good catch. We will revise to "Updated exposure ages for all samples were calculated using version 3 of the online…*

References:

Ackert Jr, R.P., 2000. *Antarctic Glacial Chronology: New constraints from surface exposure dating*. MASSACHUSETTS INST OF TECH CAMBRIDGE. PhD thesis.

Balter-Kennedy, A., Bromley, G., Balco, G., Thomas, H. and Jackson, M.S., 2020. A 14.5-million-year record of East Antarctic Ice Sheet fluctuations from the central Transantarctic Mountains, constrained with cosmogenic 3 He, 10 Be, 21 Ne, and 26 Al. *The Cryosphere* 14(8), pp.2647-2672.

Hall, B.L., Denton, G.H., Heath, S.L., Jackson, M.S. and Koffman, T.N., 2015. Accumulation and marine forcing of ice dynamics in the western Ross Sea during the last deglaciation. *Nature Geoscience* 8(8), pp.625-628.

Kaplan, M.R., Licht, K.J., Winckler, G., Schaefer, J.M., Bader, N., Mathieson, C., Roberts, M., Kassab, C.M., Schwartz, R. and Graly, J.A., 2017. Middle to Late Pleistocene stability of the central East Antarctic Ice Sheet at the head of Law Glacier. *Geology* 45(11), pp.963-966.

Margerison, H.R., Phillips, W.M., Stuart, F.M. and Sugden, D.E., 2005. Cosmogenic 3He concentrations in ancient flood deposits from the Coombs Hills, northern Dry Valleys, East Antarctica: interpreting exposure ages and erosion rates. *Earth and Planetary Science Letters* 230(1-2), pp.163-175.

Thanks for your thoughtful and constructive comments – we appreciate it!

Author responses to reviewer comment #2

Cosmogenic nuclide exposure age scatter in McMurdo Sound, Antarctica records Pleistocene glacial history and processes

Andrew J. Christ, Paul R. Bierman, Jennifer L. Lamp, Joerg M. Schaefer, and Gisela Winckler

Author responses are recorded in italics below reviewer comments.

General Comments:

This paper suggests something very interesting, a moraine from MIS8 in the Ross Sea Region would be a substantial find. However, as the manuscript stands I don't think that the data set presented is robust enough to make this claim. The authors could talk about the possibility of a MIS8 landform, but simply put they need more data from this landform. By toning down the rhetoric and qualifying their statements they could give their work the amount of discussion and speculation as supported by their small, albeit important dataset (n=3). I think this would strengthen the paper and make it clear that this needs to be a target of further research.

Response: *We agree that the potential MIS 8 glacial deposit on Mount Discovery is indeed an exciting find but understand that we should report this with greater caution given the small number of samples from this limit. We will adjust our discussion of this finding with a softer tone. Hopefully, by softening our discussion of the Upper Discovery deposit, will also help to highlight that the primary contribution of this manuscript (in our view) is the exploration of nuclide scatter in a glacial deposit with an independently known age. We removed mention of MIS 8 in the abstract and made clear the caveats about this interpretation in the discussion section.*

Line 26-28: "With the magnitude and geological processes contributing to age scatter in mind, we examine exposure ages of older glacial sediments deposited by the most extensive ice sheet to inundate McMurdo Sound during the Pleistocene."

Line 411-412: "While our current dataset is limited by the low number of samples and exposure age scatter, maximum ice sheet expansion during the end of MIS 8 is compatible with other Pleistocene glacial records from the McMurdo Sound region."

Lines 454-456: Although the small number of samples as well as prior exposure and boulder erosion limits a precise age of such older deposits, it may be rare geologic evidence of Antarctic ice sheet volume during MIS 8, a glacial period marked by generally warmer Antarctic temperature and higher global sea level.

Additionally, the authors do not discuss correction for nucleogenic ^{3}He production via geologic processes. This could be a reason for the systematically older ^{3}He ages. If this is the case then their data set might settle on specific age ranges for their respective landforms, regardless of rock type. Furthermore, the overarching statements about all of one rock type consistently having a previous exposure history seems to be a bit of a stretch. The distribution of bedrock is hard to know under the ice sheet however, some seemingly omnipresent rock units in the area must have bedrock cropping out under the ice sheet (e.g. Beacon Sandstone and Ferrar Dolorite). I feel it is important to think about the volumes of sediment flux here. The total amount of exposed bedrock next to an outlet glacier like Byrd Glacier is very small compared to the whole catchment (~1,000,000 km^{2}). Simply put, are the relatively small nunataks areas shedding enough material to totally flood the depositional landforms with sediment that has a complex exposure history? The outlet glacier systems mentioned in the manuscript which impinge on the Southern Dry Valleys at the LGM (Byrd, Mullock, and Skelton) are connected to the EAIS, I think it is reasonable to assume that most of the sediment will be derived from subglacial processes happening in different portions of the polythermal outlet glaciers in both current and extended ice sheet configurations. A good dataset to juxtapose the sediment recycling idea against is Tucker Glacier in Northern Victoria Land. Tucker is not connected to the EAIS and has a restricted sediment supply with presumably large amounts of clast recycling or supraglacial input from the Admiralty Mountains to the north and the Victory Mountains to the south (Balco et al., 2019 and Goehring et al., 2019). It could be worthwhile to run the samples from this area for a second nuclide to comprehensively evaluate if they have a complex exposure history before you make the claim that they do. I recognize that further analysis presents more work but, it could answer some of the questions around complex exposure histories.

