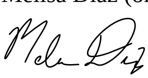
Dear Dr. Koppes,

We are pleased to submit our revised manuscript, “Relative terrestrial exposure ages inferred from meteoric ^{10}Be and NO_3^- concentrations in soils along the Shackleton Glacier, Antarctica.” We are very thankful to both Dr. Goehring and an anonymous reviewer for providing thoughtful comments, suggestions, and edits, which have guided this revision. We have made the corrections proposed by Dr. Goehring and Referee #2 in the tracked-changes manuscript at the end of our responses. However, due to the substantial nature of the revisions, our edits are more clearly distilled and described below. In addressing the concerns and questions raised in the two reviews, the manuscript has substantially improved for publication.

To summarize, we agreed with both Dr. Goehring and Referee #2 that the manuscript would greatly benefit from re-framing and clarification, particularly in the introduction, methods and discussion. We have modified the narrative to focus on the distributions of meteoric ^{10}Be and NO_3^- and how these data inform biogeography, climate, and glacial history for discrete points along the Shackleton Glacier. As Referee #2 points out, we originally did not discuss the study design, which is that of a biological survey. This is now included and strengthens the narrative. Lastly, we have clarified our exposure age techniques, especially the relationship between NO_3^- and meteoric ^{10}Be since this is a new method. Our data and results offer some of the only surface exposure ages in the Shackleton Glacier region and suggest that much of the southern portion region has remained hyper-arid since at least the Pleistocene. These findings are particularly important in understanding ecological succession and glacial history in the Transantarctic Mountains.

Best regards,

Melisa Diaz (on behalf of all authors)



Postdoctoral Scholar
Woods Hole Oceanographic Institution
The Ohio State University
Byrd Polar and Climate Research Center

Brent Goehring (Referee)
bgoehrin@tulane.edu
Received and published: 14 August 2020

General Comments Diaz et al. present a compelling study showing the utility of combining measurements of meteoric 10Be with soluble nitrate as a means to determine surface exposure ages. In this case, they apply their new method to soils adjacent to Shackleton Glacier, Antarctica. However, their new methodology, particularly the combined use of nitrate and 10Be is not well-enough described. Additionally, and as noted below, there needs to be a rigorous uncertainty analysis completed. All that being said, I will very much enjoy seeing this paper published, but for now it needs revision. The methods and results are interesting from an applied sense in that it could be used elsewhere, but their work also adds to the glacial history of the Transantarctic Mountains. Below I present general comments and then further below I present a number of detailed comments and suggest changes.

As detailed in our response to Referee #2, we believe that the narrative re-framing to include wetting history and biogeography has significantly improved the manuscript. We have greatly expanded our NO_3^- and meteoric ^{10}Be methodology in Sections 2.2 and 5.3.2.

The one supplementary figure showing the relationship between max 10Be concentration and total 10Be inventory should not be buried in the supplement.

This is now included in the main text as Figure 7.

I find that the introduction reads too much like a thesis introduction. All of the content is very good, but I think it could use a bit of streamlining that will help motivate the rest of the paper a bit better, as I think you need to also address the limitations of in situ exposure dating, as you mention later on, but it could benefit from being a bit earlier.

As per Referee #2's proposed manuscript structure, we have re-framed and rewritten the introduction to focus on the original goals behind collecting and interpreting these data – to understand relative surface soil ages for biological survey purposes.

Bear in mind this is purely a stylistic opinion can certainly be ignored. Throughout the manuscript, anywhere there is a reference to an age, rather than a duration, need to use Ma instead of Myr.

We have made these changes to follow discipline formatting.

There is overall a lack of uncertainty analysis that needs to be completed, particularly exploring the sensitivity of your various age determination models to parameter variance. The measurement uncertainties in this case are tiny compared to other uncertainties. A full error analysis will greatly strengthen the conclusions made in the paper and really needs to be done before publication. A bootstrap approach should be sufficient.

The models that we have used in this work have been described and tested in great detail in previous studies, which include sensitivity analyses (e.g. Willenbring and von Blanckenburg, 2010; Graly et al., 2010). In general, the exposure age estimates using equations 1-6 are particularly sensitive to erosion, deposition rates, and inheritance. Since these values could not be determined for each sampling location, we chose to refer to our ages in a relative framework. Additionally, our ages are not absolute due to the inability to correct for initial inventory and/or inheritance. These uncertainties are further described in Sections 4.3.1 and 5.3.

There is far too much framing of the study around Pliocene glacier dynamics, and particularly the Sirius formation. I'd much prefer to see the expansion of the possible newish and important approach that can be implemented combining 10Be with nitrate as a measure of surface exposure duration.

We have shifted the focus away from Pliocene glacier dynamics towards the description and application of our analyses. We now focus on estimating surface exposure ages and the use of atmospherically derived salts in estimating wetting history and exposure ages. This is detailed in Sections 1 and 2.

Figure 8 demonstrates very nicely a coherent pattern of ice thinning/retreat. This needs to be played up, and the return late in the manuscript to the Sirius Group detracts from the novelness of the work.

We now focus on our novel approach to estimating relative exposure ages and how these data contribute to our understanding of ecological succession and glacier change.

Detailed Comments

Line 37: Please provide a citation or two for the first part of the sentence. There is actually quite sparse direct evidence for smaller interglacial extents relative to the Holocene and much is largely inferred from distal evidence or modeling. Additionally, the Ross Embayment is a large area and thus this statement is somewhat vague.

We have better clarified our introduction on glacial history.

Line 51: How are calculated and estimated exposure ages any different from each other? I know this seems nit-picky, but it is somewhat strange wording as your estimated exposure age had to be calculated first.

We have explicitly defined our terminology in Sections 2.3 and 5.3. In brief, “measured” ages are ages we calculated based on the meteoric ^{10}Be profiles we measured (Robert Massif, Bennett Platform, and Thanksgiving Valley); “estimated” ages are those we calculated based on the estimated ^{10}Be concentrations from the power-law relationship between NO_3^- and ^{10}Be; “inferred” ages are those we calculated based on the inferred relationship between maximum ^{10}Be concentration and inventory.

Line 62: Unsure what "these studies" are. Are you referring to those cited at the end of the sentence or the sentence prior? If the sentence prior, why do you have a new set of citations?

Section 2.1 Should be worked more into the introduction in my view.

We have clarified the introduction.

Line 78: Nishiizumi et al., 2007 is not actually a half-life study, an outcome of the standardization is that a different half-life than had been used must be used. Recommend citing: â˘A´c Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U., Knie, K., Rugel, G., Wallner, A., Dillmann, I., Dollinger, G., Gostomski, C., Gostomski, C., Kossert, K., Maiti, M., Poutivtsev, M., Remmert, A. (2010). A new value for the half-life of 10Be by Heavy-Ion Elastic Recoil Detection and liquid scintillation counting Nuclear Instruments & Methods In Physics Research Section B-Beam Interactions With Materials And Atoms 268(2), 187 - 191. https://dx.doi.org/10.1016/j.nimb.2009.09.020 â˘A ´c Chmeleff, J., Blanckenburg, F., Blanckenburg, F., Kossert, K., Jakob, D. (2010). Determination of the 10Be halflife by multicollector ICP-MS and liquid scintillation counting Nuclear Instruments & Methods In Physics Research Section B-Beam Interactions With Materials And Atoms 268(2), 192 - 199. https://dx.doi.org/10.1016/j.nimb.2009.09.012

We thank Dr. Goehring for the reference and have updated our citation.

Line 101: Given the general absence of anything resembling soils or till in most of Antarctica, one could argue that applying meteoric 10Be is far more spatially limited, e.g. to regions of the Dry Valley, for example. Thus, I am not sure I would argue for your method by arguing that in situ exposure dating is limited, but instead argue that they are complementary.

We have revised this point in Section 2.1.

Starting line 107: I am not sure the bedrock lithology is all that relevant. I understand you want to show the protolith for weathering products, but I think it could be said more concisely. I think the geologic setting paragraphs could be combined.

As Dr. Goehring has mentioned, the lithology is important in understanding weathering products and material source. We believe this information is particularly important now that we have added more detail on the sample site descriptions in Table 2.

Line 123: Suggest changing "glacial dynamics" to "glaciers"

We have changed this terminology throughout.

Line 128: By two samples, do you mean two surface samples? Suggest clarifying the text here, especially since you have depth profiles samples from elsewhere.

Line 130: In your reference to sample distance from the glacier, are you largely referring to further away as controlled by elevation, or by horizontal distance? I think some clarification of this could be useful, as depending on the valley geometry, changes in ice thickness might not be significantly further away from the glacier, or vice versa. It might be more constructive and more generalizable to perhaps say that two samples were collected, one adjacent to the glacier, characteristic of times similar to the current extent and one further away representative of significant changes in glacier size (larger). A useful column in your table and the way most Antarctic glacier change is expressed is as change in ice thickness.

