Geochronology Discuss., author comment AC2
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Reply on RC2

Andrew J. Christ et al.

Author comment on "Cosmogenic nuclide exposure age scatter records glacial history and processes in McMurdo Sound, Antarctica" by Andrew J. Christ et al., Geochronology Discuss., https://doi.org/10.5194/gchron-2021-21-AC2, 2021

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 glacial deposit. We will adjust our discussion of this finding with a softer tone. Hopefully, 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.*

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.*

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.*

- 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 $^3He_{pyx}$ 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-corrected 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 one 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 (yr)*	*Age (yr)*	*Difference (yr)*	*Age (yr)*	*Difference (yr)*
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

- 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.*

- 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 a final revised version, hopefully we will supply better formatted tables as PDFs.*

- 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 will report this information in the tables accordingly.*

- 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.*

- Make sure that you are consistent about what you call the online calculator you used to produce your results.

Response: *We will make sure we are consistent in the revised manuscript.*

- 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 will tone down how we discuss the potential MIS 8 age of this deposit and reframe its discussion to be more forward looking for future research.*

- 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 as we revise the manuscript.*

Technical Comments:

- Line 22: the Ferrar Dolerite crops out not outcrops.

Response: *This will be 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.*

- 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 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 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.

"We compiled new and previously published (Anderson et al., 2017; Brook et 125 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 will make those labels easier to see.*

- 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 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.*

- 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 can add these details about the AMS facility (LLNL).*

- 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.*

- 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 will alter the colors/symbology of the different Quaternary units to make them easier to differentiate.*

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

Response: *Good suggestion – we will change the symbology to different shapes to show different lithologies. In Figure 5 we have used the colors of the glacial deposits (yellow for Ross Sea Drift and orange for older glacial deposits) shown in our geologic map on Figure 4.*

- 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: *This will be 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.*

- 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, $^3He_{pyx}$ exposure ages still tend to be "too old" meaning that these clasts carry an inherited nuclide inventory.*

- Line 350-351: Rephrase this, rock fall is a form of mass wasting that is subject to physical weathering processes.

Response: *We will change this to "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 will change it to the following: "The $^3He_{olv}$ 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, $^3He_{olv}$ 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 will add this explanation . "…as observed with in Ross Sea drift, outlier $^3He_{pyx}$ 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. Based on 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. This is too little erosion 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.*

Author Comment References:

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