Response: *Thanks for introducing the ideas about glacier catchment area and sediment flux. Indeed, the vast majority of Antarctica's geology is concealed beneath the present ice sheet, but the supraglacial debris sources should be considered as well. The presence of extremely old exposure ages in Ross Sea drift suggests that even if clasts are originally sourced from subglacial sources, many have been exposed during previous glacial low-stands, incorporated by cold-based ice, and/or incompletely eroded. Or, as you point out, some samples may have been recycled by repeated ice sheet expansions and retreats over time. In the revised manuscript we will explain this nuance better. Thanks for the suggestion to read the recent work from Tucker Glacier. While running additional nuclide analyses would certainly reveal information about clast exposure-burial history, it is no longer possible due to lack of funding and COVID constraints. However, we will add in the discussion that analyzing multiple nuclides on these samples is an important strategy for future sampling campaigns.*

Lines 342-346: Ferrar Dolerite bedrock is likely present below many outlet glaciers draining the EAIS and tributary alpine glaciers in the Transantarctic Mountains. Presumably dolerite clasts are also sub-glacially plucked and entrained into over-riding ice, which would generate exposure ages that reliably record clast emplacement on moraines. However, it appears that many clasts in Ross Sea drift have older than expected exposure ages that indicate a complex exposure history and nuclide inheritance.

I am extremely interested to see how this manuscript changes. I think there is some valuable observations here, but they need to be given proper context.

Many thanks,

Dr. Ross Whitmore

Response: Thanks so much for your thoughtful and detailed comments about our work.

Specific Comments:

- You are not working in McMurdo Sound you are working on the exposed bedrock around the sound. You could say the McMurdo Sound Region or the Southern McMurdo Dry Valleys.

Response: *We will change our phrasing to "McMurdo Sound region" throughout the manuscript.*

Changed at multiple locations across manuscript.

- Please consider the role of nucleogenic ^{3}He in the rocks when recalculating your results.
    - *Response: Thank you for pointing out the need for a nucleogenic ^{3}He correction. In the submitted version of the manuscript we did not apply this correction. We recalculated the dolerite exposure ages using the correction of 3.3E+06 atoms/g reported by Balter-Kennedy et al. (2020), as well as the 5E6 to 7E6 at/g correction reported in earlier papers from Antarctica (Ackert,2000; Kaplan et al., 2017; Margerison et al., 2004) . These corrections decrease the $^{3}He_{pyx}$ exposure ages of dolerite samples in Ross Sea drift by ~12.6 kyr (3.3E6 at/g correction), 19 kyr (5E6 at/g correction), and ~26 kyr (7E6 at/g correction). See the table below for a comparison of the non-correct and corrected ages (using the LSDn scaling scheme) below. Regardless of the correction, nearly all of the exposure ages of dolerite in Ross Sea drift are older than the timing of the local LGM, indicating that our original observation about inherited nuclide inventories in dolerite clasts remains valid. This sensitivity test suggests that the 7E6 at/g correction is likely too much for these samples, as it produces an apparent exposure age that appears modern (ACX-13-08: 161 yrs). This would be the only sample in the entire dataset (regardless of lithology or nuclide) to generate such a young age. The 5E6 at/g correction produces an apparent exposure age for this sample that is plausible but still too young (7.7 ka). The 3.3E6 at/g correction produces an exposure age (14.3 ka) that corresponds to the timing of the local LGM in McMurdo Sound. In the revised manuscript we will include the information about the nucleogenic correction in the methods section and cite papers relevant to nucleogenic ^{3}He in pyroxene (Ackert, 2000; Balter-Kennedy et al., 2020; Kaplan et al., 2017) you have kindly supplied. We will report exposure ages using the 3.3E6 at/g nucleogenic correction reported by Balter-Kennedy et al., 2020 as this is the*

most up-to-date value used in the Antarctic cosmogenic nuclide community and produces exposure ages that are more plausible than higher correction values.