We have clarified our sampling procedure and terminology throughout the text.

Line 142: Why not report the fraction between 2mm and 425 microns? Was none present? Sand usually extends to 2 mm.

We thank Dr. Goehring for identifying this error and have corrected the text and figures.

Line 170: Suggest not starting paragraph with "However. . .." I suggest that when laying out your calculation methods, that the equations flow more within the paragraph, rather than being at the end of each paragraph. I found it somewhat hard to ready.

We have attempted to re-integrate the equations in Section 4.3.

Line 179: Suggest adding "any" before "have meteoric" Line 197: Delete "which"

We have clarified the text.

Line 202: Confused because didn’t you calculate two samples from every location, only profiles from only a few?

We measured meteoric ^{10}Be and NO_3^- concentrations from at least two samples (generally near glacier and furthest away) at all sites. We measured one profile at each site for nitrate and profiles from Roberts Massif, Bennett Platform, and Thanksgiving Valley for ^{10}Be. We have clarified this throughout the text.

Line 206: The lack of an expected concentration based on regressions against distance and elevation might just be spurious and making predictions from these regressions very tenuous. I suggest removing this sentence.

We have removed this portion and the associated figure (formally Figure 5).

Line 222: The ages are not necessarily minimum ages, as while you may be overcorrecting for inheritance because you don't know the background inventory, you also do not a priori know the erosion rates of the soils, even though you make assumptions. I suggest that rather than couching the ages as minimum, as they are only minimum relative to your max limiting no inheritance ages, you just present them as best estimate given knowledge of the parameters.

Our inheritance corrections in the original text were estimates since our depth profile concentrations of ^{10}Be did not reach background levels; we could not assess whether they were accurate. As a result, we have redone the calculations to reflect ages with and without erosion (as erosion from boulders was used). The ages are now reflective of maximum ages with the erosion term and are probably still overestimates without erosion. See Section 5.3.1 lines 290-293 and Section 6.1 line 351.

Section 5.3.1 This section is very confusing in terms of what you did and is not represented in the methods at all, thus the results presented here come out of nowhere. There needs to be a clearer explanation of what was done. I think the approach is really neat and valuable, but right now it just isn't explained well-enough. I am also very confused upon the first and second read as to what was done with what profile, as the second paragraph mixes results from sites with both measurements and sites without. Section 5.3.2 Like the prior section, where there are a number of inferred methodological requirements, more expansion of the discussion is needed to aid the reader that may only have casual knowledge of meteoric 10Be knowledge as I can see many readers being most interested in the inferred ice history. I think one thing that will help immensely is that this and the prior section are more traditionally considered as part of the discussion and the results purely your 10Be and NO3- measurements. Now, if you were to present the calculation methods using nitrate and the inventory vs max concentration analyses in the methods, then you could keep in the results. At present, there is just a bit too much mixing and overall not enough time dedicated to these important sections that you then use extensively in the discussion below. Also, best I can tell Figure 8 does not show the relationship *between max concentration and total inventory, please investigate, or do you mean to only present the max exposure ages.*

We have more clearly defined our methodology for NO_3^- and ^{10}Be in Sections 2.1-2.3, 4.3, and 5.3. As stated earlier in this review, we have explicitly defined our terminology for the different exposure age estimates.

Line 247: Please elaborate or define what the model limits are, as this is not defined. Presumably just the influence of the time scale to 10Be saturation given an erosion rate. I also wish there were different terminologies used with regards to calculated vs estimated. Perhaps refer to one as the apparent max limiting age and the other a model age?

We mention that the maximum age the model can calculate is >6 Ma. The model limits are dependent on erosion and initial inventory, as described in 4.3.1. We have also more clearly defined our terminology.

Line 260: The correspondence with in situ ages is quite remarkable. What is lacking though is a clear representation of the two different data sets. This is why I suggested that perhaps you determine the elevation above modern ice surface and thus you can then make age vs elevation plots for your data and the in situ data. I think will drive home much more clearly the correspondence.
Or you could consider maps showing the various bits of data, but I think they will get very busy very quickly. While the correspondence in many scenarios is striking, one thing to consider and make sure you make clear is whether the in situ data are from bedrock or from erratics, as they will have quite different exposure ages and thus your soil ages might always be older than nearby in situ erratic exposure ages. The fact that your meteoric ages, including nitrate corrected, agree so much with in situ erratic ages suggests some mechanism for resetting and flushing of 10Be or that your model is determining the pre-LGM inherited concentration quite clearly. I think this needs further discussion and is important to highlight more.

We agree that we needed to represent the data comparisons in a clearer manner. We have added two figures, 8 and 9, that show how our data compare to those from previous studies.

Line 272: Need a reference for exposure dating results from Beardmore Glacier.

We have removed the discussion from the Beardmore since we are unsure if we are sampling comparable drifts or features.

Line 288: The arguments about the suitability seem out of place *and kind of come out of nowhere and seem to set up a strawman for no apparent reason. I suggest removing and focusing on the apparent success of the nitrate correction given the good agreement with in situ exposure dating.*

We have focused the discussion on the shapes of the NO_3^- and ^{10}Be depth profiles, the age estimates, and implications for climate and glacial advance and retreat.

Starting line 292: The first few sentences of this paragraph read too much like a conclusions section. Suggest revision.

We have revised this section, now Section 6.2.

Line 303: As mentioned above, the nitrate regression models needs further description and elaboration, particularly since this really is the first major combined use of these two measures.

We have elaborated the NO_3^- regression in Sections 5.2 and 5.3.2.

Line 306: Wouldn't a lack of correlation be expected given the exponential fall off of a 10Be profiles, so that below a certain depth there will be little to no variance in the 10Be concentration and presumably the same in nitrate?

We have clarified this point in Sections 5.2 and 6.3

Line 352: Suggest rather than saying delayed response that you more generalize it and just say different response from Ross Ice Shelf confluent outlet glaciers, or something to that effect.

We have removed this text.

Line 358: This conclusion is spot on and is a major finding of the paper, however its use, the details, etc. are not elaborated on enough earlier in the manuscript.

As stated previously, we have elaborated on the relationship between NO_3^- and ^{10}Be throughout the text, especially in Section 6.2.

Line 365: The broader question then becomes, how do we differentiate between a site with inherited meteoric 10Be that was covered by LGM ice from a site that was never covered during the LGM and more recent glaciations. This is a question that the in situ community has struggled with. We are only starting to get clarity from a focus on erratic exposure dating with long-lived nuclides or application of *in situ 14C to erratics and bedrock. Recent work in the Weddell Embayment with very old erratic and bedrock in situ ages were clearly covered by LGM ice as shown by in situ 14C, including preservation of delicate features like moraines (e.g., Nichols et al., 2019). Thus, during a say 10 kyr long ice cover period, how much of a reduction in the meteoric 10Be signal can be expected? What about reduction in nitrate? Presumably unless the ice is wet based, neither will be mobilized and then you need the correct pH conditions. These thoughts are briefly touched on, but the manuscript could use a bit more elaboration on the long-term interpretation of the signal recorded by your methods and what its implications are for interpreting surface processes in Antarctica. Thus, it could be useful to elaborate on the presence of polythermal moraines, why are some areas reset for the meteoric and in situ methods.*

Dr. Goehring brings up some very important questions. However, the answers to many of these questions are unknown. Since we do not initially know which, if any, sites were disturbed by repeated glaciations, we cannot correct for inheritance. Additionally, our profiles could not reach background concentrations of ^{10}Be for an initial inventory correction. We can only rely on the data we've collected. Due to uncertainties with sediment transport, both modern and in the past, it is unclear how meteoric ^{10}Be and NO_3^- would be affected over extended periods of time. We mentioned in the text (e.g. Lines 440-451) that some locations may actually be accumulating particles with ^{10}Be instead of erosion. However, under persistent arid conditions, we expect both ^{10}Be and NO_3^- to be largely conserved. We have described this throughout the text.

Figure 1: Not sure if this is supposed to be this way of if some strange PDF artifact, but the exposed rock areas are banded. I also think you could make the overview map larger scale to give readers a better context of the Shackleton Glacier.

The exposed rock areas where we samples are indeed banded, hashed, and checkered in the figure to indicate lithology as per the key. We made the overview map larger.

Figure 3: A similar figure thinking about the fate of nitrate during ice cover would be informative.

We hope that the expanded text will suffice instead.

Figure 4: Add panel labels please. Also, it is confusing that in the Shackleton glacier map, the coloring represents concentration, but you then use the same colors for the different sites, or is it only the arrows? This is somewhat confusing, and I suggest not using colored arrows that are the same as the color scaled points for concentration. Here the figure is trying to show too much.

We have updated this figure.

Figure 5: This figure and all figures. Are uncertainties shown, but smaller than the symbol? Please note this or add uncertainties if need be.