Sample name	*No nucleogenic correction*	*3.3E6 at/g nucleogenic correction*		*5E6 at/g nucleogenic correction*		*7E6 at/g nucleogenic correction*	
	Age (yr)	*Age (yr)*	*Difference*	*Age (yr)*	*Difference*	*Age (yr)*	*Difference*
ACX_13_008	*26,978*	*14,300*	*-12,678*	*7,752*	*-19,226*	*161*	*-26,817*
ACX_13_009	*44,503*	*31,938*	*-12,565*	*25,407*	*-19,096*	*17,722*	*-26,781*
ACX_13_012	*42,320*	*29,565*	*-12,755*	*23,014*	*-19,306*	*15,307*	*-27,013*
ACX_13_048	*255,752*	*245,901*	*-9,851*	*240,827*	*-14,925*	*234,857*	*-20,895*
ACX_13_052	*239,440*	*229,235*	*-10,205*	*224,133*	*-15,307*	*218,130*	*-21,310*
ACX_13_061	*357,598*	*347,931*	*-9,667*	*341,487*	*-16,111*	*335,043*	*-22,555*
ACX_13_068	*242,780*	*232,358*	*-10,422*	*226,990*	*-15,790*	*220,674*	*-22,106*
ACX_14_005	*376,717*	*361,628*	*-15,089*	*353,854*	*-22,863*	*344,709*	*-32,008*
ACX_14_015	*52,310*	*35,999*	*-16,311*	*27,519*	*-24,791*	*17,543*	*-34,767*

Changes in text: Line 179-181: We subtracted a non-nucleogenic ^{3}He correction of 3.3 x 10^6 atoms g^{-1} (Balter-Kennedy et al., 2020) to all ^{3}He measurements, as this is the most up-to-date correction measurement and higher correction values (5 - 7 x 10^6 atoms g^{-1}) generate some exposure ages that produce modern exposure ages that are unreasonably young.

- Please tone down the rhetoric and qualify your statements for the potential MIS8 landform. This is a good target for robust work to demonstrate that the landform is of a consistent age from east to west and across its apparent age range.
    - ***Response:*** *We will soften the tone about the certainty of the MIS 8-age of this moraine. We agree it's important to highlight that the exposure ages support that this limit / landform has a consistent age from east to west.*

Changes in text lines 389-396: The Upper Discovery deposit marks the maximum limit of glaciation of McMurdo Sound. The decreasing elevation of the Upper Discovery limit around Mount Discovery from 776 m in the east to ~450 m in the west suggests a larger ice sheet in the Ross Sea overflowed into McMurdo Sound during a glacial period prior to the local LGM. As there are no erratic lithologies present above this limit, the Upper Discovery deposit delineates the largest and thickest ice sheet in the western Ross Sea to inundate McMurdo Sound since Mount Discovery formed 5.5 to 4.5 Ma (Kyle, 1990).

Taking into consideration exposure age scatter, nuclide inheritance, and the few exposure ages available in our dataset, it is possible that the Upper Discovery deposit dates to glacial Termination III at the transition from the late MIS 8 glacial period to the early MIS 7 interglacial period.

- Some discussion about how sampling proceeded and what type of material was collected would be useful. E.g. when working on a glacial dip stick samples are selected based on morphology and position in the landscape. While clast morphology is not a panacea to filter anomalously young or old erratics it is a good general principal to guide in sample selection.
    - Response: In section 3.2 (lines 154-162) we have reported our sampling strategy for this study as you suggest.