Due to the log scale, the measurement uncertainties are small, as indicated in Table 3.

Figure 6: Suggest removing the lines connecting the points, as it implies that there is a trend in grain size % between the points. The measurements are point measurements.

We have kept the lines the help the reader connect the points.

Figure 7c: Please provide equations for the fits along with uncertainties on the fit parameters. These uncertainties then need to be used for error analysis on the resulting ages.

We have removed the regressions.

Table 2: I suggest presenting uncertainties using the same exponent for the measured value and Uncertainty.

Normally we would agree, but if we change to the same exponent, there are too many zeroes.

Anonymous Referee #2

Received and published: 15 August 2020

I. Summary.

The summary of this review is that the data collected in this paper are useful, interesting, and valuable to publish. In general, the idea that accumulation of atmospheric constituents in Antarctic soils is useful for estimating soil ages and residence times is important from many perspectives, including glacier change, paleoclimate, and biology, and this paper contains a lot of data that are relevant to this topic.

II. Overall motivation of paper.

II.1. The way the paper is motivated makes the experimental design look bad when, in fact, it is not.

The experimental design of this study is very well designed from the perspective of a biological survey. The use of atmospheric fallout constituents of soils to rapidly get an approximate idea of the soil age, and distinguish soils that were ice-covered during the LGM from soils that have not been ice-covered for millions of years, is a smart, well-designed approach that is likely to be effective for its intended purpose. On the other hand, the study is not well designed for the purpose of reconstructing past glacier change.

The point here is that if the present study was motivated by the original objectives of collecting geological information needed to study ecosystem succession, it would be perceived by readers as well-conceived and well-designed. If motivated as a study of glacier change as in this paper, on the other hand, the experimental design appears weak and inadequate by comparison to other studies.

I very strongly urge the authors to change this emphasis. They should clearly explain the purpose of the overall project that led them to the experimental design used here. It is true that the data collected for this purpose also have value in quantifying glacier change, so there is nothing wrong with focusing additional discussion on that later in the paper, but motivating the entire paper from this perspective makes the paper much weaker than it should be.

Referee #2 is indeed correct that the samples collected for this study and for this analysis were for a larger study on ecosystem succession following changes in climate – in this case, glacial advance and retreat. The goal of this smaller study remains the same. We sought to determine relative surface exposure ages of ice-free areas along the Shackleton Glacier. Though these data can be useful in understanding glacial change, we agreed that the introduction and discussion should be refocused to emphasize our broader goals and significance to ecological refugia. As such, much of these sections have been rewritten to include these points.

II.2. The way the paper is motivated leads the paper off into vague theories that can't be addressed by the data.

The most problematic part of the paper from this perspective is the first two paragraphs *of the introduction (lines 33-45) and section 2.1 ("Stability of the EAIS"), lines 55-76. The introduction discusses the fact that the Antarctic ice sheets are proposed to have been a lot smaller during some warm periods in the past. While it is certainly true that this has been hypothesized and that in a very general sense this is a strong motivation for studying past changes in the size of the Antarctic ice sheets, there is almost no connection between this overall idea and the specific observations described in this paper. As discussed above, if this is the motivation for the work, the work looks inadequate.*

Section 2.1 is much more problematic. It would be clearer to simply state that it is not yet known whether or not the East Antarctic Ice Sheet was significantly smaller during past warm climates. The second problem in this section has to do with confusion between ice sheet change and climate change. The discussion of how long polar desert conditions have prevailed in the TAM is important in this paper because it gives context for one potential application of salt deposition in soils, i.e. the idea of a "wetting age" in which the amount of salt that has accumulated can give information on when liquid water was last present. However, this important implication of the idea is not at all mentioned here.

We have changed the focus of the introduction to discuss ecological dispersal and refugia during glacial periods, the overall glacial and climate history of Antarctica, the need to understand exposure ages in this region, the goals of this study to understand soil ages, and the applications both to ecology and geomorphology. We have removed much of the text on East Antarctic Ice Sheet stability and instead shift the focus to persistent arid conditions, as the desert climate is particularly important for salt accumulation and the development of our NO_3^- proxy.

III. Oversimplified explanation of atmospherically produced Be-10.

With regard to section 2.2, the main thing the authors need to get across here is that meteoric Be-10 builds up in soils, so the total amount of Be-10 present in a soil profile is related to the age of the soil. This information is here, but it is missing some important context and mixed up with other confusing things. One, the authors should clearly state that meteoric Be-10 is mobile in the soil, so it is not the concentration at any particular location that is proportional to the exposure age, but instead the total inventory in the entire soil profile. Two, the behaviour of meteoric Be-10 and salts in soils may be quite different, for example because Be-10 remains bound to particles even when the soil is wet, whereas salts are mostly mobile in water.

While we do discuss meteoric ^{10}Be systematics later in the text, we agreed that it would be beneficial to better describe the system in more detail here and have done so. We also added in Section 2.2 on NO_3^- systematics.

The other important area here that needs to be either here or in the section on study sites is a discussion of exactly what landforms were sampled and how that relates to meteoric Be-10 systematics.

We have added Table 2, which describes the landforms and features we sampled at each location and any notable features, such as nearby ponds, polygonal ground, etc. Mapped geomorphologic features, such as drifts and moraines, are poorly documented in this region. The only published data are from Roberts Massif and Bennett Platform. We made sure to mention any constructional landforms in Table 2.

Section 4.3 is about how to quantitatively interpret Be-10 concentrations as an exposure age of the soil. This section would benefit from several improvements. Specifically, Equation (1) seems to be missing important elements.
A common approach in the meteoric Be-10 literature to simplify this relationship and make it more useful is to write the governing equation for the soil inventory I (atoms per cm2, vertically integrated) instead of the concentration, like:
$dI/dt = Q - \_I - ENs$ *(2)*
where Ns is the surface concentration (atoms/g) and E is the erosion rate in mass per area units. Using this equation instead of Equation (1) would make this paper much clearer. Alternatively, this paper could simply refer to other literature that describes meteoric Be-10 systematics in detail – it is not necessary to reinvent the wheel here.

We understand that the simplicity of Eq. 1 was misleading. We have removed the equation and replaced it with a more comprehensive equation, per Referee #2’s suggestions.

Finally, an important point for these sites is that it is not even clear that erosion is taking place throughout the ice-free at areas all. Perhaps the only process that can bring new sediment to the surface and permit deflation would be periglacial disturbance of the soil. This issue reminds me that an important thing that needs to be added to section 3 is some discussion of the surface characteristics of each site, including presence or absence of boulder pavements and periglacial features like cracks and polygons, because these features are relevant to interpreting the Be-10 data.

The overall point of this section is that it is not at all clear to me that erosion should even be included in the relationship between inventory and age for these sites. For this paper, I think it might make the most sense to simply relate inventory to exposure age by $dI/dt = Q - \_I$*, i.e. disregarding erosion and deposition, and accept that this approach might be either under- or over-estimating exposure ages.*

As mentioned previously, we added a table describing the surface features of each sample location, including whether the samples were collected on valley floors or hillslopes. While we did not sample features such as polygons and boulder pavements, it is crucial to indicate such. With the sample locations further described, we believe the inclusion of erosion rates is clearer, though we acknowledge that true soil erosion rates are unknown for these features. We also calculated the exposure ages without erosion and report both throughout the text.

> *[T]his section has to clearly explain how one measures the Be-10 inventory. As already discussed in the paper, this can be done in two ways, either by measuring a complete depth profile and integrating, or using an empirical relation between surface concentration and inventory as in the Graly paper.*
>
> *An additional problem with this section is that "inheritance" is not clearly defined, which is confusing.*
>
> *Finally, a clear definition of "background" in the context of a depth profile is needed here. The basic concept (that the concentration is supposed to decrease with depth until you reach a depth where the concentration becomes invariant with depth) is correctly described near line 182, but what is missing is a clear statement of how one knows that one has observed this. Overall, what I suggest doing here is noting that in principle the depth profile method is one possible way to estimate I, but it can't be used in this application because insufficient data were collected – and then move on to discussing the approach of using an empirical correlation between N and I to estimate I.*

We have clearly defined both inheritance and background (initial inventory) in the context of our study on Lines 203-217. We also note that we are unable to correct for either of the two with the data we measured. Referee #2 correctly mentions that we have not satisfied the typically criteria for attaining background measurements of meteoric ^{10}Be. We have communicated this in the text.

IV. Data analysis.

> *I did not understand what the purpose of these regressions is [Fig. 5]. Because I don't see any basic physical relationship that would support linear regression of concentration against elevation/distance, as a reader I am left with the impression that the authors simply felt that there should be some linear regressions in the paper. I am not sure this is the impression that the authors want to give the reader. It makes the paper seem weak and confused, and I urge them to remove this section of the paper.*

We have removed this figure and the associated text.