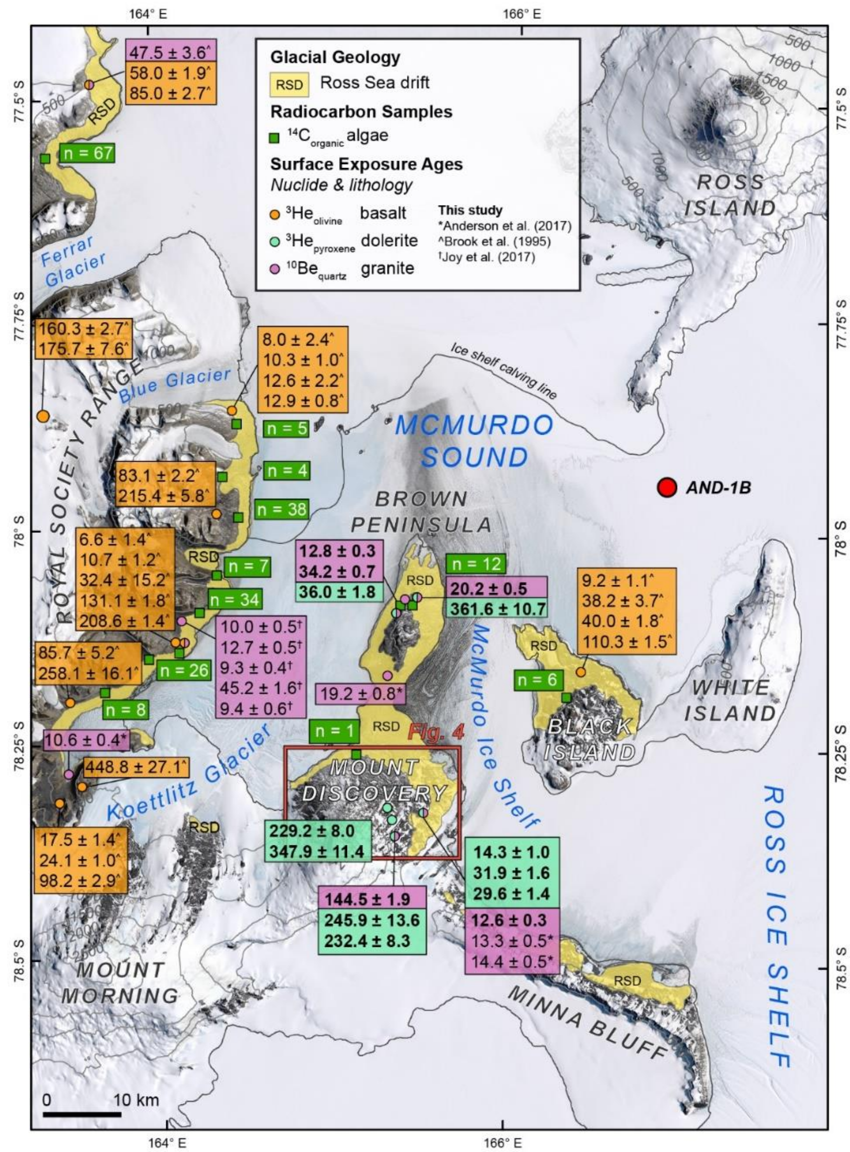
- Carefully format all of you tables so they are legible. If this means turning the table sideways then go for it.
    - *Response: We agree – the legibility issues were due to table formatting in Microsoft Word. In the final revised version, we made sure the tables were legible and better formatted.*
- Make sure that you have presented all of the data necessary for your work to be recalculated in the future. (i.e. denudation rate, pressure flag, g of sample, carrier concentration, etc.).
    - ***Response:*** *Good point. We report this information in the tables and methods section.*
- Incorporate your blank scheme into the wider data calculation tables to remove ambiguity about what samples used what blank.
    - ***Response:*** *We will be more specific in the ^{10}Be and Blanks tables about which samples used which blanks. We added clarification in both tables 2 and 3 and in the ^{10}Be methods section.*
- Make sure that you are consistent about what you call the online calculator you used to produce your results.
    - ***Response:*** *We revised to be consistent in our language about the calculator.*
- Please think about statistically significant results. Three samples from one landform isn't that robust for the claims you are making (MIS8 moraine).
    - ***Response:*** *Agreed, we toned down how we discuss the potential MIS 8 age of this deposit and reframed its discussion to be more forward looking for future research.*

    Lines 40-412: "Additional exposure age constraints from the Upper Discovery deposit as well as other higher elevation Pre-LGM glacial sediments in the McMurdo Sound region will further test if a glacial high-stand occurred during MIS 8.

    While our current dataset is limited by the low number of samples and exposure age scatter, maximum ice sheet expansion during the end of MIS 8 is compatible with other Pleistocene glacial records from the McMurdo Sound region.
- I know you have provided your data to a repository that you started, but since you got so much from ICE-D it would be good to use that community resource too. Besides having your data present in a number of places is a good thing for your own exposure.
    - ***Response:*** *Absolutely. We will upload these new exposure age datasets to ICE-D*
    -
    - Technical Comments:
- Line 22: the Ferrar Dolerite crops out not outcrops.
    - ***Response:*** *Changed as you suggest.*
- Line 33: "dating landforms and surfaces (Christ et al., 2021a; Wells et al., 1995), reconstructing changes in climate over millions of years (Bierman et al., 2016; Schaefer et al., 2016; Shakun et al., 2018), among many other applications." Should be changed to "dating landforms/exposed bedrock surfaces (Christ et al., 2021a; Wells et al., 1995), and reconstructing changes in climate over millions of years (Bierman et al., 2016; Schaefer et al., 2016; Shakun et al., 2018); among many other applications.
    - ***Response****: This will be changed as you suggest.*
    - *Lines 31-34: In situ cosmogenic nuclides, which accumulate in near-surface materials during exposure to cosmic radiation, can be measured across a wide range of environments and*

timescales to quantitatively describe earth surface processes, including quantifying erosion rates (Portenga et al., 2019), dating landforms and exposed bedrock surfaces (Christ et al., 2021a; Wells et al., 1995), reconstructing changes in climate over millions of years (Bierman et al., 2016; Schaefer et al., 2016; Shakun et al., 2018), among many other applications.

- Line 80: "During past glacial periods when southerly EAIS outlet glaciers expanded into the Ross Sea, grounded ice circumvented volcanic features and overflowed into McMurdo Sound from the east (Christ and Bierman, 2020; Denton and Marchant, 2000; Greenwood et al., 2018; Hall et al., 2015; Stuiver et al., 1981) (Fig. 1)." to something like "Grounded EAIS ice overroad some or all of the volcanic features in teh McMurdo Sound region, impounding the flow of Koettlitz Glacier and other portions of the McMurdo Dry Valleys (use your citation)"
    - Response: This will be changed as you suggest.
    - *Lines 80-84: During past glacial periods when southerly EAIS outlet glaciers expanded into the Ross Sea, grounded EAIS ice over-rode some or all of the volcanic features in the McMurdo Sound region, impounding the flow of Koettlitz Glacier and other portions of the McMurdo Dry Valleys (Christ and Bierman, 2020; Denton and Marchant, 2000; Greenwood et al., 2018; Hall et al., 2015; Stuiver et al., 1981) (Fig. 1)*
- Lines 87-89: Not all of the outlet glacier reconstructions in the region have had issues. See Jones et al 2015, Jones et al., 2021, Stutz et al., (in review The Cryosphere). If you want to keep this text the way it is you could say "yet, previous effort at Koettlitz Glacier have yielded a pattern of complex exposure histories (use your citations)."
    - ***Response:*** *Good point and you are correct about the excellent datasets by Jones. We will revise as you suggest.*
    - *Lines 89-91: The diversity of lithologies in glacial sediments in the McMurdo Sound region provides targets for multiple cosmogenic nuclides to calculate exposure ages; yet, previous efforts in the McMurdo Sound region yielded a complex exposure history (Anderson et al., 2017; Brook et al., 1995; Joy et al., 2017).*
- Lines 125-128: is a run-on sentence. You could break it into component parts and explain what you mean.
    - *Response: We streamlined this sentence to be more straightforward. See below.*
    - *Line 127-130: We compiled new and previously published (Anderson et al., 2017; Brook et al., 1995) exposure ages of different lithologies in Ross Sea drift to quantify the magnitude of exposure age scatter and investigate surface processes that contribute to, prevent, or reduce nuclide inheritance in Antarctic terrestrial glacial sediments.*
- Figure 2: white text on some parts of the map is really hard to see. I didn't realize that Mount Discovery and Black Island had text on them until I went to comment about the lack of text. I always struggle with it when making maps of Antarctica. You could try bolding the outline of the words more, make a shaded box to highlight the text, or move the name below the feature like you did for Minna Bluff.
    - ***Response:*** *Thanks for pointing this out – we thickened the line weight of the border.*



- Line 176: Some discussion around why you choose the LSDn scaling scheme would be nice. What are the benefits of using it to this work? (e.g. We recalculate the legacy data and apply the LSDn scaling scheme to all samples for ease of comparison between samples collected in the 1990's and 2010's...orwhatever your reason was for selecting it)
    - ***Response:*** *Thanks for bringing attention to this, we recognize that we should have clarified our decision about the scaling scheme. We employed the LSDn scaling scheme, which is time dependent, because the compiled dataset spans a wide timescale over the past 500 kyr and to standardize exposure ages of samples collected in the 1990s and more recently. As you have suggested, we applied the LSDn, Lm ,and St scaling schemes for sensitivity testing on the exposure age dataset. Regardless of the scaling scheme applied, we still observe the same trends according to nuclide and lithology. The LSDn scheme indeed produces younger exposure ages than St or Lm, but the difference is usually less than 1 kyr for samples with exposure ages <50 ka. None of the samples younger than 20 ka in McMurdo Sound have differences greater than 880 yr; this means our interpretations about the exposure age scatter relative to the radiocarbon constrained timing of the local LGM are not affected. The exposure age difference between scaling schemes becomes*

greater for older samples, but again does not affect our interpretations. As we revise the paper, we will include these details about the scaling scheme sensitivity testing.