> *The second area that seems problematic to me in this section of the paper is how the authors approach estimating the Be-10 inventories in section 5.2.*
>
> *What I suggest doing here is removing section 5.2, noting that the depth profile data do not allow estimating I accurately, and rely entirely on the empirical-correlationbetween-I-and-N approach for estimating I, which is already clearly covered in section*

5.3.2. This is not really a major substantive change to the paper, because at most of the sites there are only surface data in any case.

We have decided to keep the inventory calculations for Roberts Massif, Bennett Platform, and Thanksgiving Valley since we have ^{10}Be depth profiles for these locations. We also calculated inventory using the NO_3^- and ^{10}Be power-law relationship (Sections 4.3 and 5.3). We did not attempt correct for initial inventory (background) or inheritance. This is stated in those sections. We mainly kept the I and N calculations as written.

The third area that I think needs additional discussion in this section is the discussion of the relation between Be-10 and nitrate concentrations. To summarize, this section needs to be made much more clear so that the reader can understand when concentrations, surface concentrations, and inventories are being discussed, and what differences in behaviour of Be and NO3 could lead to positive or negative correlation. This may require making this section substantially longer in order to explain the reasoning step by step so that the reader can follow it.

We agree with Referee #2 that this section can and should be greatly expanded upon. We added additional text describing the relationship between ^{10}Be and NO_3^- for each of the three soil profiles and the factors which have likely contributed to the observed concentration behavior in Sections 5.2, 5.3.2, 6.2, and 6.3.

V. Discussion and interpretation areas.

The first aspect of the discussion that needs additional work is that the most basic prediction of the experimental design is that, first, Be-10 inventories and/or concentrations should increase with distance from the ice margin at each site, and, second, Be-10 inventories/concentrations for the ice-proximal samples that are supposed to have been exposed after the LGM should have magnitudes that are appropriate to post-LGM exposure, i.e. 10-15,000 years of surface exposure.
I would do this with a figure for each site showing distance from the nearest ice margin on the x-axis, and Be-10 and NO3 concentrations on the y-axis.

We agree that an additional figure showing ^{10}Be concentration versus distance from glacier would be beneficial in supporting the overall experimental design. However, some samples were collected on ridges and we would only be able to estimate aerial distance, which is not very helpful from a glaciological context. Instead, we have added Figures 8 and 9 which show the ages with elevation and on maps.

The second aspect of the discussion that is incomplete/too abbreviated is the section beginning on line 260 that compares the results to existing exposure-age data from glacially transported boulders. Personally, what I would view as minimally adequate *here is a map view of each site where there are existing/published exposure age data, showing the location of the soil pits described here, the location of any moraines or drift boundaries including any hypothesized LGM ice limit, and also the location of the independent exposure-age data, which will be mostly boulders dated by some in-situ produced nuclide. Alternatively, instead of maps, these could take the form of plots with distance from the ice margin on the x-axis, and exposure ages calculated from the various data on the y-axis.*

A second issue here is that some of the other exposure-age data (e.g., Thanksgiving Point, Mt. Franke) appear to be available in online databases but not yet published in journal articles. I am sure the data are fine, but this may cause some citation problems. I refer that issue to the editors.

Though there are only published data from Roberts Massif, we agree that it is helpful to plot the *in-situ* data from previous studies and ICE-D alongside our data to support our comparisons. This is done in Figures 8 and 9. Confident estimates of the LGM trimline and mapped drifts for the other sites and features we sampled in the Shackleton Glacier region do not currently exist. Regarding the citations, we cite Balco, 2020, which includes the ICE-D dataset.

In addition, some of the text in this section gives the impression that the authors have a misunderstanding of the existing exposure-age data set. For example, consider the remark in line 273-ish about exposure ages from the Beardmore Glacier region, which states that exposure ages become younger downglacier for Shackleton and Beardmore Glaciers. In principle, it is possible that pre-LGM deposits are less common at low elevations, but that would have to be established via systematic mapping of these deposits. Thus, this section of the paper needs to be significantly reworked to focus on a comparison between specific mapped deposits of known or estimated ages, and not on a broad geographic analysis of a set of ages that is probably the result of selection bias.

Considering the concerns Referee #2 raised regarding this section, we decided to largely remove it.

The third aspect of this part of the review is that I could not understand the paragraph in lines 292-302. This mixes observations that the relationship between Be-10 and NO3 concentrations in depth profiles is complicated (which is true) with statements that have no clear connection to this observation such as "through a coupled approach...we developed a useful model for estimating soil exposure ages."
I suggest starting again with this paragraph and trying to lead more clearly from observations to conclusions.

With the overall manuscript reframing and editing of the discussion, clarity has improved throughout. In particular, we outline our methodology in Sections 4.3, 5.2, and 5.3.2.

Finally, the last important thing here is that I found the disconnect between observations and conclusions to be most serious in section 6.3 ('Implications for ice sheet dynamics.'). This section contains several very broad statements. Only one of them (the discussion of the Sirius Fm.) is clearly related to the observations.
The other conclusions here are not related to the observations, and I think this area of the paper needs work. For example, "Our data support models...suggesting that EAIS advance and retreat was not synchronous..." (line 321). The fact that higher-Be-10 concentration soils are only found at more inland sites only shows that the authors were able to locate older deposits at inland sites, but did not find them at lower-elevation sites.
The discussion around line 333 also appears oversimplified and to not take into account basic glaciological principles. To conclude that one site has a younger exposure age than another should involve showing that the difference between measured concentrations is significantly larger than we expect based on the scatter of the data used in the concentration-inventory transfer function. My overall point is that the oversimplified nature of this discussion gives the impression that the authors have not thought very hard about this. To get from the actual observations in this paper to a conclusion about glacier change, I would expect to the following steps: first, clearly describe, map, and identify glacial deposits that have been sampled; second, show whether or not samples from the same deposits are the same age, and then, third, conclude whether or not each mapped deposit is synchronous or time-transgressive. Many of these steps are absent here.

These are all very valid points. Given the other suggestions and changes throughout the manuscript, the revisions we made rectified much of Referee #2's concerns. Instead of focusing on EAIS behavior, the revised manuscript focuses on the relationship between meteoric ^{10}Be and NO_3^- concentrations to estimate relative ages and understand landscape disturbance from wetting events. Since there are few, if any, data from many of the ice-free areas we sampled, we believe our data and measurements are important and have emphasized this. Additionally, by focusing on smaller-scale processes, we were able to make inferences regarding arid conditions in the CTAM (see Section 6.3). As we and Referee #2 point out, the shape of NO_3^- and ^{10}Be profiles should appear similar in persistent arid conditions since both constituents are atmospherically derived. Deviations from this expected relationship can indicate wetting or ^{10}Be erosion/deposition, which have particularly important implications for ecological succession. These points primarily constitute the discussion and conclusions.

VI. Suggested reorganization.

This section makes some suggestions for how I would rewrite this paper to make it better. Mainly, I suggest significantly simplifiying the paper, focusing much more on the data that were actually collected in this study and not on broader topics that may seem more important but lack a clear relation to the data, and also being much more clear on the chain of reasoning between observations and conclusions. I suggest an outline *that looks like the following:*

1. Begin the paper by describing why the study was designed and conducted in the way that it was – as a means of estimating surface age for biological survey purposes – and then pointing out that the purpose of this paper is to describe the soil age data, which may also be useful for understanding geomorphology and glacier change in this area. I would remove the claim in the introduction that these data are likely to provide significant information as to the stability of the Antarctic ice sheets in warm periods.

2. Describe the sample sites and the approach of sampling a likely-post-LGM and likely-pre-LGM site in each area. Discuss in detail the physical and geomorphic characteristics of the site as well as any evidence for the mode of deposition of the parent material and also whether the soil is inflationary or deflationary.

3. Explain how meteoric Be-10 in soils works in a way that is simpler and clearer than it is in the present paper, by removing Equation 1 and focusing on the relationship between inventory and age and the need to relate concentration to inventory to make an estimate of the age from one surface sample. Explain both ways of relating N to I. Be clear about what "inheritance" is.

4. Explain the expected relationship between Be-10 and NO3.

5. In the data analysis section, begin by establishing whether the basic premises of the study (ice-distal sites should have more Be-10, and LGM-age sites should have the amount of Be-10 expected to have accumulated since the LGM) are true. Note that the depth profile data are not adequate to estimate background concentrations, and remove this section of the discussion. After addressing the basic validation of the approach, move on to secondary questions such as whether presumed LGM-age sites have similar Be-10/NO3 inventories up and down the glacier, and differences in Be-10/NO3 inventories among pre-LGM sites.

6. Convert concentrations to exposure ages and compare these to the expected distribution of LGM deposits as well as other exposure age data for the sites where there are some data. Use maps of these sites to clearly show the geographic relationship between your and other data.