  - *Lines: 186-188: We employed the LSDn scaling scheme, which is time dependent, because the compiled dataset spans a wide timescale over the past 500 kyr. We note that exposure ages using the St or Lm scaling schemes generate slightly older exposure ages, but do not change observed patterns in the wider dataset.*

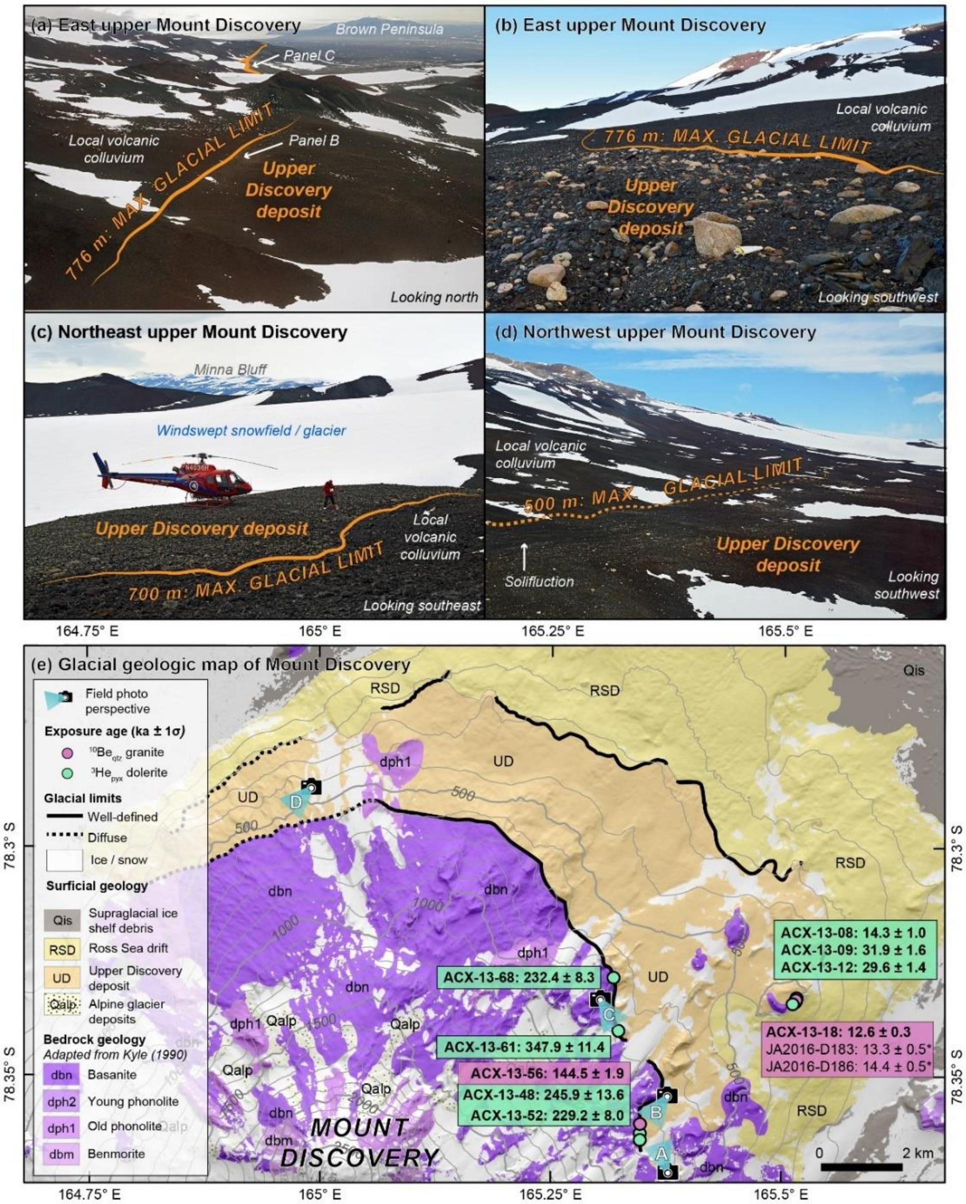
- Line 180: You should really cite the original sources for purification procedures (Brown et al., 1991 and Kohl and Nishiizumi, 1992).
  - ***Response:*** *We will add these citations to the manuscript.*
- Lines 180-181: It would be useful to give the specifications of the AMS used for the work.
  - ***Response:*** *We added details about the AMS facility (LLNL).*

Changes relevant to the two comments above in Lines 193-194

$^{10}Be/^{9}Be$ ratios were measured at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory, and normalized to 07KNSTD3110, which has an assumed $^{10}Be/^{9}Be$ ratio of 2.85×10^{-12} (Nishiizumi et al., 2007).

- Line 200: You say the maximum elevation is 775 m previously in the text and 770 m here.
  - ***Response:*** *Good catch, we meant to report 775 m. Changed as you suggest.*
- Figure 4: It would be useful to have more distinct colors representing your Quaternary units. The yellow's, while the standard geologic mapping color for Q units, are hard to differentiate.