7. With regard to the implications of these results for larger-scale issues having to do with ice sheet change during warm periods, I don't think the exposure age aspect of these results significantly changes the overall picture that previous research has derived from the existing several thousand exposure ages from Antarctica. On the other hand, the idea that salt accumulations can give some information on past warm climates (was it warm enough for liquid water to be present in soils, and if so, when?) could be very significant. Unfortunately, there is very little discussion of this in the paper. From first principles, I would expect NO3 and Be-10 to be correlated in dry soils, because both would accumulate and not be removed. But as soon as water is present and leaching of NO3 can occur, one would expect a lack of correlation. Thus, the relationship between these two soil age proxies could be quite valuable for paleoclimate. I would give this more attention in a revised paper.

In general, in rewriting this paper, I very strongly urge the authors to focus much more *on the specific things that they measured and observed.*

We are grateful to Referee #2 for such a detailed review and have used their suggested organization as a guide for our revisions.

VII. Minor comments, by line number.

> *Line 37 (The WAIS has been drastically reduced in size) and line 52 (A growing body of work that suggests...susceptible....). These areas incompletely describe the evidence for ice sheet change during warm periods. There exist model simulations that show that deglaciation of very large marine-based areas of the ice sheets is possible during warm climates. These are not evidence, but hypotheses that the model simulations show are physically possible. There is some indirect evidence (e.g., marine oxygen isotope data) that, given several assumptions, may be consistent with this hypothesis, but is also consistent with the hypothesis that minimal deglaciation occurred. There is one piece of direct evidence (Be-10 in Siple Coast subglacial till; see Scherer and others) showing that the WAIS was smaller by an unknown amount sometime during the later Pleistocene. There is no direct evidence that hypothetical collapses simulated by ice sheet models took place. In fact, the best effort so far to test this hypothesis by subglacial bedrock recovery drilling in West Antarctica (Stone and others, recent WAIS meeting abstracts describing bedrock recovery drilling at Pirrit Hills) did not show any evidence for WAIS collapse. Thus, ice sheet collapses during warm periods need to be presented as a hypothesis and not as an accepted fact.*
>
> *Note that the text around line 75 is much more clear in this regard and correctly distinguishes evidence and model predictions.*

We have considered these comments and made the changes in our introduction.

> *Near Line 100 . The authors should not mix up evidence for sustained aridity in icefree areas with evidence for changes in the size of the ice sheet. Aridity does not necessarily require a large ice sheet, and ice sheet collapses due to marine ice margin instabilities could have occurred during cold, arid conditions. These two lines of reasoning should be kept separate.*

We have separated these lines of reasoning in the introduction and discussion.

> *Line 101-102. I did not understand these sentences.*

We have removed these sentences.

> *Line 117. "High rates" is incorrect. Because this area is extremely arid by global standards, salt is delivered at a very low rate when compared to normal places. What is different here is not a high rate of supply but a low or zero rate of removal.*

We have made this correction.

Line 122-3. This discussion gives the impression of not being well founded in glacial geological observations. The critical difference between moraines deposited by frozenbased and wet-based ice is not their size, but rather their sedimentology. I looked at imagery of the Bennett Platform moraines and although they are large, they appear to be mostly composed of large boulders. No evidence is given in this paper that they include a fine-grained, matrix-supported till with striated clasts that would indicate formation by wet-based ice. If the authors did observe this, they should certainly describe it, with pictures, because matrix-supported tills near the ice margin in this region would be very surprising. It seems more likely that these moraines are typical boulder moraines deposited by frozen-based ice, and their anomalous size may simply be related to the supply of boulders from large overhanging cliffs.

We agree with Referee #2 and have made this correction (see Line 135).

Line 140-ish. I think this could be stated more clearly simply by saying "We collected surface samples at all sites and 3-sample depth profiles at three sites."

We have clarified the sampling methodology.

Line 198ish. Because the sites you are sampling are soils and not rocks, I don't think these rock surface erosion rates are relevant. I suggest looking at papers by Dan Morgan and Jaakko Putkonen about the Dry Valleys to get an idea of the expected range for erosion rates of unconsolidated material. However, as noted above, most of these data are from hillslopes (although not all) and it's very possible that sediment deposition, rather than erosion, is taking place at some of the sites in the present paper.

It is documented that ash layers and hillslopes have relatively high erosion rates, likely much higher than the rates expected for soils in the CTAM. We do not think these erosion rates are applicable for the Shackleton Glacier region as a whole. We are explicit in saying we are using a rock erosion rate, note the limitations, and provide ages without erosion terms (Sections 4.3, 5.3, and 6.3).

line 204. What is the "coast"? It appears that the "coast" here is where the glacier flows into the ice shelf, but that makes very little sense in this context if one is thinking of the ocean as the source of salts. Open ocean is much farther away.

Coast in this context represents the point where the glacier is no longer constrained by the TAM and flows into the ice shelf. We do not rely on distance to open ocean due to seasonal and yearly changes in this distance from sea ice extent, and to be consistent with biological literature. We have clarified in the text (Line 143).

Line 269. The amount of time that soils are ice free must be longer for sites that are farther away from the glacier simply because of geometry. The ice sheet cannot cover more ice-distal sites unless it has already covered the ice-proximal sites. Thus, for any ice advance-retreat history, ice-distal sites will always be exposed longer. My point is that this is not a conclusion of the study (which is what this text sounds like), but it must be true under any circumstances no matter what the results.

We agree and have removed this statement from the conclusions.

Relative terrestrial exposure ages inferred from meteoric ^{10}Be and NO_3^- concentrations in soils along the Shackleton Glacier, Antarctica

Melisa A. Diaz[1,2], Lee B. Corbett[3], Paul R. Bierman[3], Byron J. Adams[4], Diana H. Wall[5], Ian D. Hogg[6,7], Noah Fierer[8], W. Berry Lyons[1,2]

[1]School of Earth Sciences, The Ohio State University, Columbus, OH, 43210, USA
[2]Byrd Polar and Climate Research Center, The Ohio State University, Columbus, OH, 43210, USA
[3]Department of Geology, University of Vermont, Burlington, VT, 05405, USA
[4]Department of Biology, Evolutionary Ecology Laboratories, and Monte L. Bean Museum, Brigham Young University, Provo, UT, 84602, USA
[5]Department of Biology and School of Global Environmental Sustainability, Colorado State University, Fort Collins, CO, 80523, USA
[6]Canadian High Arctic Research Station, Polar Knowledge Canada, Cambridge Bay, NU, X0B0C0, Canada
[7]School of Science, University of Waikato, Hamilton, 3216, New Zealand
[8]Department of Ecology and Evolutionary Biology and Cooperative Institute for Research in Environmental Science, University of Colorado Boulder, Boulder, CO, 80309, USA

Correspondence to: Melisa A. Diaz (diaz.237@osu.edu)

Abstract. Modeling studies and field mapping show that increases in ice thickness during glacial periods were not uniform across Antarctica. Rather, outlet glaciers that flow through the Transantarctic Mountains (TAM) experienced the greatest changes in ice thickness. As a result, ice-free areas that are currently exposed may have been covered by ice at various points during the Cenozoic, ~~thereby providing a record of past ice sheet behavior~~creating an enigma in understanding ecological succession in TAM soils. We collected soil surface samples and depth profiles every 5 cm to refusal (up to 30 cm) from eleven ice-free areas along the Shackleton Glacier, a major outlet glacier of the East Antarctic Ice Sheet (EAIS). We ~~and~~ measured meteoric ^{10}Be and NO_3^- concentrations to calculate measured (using ^{10}Be inventory), ~~and~~ estimated (using NO_3^-), and inferred (using surface ^{10}Be) surface exposure ages, both with and without an assumed erosion term. Exposure ages ranged from 58 ka to >6.5 Ma with an assumed erosion value and 57 ka to 1.9 Ma without erosion, with the youngest ages near the glacier terminus and at lower elevations. We correlated NO_3^- concentrations with meteoric ^{10}Be to estimate exposure ages for all locations with NO_3^- depth profiles but only surface ^{10}Be data. ~~These~~Our results indicated that NO_3^- concentrations can be used in conjunction with few meteoric ^{10}Be to ~~help interpret EAIS dynamics over time~~rapidly and efficiently estimate relative surface exposure ages. Lastly, in comparing NO_3^- and ^{10}Be depth profile measurements, we found that much of the southern portion of the region has likely developed undisturbed under a hyper-arid regime.