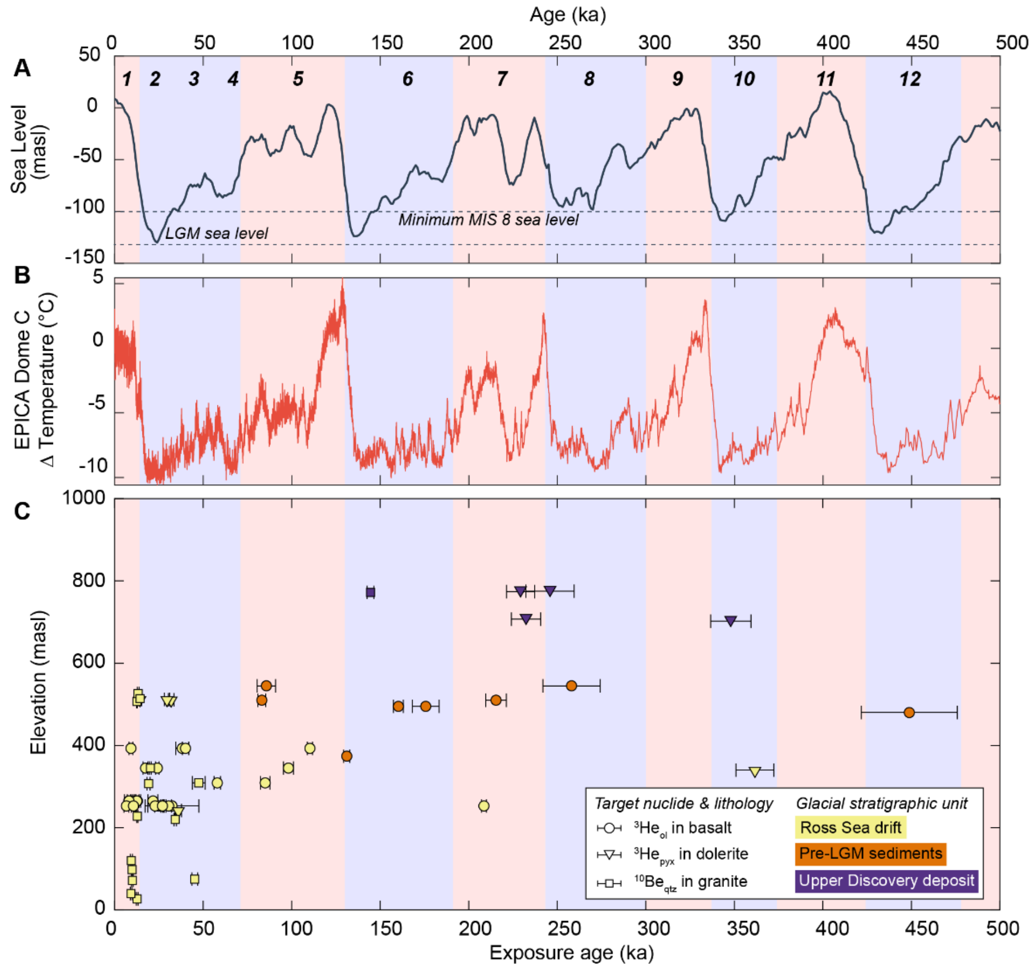
- *Response: Thanks for pointing this out – we changed the Ice Shelf surficial debris unit from yellow to dark-gray brown.*



-

- Figure 5: It would be quite useful to see a different symbol or different colour representing different lithologies.

- ***Response:*** *Great suggestion –. We revised Figure 5 to show target nuclide and lithology as different symbol shapes and used different colored symbols for Ross Sea drift (yellow), pre-LGM deposits (orange), and the Upper Discovery deposit (purple). See new figure below.*



- Lines 290-291: Can you really quantify the magnitude of and processes responsible for the exposure age scatter with such a small data set that has not taken into consideration all of the necessary variables to calculate an exposure ages? This would be better softened and qualified. Additionally, multiple nuclides on the same samples will tell you if there is a complex exposure history.
  - ***Response:*** *We agree there are many variables which affect how exposure ages are calculated. Given the scope of this project and the funding constraints we are unable to measure additional nuclides. In this portion of the discussion, we will again highlight that a majority of exposure ages are older than the radiocarbon-constrained age of Ross Sea drift, and thus there must be a geologic and/or geomorphologic reason. We will soften our introduction of the bedrock source and entrainment history hypothesis.*
- Line 313: Close the parentheses here.
  - ***Response:*** *Changed as you suggest.*
- Line 320: To be fair, from what I have seen you cannot tie all of one rock type back to a single outcrop in the Dry Valleys or the wider Transantarctic Mountains region (with one rare exception). The units where your material has been derived are almost omnipresent and exist both above and below current and paleo-ice sheet configurations. I think you might be over extending your argument.
- Sections 5.3.1-5.3.2: This is a bit too simplistic. While yes there are specific rock types exposed adjacent to the glaciers other extensive units must also be present at some point along the glacier as well and there is no telling where the erratic was plucked from under the glacier.