~~Using ^{10}Be inventories from three locations, calculated maximum exposure ages range from 4.1 Myr at Roberts Massif near the Polar Plateau to 0.11 Myr at Bennett Platform further north. When corrected for inheritance of ^{10}Be from prior exposure, the ages (representing a minimum) range from 0.14 Myr at Roberts Massif to 0.04 Myr at Thanksgiving Valley. We correlate NO_3^- concentrations with meteoric ^{10}Be to estimate exposure ages for all locations with NO_3^- depth profiles but only surface ^{10}Be data. These results indicate that NO_3^- concentrations can be used in conjunction with meteoric ^{10}Be to help interpret EAIS dynamics over time. We show that the Shackleton Glacier has the greatest fluctuations near the Ross Ice Shelf while tributary glaciers are more stable, reflecting the sensitivity of the EAIS to climate shifts at TAM margins.~~

1. Introduction

One of the most intriguing questions in biogeography concerns the relationship between the evolution of terrestrial organisms and landscape disturbance (e.g. glacial overriding), particularly in Antarctica. Current data indicate that organism lineages have survived in some Antarctic soils for possibly millions of years, despite multiple glaciations throughout the Pleistocene (Convey et al., 2008; Fraser et al., 2012; Stevens and Hogg, 2003). It is still unclear how and where these organisms found suitable glacial refugia given the high salt concentrations in high-elevation soils (Lyons et al., 2016). The most biodiverse soils in the Ross Sea sector are at low elevations near the coast, where the Ross Ice Shelf or sea ice meet the Transantarctic Mountains (TAM) (Collins et al., 2020). These soils are also those which are most susceptible to glacial overriding during glacial maxima, though the timing of retreat and glacial extent is still unknown on local scales (Golledge et al., 2012; MacKintosh et al., 2011).

Antarctica is believed to have maintained a persistent ice sheet since potentially the Eocene epoch, and the East and West Antarctic Ice Sheets (EAIS and WAIS, respectively) have waxed and waned since at least the Miocene (Gasson et al., 2016; Gulick et al., 2017). Sediment core records collected from the Ross Sea and ice cores from the Antarctic interior indicate that the EAIS and WAIS have undergone several glacial and interglacial cycles (Augustin et al., 2004; Talarico et al., 2012). The WAIS is a marine-terminating ice sheet with a grounding line below sea level, which decreases the stability of the ice sheet and results in rapid ice sheet advance and retreat during interglacial periods compared to the EAIS (Pollard and DeConto, 2009). The EAIS is grounded above sea level and is generally more stable than the WAIS. The EAIS and WAIS were at their most recent greatest extent during the Last Glacial Maximum (LGM) (~22,000 yrs. ago) (Clark et al., 2009). During the LGM, the EAIS expanded along its margins and the greatest increases in height occurred at outlet glaciers, which flow through exposed peaks of the Transantarctic Mountains (TAM) and drain into the Ross and Weddell Seas (Anderson et al., 2002; Golledge et al., 2012; Mackintosh et al., 2014). As a result, many of the currently exposed TAM soils were overlain by ice during the LGM and some may have only recently been exposed.

Much of the Antarctic continent is a polar desert regime and geomorphological data from ice-free soils in the McMurdo Dry Valleys indicate that some regions have likely been hyper-arid for as long as 15 Mya (Marchant et al., 1996; Valletta et al., 2015). ~~Following several reviews of the stable versus dynamic EAIS debate, Barrett (2013) concluded that the~~

~~EAIS maintained polar desert conditions with minimal retreat throughout the Pliocene.~~As such, atmospherically-derived constituents, including salts and metals, can accumulate in exposed Antarctic soils at concentrations similar to those from the Atacama and Namib Deserts (Diaz et al., 2020; Lyons et al., 2016; Reich and Bao, 2018). Using soil nitrate concentrations from the Meyer Desert in the Beardmore Glacier region and nitrate fluxes calculated from a Dominion Range ice core, Lyons et al. (2016) estimated that at least 750,000 years have passed since the Meyer Desert had wide-spread soil wetting. It is likely that other high elevation and inland locations in the TAM also have high concentrations of salts and similarly old "wetting ages".

~~Here, we~~We ~~evaluated fluctuations of the EAIS during glacial and potentially interglacial periods~~calculated relative surface soil exposure ages of ice-free areas along the Shackleton Glacier, a major outlet glacier of the EAIS. Outlet glaciers are among the most sensitive areas to glaciological change in Antarctica, and changes in their extents over time are recorded in nearby sedimentary deposits (Golledge et al., 2013; Jones et al., 2015; Scherer et al., 2016; Spector et al., 2017). ~~We focus on the Shackleton Glacier, a major outlet glacier of the EAIS.~~ The Shackleton Glacier ~~has~~flows between several exposed peaks of the Central Transantarctic Mountains (CTAM) ~~along the length of glacier, including at~~and ice-free areas are present at both low and high elevations. We report concentrations of meteoric ^{10}Be and nitrate (NO_3^-) in soils from eleven distinct ice-free areas and use these data to ~~calculate and estimate~~calculate the ~~-~~exposure ages. The sampling methodology was designed to capture soils which have low salt concentrations due to recent exposure from glacial retreat following the LGM and soils which were exposed since at least the last glacial period. ~~Our findings contribute to a growing body of work suggesting that some portions of the EAIS are susceptible to rapid advance and retreat.~~These age data are important for biologists seeking to understand how ecosystems structure and function following glacier advance and retreat, and can be coupled with additional geomorphological data in the CTAM to understand how the EAIS responds to changes in climate.

~~Exposed terrestrial surfaces in Antarctica have previously been used to elucidate glacial history and assess ice sheet stability during warm periods (Balco, 2011; Denton et al., 1993; Mackintosh et al., 2014). While Antarctica is thought to have had a permanent ice sheet since the Eocene, both the East and West Antarctic Ice Sheets (EAIS and WAIS, respectively) have fluctuated in extent and thickness throughout the Cenozoic (Barrett, 2013; DeConto and Pollard, 2016; Huybrechts, 1993). The WAIS has been drastically reduced in size during interglacial periods and there is evidence from~~

ANDRILL marine sediment cores suggesting there have been numerous times over the last 11 Ma with open water in the Ross Embayment (Barrett, 2013; McKay et al., 2009; Shakun et al., 2018). The most recent partial collapse of the WAIS was during the Pleistocene, and the most recent total collapse was during the Pliocene (Naish et al., 2009; Scherer et al., 1998). There are two competing hypotheses regarding the stability of the EAIS, though more information from various regions in Antarctica is necessary to fully refute or support either hypothesis. “Stabilists” argue that the EAIS is stable and has not fluctuated in size significantly over the last ~14 Ma (e.g., Denton et al., 1993), while “dynamicists” suggest that the EAIS is dynamic and waxes and wanes (e.g., Webb and Harwood, 1991).

The collapse of the WAIS during the Pliocene contributed ~5 m to sea level, but Pliocene sea levels were at least 25 m higher than today, indicating additional water sources, likely from the EAIS and Greenland Ice Sheet (GIS) (Dwyer and Chandler, 2009; Pollard and DeConto, 2009). There is substantial evidence indicating that the WAIS is susceptible to collapse due to warming (Pollard and DeConto, 2009); however, the overall stability of the EAIS has also been questioned (Huybrechts, 1993; Scherer et al., 2016; Sugden, 1996; Wilson, 1995).

Here, we evaluated fluctuations of the EAIS during glacial and potentially interglacial periods. Outlet glaciers are among the most sensitive areas to glaciological change in Antarctica, and changes in their extents over time are recorded in nearby sedimentary deposits (Golledge et al., 2013; Jones et al., 2015; Scherer et al., 2016; Spector et al., 2017). We focus on the Shackleton Glacier, a major outlet glacier of the EAIS. The Shackleton Glacier has several exposed peaks of the Transantarctic Mountains (TAM) along the length of glacier, including at both low and high elevations. We report concentrations of meteoric ^{10}Be and nitrate (NO_3^-) in soils from eleven ice-free areas and use these data to calculate and estimate exposure ages. Our findings contribute to a growing body of work suggesting that some portions of the EAIS are susceptible to rapid advance and retreat.

2. Background

2.1. Stability of the EAIS

There are two competing hypotheses regarding the stability of the EAIS, though more information from various regions in Antarctica is necessary to fully refute or support either hypothesis. “Stabilists” argue that the EAIS is stable and has not fluctuated in size significantly over the last ~14 Ma (e.g., Denton et al., 1993), while "dynamicists" suggest that the EAIS is dynamic and waxes and wanes (e.g., Webb and Harwood, 1991). Previous studies used a variety of geomorphological and exposure age dating techniques at high elevations (>1000 m) in the McMurdo Dry Valleys (MDV) to assert that the Antarctic interior maintained its aridity and cold-based glaciers since the mid-Miocene (Lewis et al., 2008; Sugden, 1996; Sugden et al., 1993, 1995). These studies suggest major thickening of outlet glaciers but no major ice sheet retreat during the Pliocene (Golledge et al., 2013; Golledge and Levy, 2011; Marchant et al., 1996).

Evidence for a dynamic EAIS is derived primarily from the diamictite rocks (tills) of the Sirius Group, which are found throughout the Transantarctic Mountains and include well-documented outcrops at the Shackleton Glacier. The Sirius Group deposits are characteristic of warm and polythermal based glaciers (Hambrey et al., 2003), but their age is not known. Some of the deposits contain pieces of shrubby vegetation, suggesting that the Sirius Group formed under conditions warmer than present with trees occupying inland portions of Antarctica (Webb et al., 1984, 1996; Webb and Harwood, 1991). Sparse marine diatoms found in the sediments were initially interpreted as evidence for formation of the Sirius Group via glacial over riding of the Transantarctic Mountains during the warmer Pliocene (Barrett et al., 1992), though it is now argued that the marine diatoms were wind-derived contamination, indicating that the Sirius Group is older (Scherer et al., 2016; Stroeven et al., 1996). Following several reviews of the stable versus dynamic EAIS debate, Barrett (2013) concluded that the EAIS maintained polar desert conditions with minimal retreat throughout the Pliocene. More recent models have suggested that portions of the EAIS, particularly outlet glaciers, were and still are susceptible to rapid retreat (DeConto and Pollard, 2016; Scherer et al., 2016). However, the degree of EAIS sensitivity to warming is model-dependent and exposure ages/proxy data are needed to constrain model results (Dolan et al., 2018).

2.12. Cosmogenic nuclide exposure age dating and meteoric ^{10}Be systematics

^{10}Be is a cosmogenic radionuclide with a half-life of 1.39 Ma (Korschinek et al., 2010) that is produced both in the atmosphere (meteoric) and *in-situ* in mineral grains. In the atmosphere, N and O gases are bombarded by high energy cosmic radiation to produce meteoric ^{10}Be. Particle reactive ^{10}BeO or $^{10}Be(OH)_2$ is produced and removed from the atmosphere by wet and dry deposition (McHargue and Damon, 1991). At Earth's surface, meteoric ^{10}Be sorbs onto clay particles and it is insoluble in most natural waters of pH greater than 4 (Brown et al., 1992; You et al., 1989). The clay particles can be redistributed to lower depths in the soil profile due to particle migration, or can be transported by winds. As such, the number of ^{10}Be atoms in a soil profile, also known as inventory, is a function of ~~Meteoric ^{10}Be accumulation in soils is controlled by~~ surface exposure duration, erosion, clay particle translocation, solubility, and sedimentation. Thus, meteoric ^{10}Be can be used as a tool to understand exposure age, erosion rates, and soil residence times (see Willenbring and Von Blanckenburg, 2009 and references within).

The measurement and use of meteoric ^{10}Be has enabled researchers to date surfaces and features ~~which otherwise lack sufficient coarse-grained quartz for *in-situ* ^{10}Be analysis~~in Antarctica. Previous studies have measured meteoric ^{10}Be in MDV and Victoria Land soils and sediments to calculate exposure ages and to determine the onset of the current polar desert regime (Dickinson et al., 2012a; Graham et al., 2002; Schiller et al., 2009; Valletta et al., 2015). In general, t~~T~~hese previous studies ~~generally show~~ found that high elevation, northern fringe regions along the Ross Embayment have been hyper-arid since at least the Pliocene. Meteoric ^{10}Be data have yet to be published from the ~~central Transantarctic Mountains (~~CTAM~~),~~ which represent ice sheet dynamics and climatic conditions closer to the Polar Plateau.

2.2~~1. Stability of the EAIS~~Nitrate systematics in Antarctic soils

Compared to the nitrogen cycle in temperate regions, the nitrogen cycle in Antarctica is relatively simplistic due to scarce biomass, and most nitrogen exists as nitrate (NO_3^-) (Cary et al., 2010; Michalski et al., 2005). The NO_3^- in CTAM soils is primarily sourced from the atmosphere, with varying contributions from the troposphere and stratosphere (Diaz et al., 2020; Lyons et al., 2016; Michalski et al., 2005). Similar to meteoric ^{10}Be, NO_3^- is deposited on exposed soils, though contrarily, nitrate salts are highly water-soluble. Once deposited on the surface, nitrate salts can be dissolved and transported to lower elevations or at depth when wetted (i.e. during ice/snow melt events). However, the hyper-arid climate of the CTAM allows NO_3^- to accumulate to high concentrations in soils (Claridge and Campbell, 1968a; Diaz et al., 2020; Lyons et al., 2016). Soil NO_3^- concentrations have the potential to inform wetting history and possibly glacial history in the CTAM, though uncertainties regarding heterogeneous deposition and post-depositional alteration (such as re-volatilization and photolysis) require further investigation (Diaz et al., 2020; Frey et al., 2009; Graham et al., 2002).

Here, we used meteoric ^{10}Be and NO_3^- concentrations to estimate CTAM relative exposure ages, acknowledging the widespread use of *in-situ* exposure age dating which we later used for cross-validation. *In-situ* cosmogenic nuclides, such as ^{10}Be, ^{26}Al, ^{21}Ne, and ^{3}He, have been used measured to determine surface exposure ages at several locations across Antarctica, particularly in the MDV and other exposed surfaces in Victoria Land (e.g. (Balco et al., 2019; Brook et al., 1993, 1995; Bruno et al., 1997; Ivy-Ochs et al., 1995; Strasky et al., 2009). There are considerably fewer studies from the CTAM (e.g., (Ackert and Kurz, 2004; Balter-Kennedy et al., 2020; Bromley et al., 2010; Kaplan et al., 2017; Spector et al., 2017), and. previously reported eExposure ages of CTAM tills moraines and boulders from these studies from those previous studies ranged from <10 ka to >14 Ma. We seek to utilize NO_3^- and meteoric ^{10}Be concentrations to attain a greater number of surface exposure ages and understand the relationship between NO_3^- and ^{10}Be in the hyper-arid environment of the CTAM.

, and their results suggest that the EAIS may have maintained persistent arid conditions since as early as the Miocene. . However, many of these age-date estimates were inferred from samples collected at the glacier heads and may not encompass fluctuations near the glacier terminus. Additionally, *in-situ* dating relies on the occurrence of coarse-grained minerals (usually quartz) in rocks and boulders, and thus is spatially limited.

3. Study sites

Shackleton Glacier (~84.5 to 86.4°S; ~130 km long and ~10 km wide) is a major outlet glacier of the EAIS which drains north into the Ross Embayment with other CTAM outlet glaciers to form the Ross Ice Shelf (RIS) (Fig. 1). The ice flows between exposed surfaces of the Queen Maud Mountains, which range from elevations of ~150 m near the RIS to >3,500 m further inland. The basement geology of the Shackleton Glacier region is comprised of igneous and metamorphic rocks that formed from intruded and metamorphosed sedimentary and volcanic strata during the Ross Orogeny (450-520 Ma) (Elliot and Fanning, 2008). The southern portion of the region consists of the Devonian-Triassic Beacon Supergroup and the Jurassic Ferrar Group, while the northern portions consists of Pre-Devonian granitoids and the Early to Mid-Cambrian Taylor Group (Elliot and Fanning, 2008; Paulsen et al., 2004). These rocks serve as primary weathering products for soil formation (Claridge and Campbell, 1968b). Deposits of the Sirius Group, the center of the stable vs. dynamic EAIS debate, have been previously identified in the southern portion of the Shackleton Glacier region, particularly at Roberts Massif (Fig. 2) and Bennett Platform, with a small exposure at Schroeder Hill (Hambrey et al., 2003).

The valleys and other ice-free areas within the region have been modified by the advance and retreat of the Shackleton Glacier, smaller tributary glaciers, and alpine glaciers. Similar to the Beardmore Glacier region, the Shackleton Glacier region is a polar desert, which results in high ~~rates of salt accumulation~~ accumulation of salts in soils. The surface is comprised primarily of till, weathered primary bedrock, and scree, which range in size from small boulders and cobbles to sand and silt. Clays have been previously identified in all samples from Roberts Massif and are likely ubiquitous throughout the region (Claridge and Campbell, 1968b). However, the clays are a mixture of those derived from sedimentary rocks and contemporaneous weathering (Claridge and Campbell, 1968b). Thin, boulder belt moraines, characteristic of cold-based glaciers, were deposited over bedrock and tills at Roberts Massif, while large moraines were deposited at Bennett Platform~~,~~ ~~characteristic of warm or polythermal glacial dynamics~~ (Fig. 2, Balter-Kennedy et al., 2020; Claridge and Campbell, 1968). Additional information on the sample locations and surface features is detailed in Tables 1 and 2.