- *Response to two comments above: Yes, all of these rock types do exist beneath the ice sheet and it is indeed impossible to trace where exactly a single clast is sourced from. However, if clasts were sourced entirely from sub-glacial sources, the exposure age should reliably record when the ice sheet retreated from moraine positions. Instead, we observe that most exposure ages are indeed too old, requiring a more complex exposure, burial, and re-exposure history.*

- *Lines 342-346: Ferrar Dolerite bedrock is likely present below many outlet glaciers draining the EAIS and tributary alpine glaciers in the Transantarctic Mountains. Presumably dolerite clasts are also sub-glacially plucked and entrained into over-riding ice, which would generate exposure ages that reliably record clast emplacement on moraines. However, it appears that many clasts in Ross Sea drift have older than expected exposure ages that indicate a complex exposure history and nuclide inheritance.*

- Line 344-346: This is why you need to get the nucleogenic concentration right.
  - ***Response:*** *We have addressed the nucleogenic contribution to the ^{3}He inventory in an earlier comment. We will update this section to clarify that even with the nucleogenic correction applied, $^{3}He_{pyx}$ exposure ages still tend to be "too old" meaning that these clasts carry an inherited nuclide inventory.*
  - *Line 358-359: Even with the nucleogenic ^{3}He correction applied, dolerite $^{3}He_{pyx}$ exposure ages still tend to be too old, suggesting nuclide inheritance.*

- Line 350-351: Rephrase this, rock fall is a form of mass wasting that is subject to physical weathering processes.
  - ***Response:*** *We changed this to Line 364-65 "Clasts sourced from rockfall events onto the glacier surface…"*

- Lines 371-375: This is a run-on sentence, break it down a bit.
  - ***Response:*** *We changed it to the following Line 384-386: "The $^{3}He_{olv}$ exposure ages are compatible with ice thinning on eastern Mount Discovery from its maximum extent after 14.0 ka to near present elevations at 7.3 ka (Anderson et al., 2017). Likewise, $^{3}He_{olv}$ exposure ages from the McMurdo Sound region agree with rapid lowering of outlet glaciers during the Early Holocene (Anderson et al., 2020; Goehring et al., 2019; Jones et al., 2015, 2021; Spector et al., 2017) as grounded ice in the Ross Sea retreated (Halberstadt et al., 2016).*

- Line 373 remove "of".
  - ***Response:*** *This will be changed as you suggest.*

- Lines 385-387: what are the odds that this is simply a coincidence? This is potentially a recycled clast from somewhere other than Mount Discovery.
  - *Response: Yes, this could be a coincidence of clast recycling – we added this explanation.*
  - *Line 401-402 "…as observed with in Ross Sea drift, outlier $^{3}He_{pyx}$ exposure ages can be preserved in the same deposit, possibly due to clast recycling."*

- Lines 387-390: What erosion rate are you assuming to make this calculation? You could fiddle with the ER until the age is what in the ball park of what you would expect and then see if the erosion rate is realistic for what we know of the area. If it is several meters of erosion than the clast may have been uncovered later or rolled through periglacial processes. Also, why didn't any of the other samples need to be adjusted for ER?
  - Response: We did not apply specific erosion rate corrections in this study because it is difficult to determine the erosion rate of individual boulders and erosion rates measured in the nearby

McMurdo Dry Valleys may not be applicable in McMurdo Sound. However give your suggestion, we did a ballpark calculation using lithology-specific erosion rates specific to granite (0.13 mm/kyr) and dolerite (0.19 mm/kyr) boulders in Antarctica determined in a recent synthesis study (Marrero et al., 2018). The exposure age difference between the granite boulder (153 ka) and the MIS 8-aged dolerite boulders (~250 ka) is too much to be explained by the difference in erosion rates between lithologies. Additionally, if we apply a relatively high (for Antarctica) erosion rate of 0.19 mm/kyr to the local landscape and assume the moraine on upper Mount Discovery is indeed ~250 ka, erosion has only removed 47.5 mm, which is too small a value to exhume the granite boulder we sampled. It is more likely that this specific granite boulder was eroding faster than regionally calculated values, which is possible since we observed a cavernous weathering pit on this particular clast. We will briefly discuss this in the revised manuscript.

- *Lines 405-411: Even if lithology-specific boulder erosion rates for granite (13 mm kyr^{-1}) and dolerite (19 mm kyr^{-1}) (Marrero et al., 2018) in Antarctica are considered, the difference between the exposure ages of the granite boulder (147 ka) and the dolerite boulders (~226-356 ka) is too much to be explained by the difference in erosion rates between lithologies. This suggests that this particular granite boulder was weathering much faster than regional average rates or it may have been affected by post-depositional movement to generate an anomalously young age. Additional exposure age constraints from the Upper Discovery deposit as well as other higher elevation Pre-LGM glacial sediments in the McMurdo Sound region will further test if a glacial high-stand occurred during MIS 8.*