4. Methods

4.1. Sample collection

During the 2017-2018 austral summer, we visited eleven ice-free areas along the Shackleton Glacier: Roberts Massif, Schroeder Hill, Bennett Platform, Mt. Augustana, Mt. Heekin, Thanksgiving Valley, Taylor Nunatak, Mt. Franke, Mt. Wasko, Nilsen Peak, and Mt. Speed (Fig. 1). These areas represent soils near the head of the glacier and near the glacier terminus at the coast of the RIS. Two samples (Table 1) were collected at each location (except for Nilsen Peak and Mt. Wasko, represented by only one sample) with a plastic scoop and stored in Whirl-Pak™ bags. One sample was collected furthest from the Shackleton Glacier or other tributary glaciers (within ~2,000 m) ~~in a transect~~ to represent soils that were likely exposed during the Last Glacial Maximum (LGM) and previous recent glacial periods. A second sample was collected closer to the glacier (between ~1,500 and 200 m from the first sample) to represent soils likely to have been exposed by more recent ice margin retreat.

Soil pits were dug by hand at the sampling locations furthest from the glacier for Roberts Massif, Schroeder Hill, Mt. Augustana, Bennett Platform, Mt. Heekin, Thanksgiving Valley, and Mt. Franke. Continuous samples were collected every 5 cm until refusal (up to 30 cm) and stored frozen in Whirl-Pak™ bags. All surface (21) and depth profile (25) samples were shipped frozen to The Ohio State University and kept frozen until analyzed.

4.2. Analytical methods

4.2.1. Meteoric ^{10}Be analysis

A total of 30 sub-samples of surface soils from all locations and depth profiles from Roberts Massif, Bennett Platform, and Thanksgiving Valley were sieved to determine the grain size at each location. The percentages of gravel (>2 mm), sand (63 ~~-425~~μm-2 mm), and silt (<63 μm) are reported in Table S1. Since there is a strong grain size dependence of meteoric ^{10}Be where very little ^{10}Be is carried on coarse (>2 mm) grains (Pavich et al., 1986), the gravel portion of the sample was not included in the meteoric ^{10}Be analysis. The remaining soil (<2 mm) was ground to fine powder using a shatterbox.

Meteoric ^{10}Be (Table 2) was extracted and purified at the NSF/UVM Community Cosmogenic Facility following procedures originally adapted and modified from Stone (1998). First, 0.5 g of powdered soil was weighed into platinum crucibles and 0.4 g of SPEX ^{9}Be carrier (with a concentration of 1,000 μg mL^{-1}) was added to each sample. The samples were fluxed with a mixture of potassium hydrogen fluoride and sodium sulfate. Perchloric acid was then added to remove potassium by precipitation and later evaporated. Samples were dissolved in nitric acid and precipitated as beryllium hydroxide ($Be(OH)_2$) gel, then packed into stainless steel cathodes for accelerator mass spectroscopy isotopic analysis at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab). Isotopic ratios were normalized to primary standard 07KNSTD with an assumed ratio of 2.85 x 10^{-12} (Nishiizumi et al., 2007). We corrected sample ratios with a ^{10}Be/^{9}Be blank ratio of 8.2 ± 1.9 x 10^{-15}, which is the average and standard deviation of two blanks processed alongside the samples. We subtracted the blank ratio from the sample ratios and propagated uncertainties in quadrature.

4.2.2. Nitrate analysis

Separate, un-sieved sub-samples of soil from all locations and depth profiles were leached at a 1:5 soil to water ratio for 24 hours, then filtered through a 0.4 µm Nucleopore membrane filter. The leachate was analyzed on a Skalar San++ Automated Wet Chemistry Analyzer with a SA 1050 Random Access Auto-sampler (Lyons et al., 2016; Welch et al., 2010). Concentrations are reported as NO_3^- (Table S2) with accuracy, as determined using USGS 2015 standard, and precision better than 5% (Lyons et al., 2016).

4.3. Exposure age model

We developed a mass balance using the fluxes of meteoric ^{10}Be ~~in and out~~ to and from~~of~~ Shackleton Glacier region soils to calculate the amount of time which has passed since the soil was exposed (Pavich et al., 1984, 1986). The model assumes that soils that were overlain by glacial ice in the past, and are now exposed, accumulated a lower surface concentration and inventory of ^{10}Be than soils that were exposed throughout the glacial period (Fig. 3). The concentration of meteoric ^{10}Be at the surface (N, atoms g^{-1}) per unit of time (dt) is expressed as a function ~~(Eq. 1)~~, where the addition of ^{10}Be is represented as the atmospheric flux to the surface (Q, atoms cm^{-2} yr^{-1}), ~~and the~~ removal ~~is~~ due to radioactive decay is~~,~~ represented by a disintegration constant (λ, yr^{-1}) ~~and,~~ and erosion (E, cm yr^{-1}) is with respect to soil density (ρ, g cm^{-3}) (Eq. 1). Particle mobility into the soil column is represented by a diffusion constant (D, cm^2 yr^{-1}) multiplied by a concentration gradient. ~~.~~

$$\frac{dN}{dt} = Q - \lambda N - E\frac{d\rho N}{dz} - D\frac{d^2N}{dz^2} \quad (1)$$

However, this function is highly dependent on dz, which represents an unknown value of depth into the soil column which is influenced by meteoric ^{10}Be deposition and removal. Additionally, the soil diffusion term is unconstrained and likely varies with depth. We ~~can~~ accounted for these~~is~~ ~~uncertaint~~uncertainties ~~y~~ and other uncertainties regarding ^{10}Be migration in the soil column by calculating the inventory (I, atoms cm^{-2}) of the soil (Eq. 2), assuming that Q ~~has~~ had not changed systematically over the accumulation interval (Graly et al., 2010; Pavich et al., 1986). The inventory is the total sum of meteoric ^{10}Be atoms in the soil profile and the change in inventory due to deposition, decay, and surface erosion is related surface exposure age (Eq. 3).

Formatted: Font: 10.5 pt
Formatted: Font: 10.5 pt
Formatted: Font: 10.5 pt
Formatted: Font: 10.5 pt
Formatted: Font: 10.5 pt
Formatted: Font: 10.5 pt
Formatted: Font: 10.5 pt
Formatted: Font: 10.5 pt
Formatted: Font: 10.5 pt
Formatted: Font: 10.5 pt
Formatted: Font: 10.5 pt
Formatted: Font: Italic

$$I = \sum N \cdot \rho \cdot dz \qquad (2)$$

$$\frac{dI}{dt} = Q - \lambda I - EN \qquad (3)$$

If~~ we know~~ the inventory of meteoric ^{10}Be in the soil profile, the concentration at the surface, and soil density are known, and ~~use~~ published values for erosion and ^{10}Be flux to the surface are used, we can combine Eqs. (1~~) and Eq. (2~~-3), and solve for time (t, years) (Eq. 4~~3~~).

$$t = -\frac{1}{\lambda} \cdot \ln\left[1 - \frac{\lambda I}{Q - E\rho N}\right] \qquad (4)$$

Equation (4~~3~~) provides a maximum exposure age assuming that the soil profile did not have meteoric ^{10}Be before it was exposed to the surface ($N_0 = 0$). Since our exposure age dating technique relies on the number of ^{10}Be atoms within the sediment column (I), any pre-existing ^{10}Be atoms in the soil ($N_0 \neq 0$) can cause the calculated age to be an overestimate (Fig. 3c-d) (Graly et al., 2010). Meteoric ^{10}Be concentrations typically decrease with depth until they reach a "background" level (Graly et al., 2010). The background is identified as the point where the concentration of meteoric ^{10}Be is constant with depth ($\frac{dN}{dz} = 0$). ~~We can use that~~ Typically, the background values ~~to~~ can be used to calculate an initial inventory~~, also referred to as inheritance~~ (I_i, atoms cm^{-2}) using Eq. (5~~4~~)~~,~~ where N_z is the ^{10}Be concentration (atoms g^{-1}) at the bottom of the profile (z, cm), and correct the observed total inventory (Eq. ~~5~~6). In this case, we assume that the initial concentration of meteoric ^{10}Be is isotropic. However, an accurate initial inventory ~~I_i~~ can only be determined for soil profiles which ~~have a~~ decrease in ^{10}Be concentrations to background levels due to the downward transport of ^{10}Be from the surface. This may not be the case in areas of permafrost where ^{10}Be is restricted to the active layer (Bierman et al., 2014).

$$I_i = N_z \cdot \rho \cdot z \qquad (5)$$

$$t = -\frac{1}{\lambda} \cdot \ln\left[1 - \frac{(I - I_i)\lambda}{Q - E\rho N}\right] \qquad (6)$$

Formatted: Indent: First line: 0", Tab stops: 6", Left

Additionally, the initial inventory can be influenced by repeated glacial advance and retreat during glacial-interglacial cycles. For this case, the soil has "inherited" ^{10}Be during each subsequent exposure to the atmosphere, some of which may be been eroded (Fig. 3c-d). For constructional landforms, such as moraines, the inheritance is equal to the background/initial inventory. Without information on drift sequences, it is difficult to correct the measured inventory for inheritance by distinguishing meteoric ^{10}Be that was deposited after the most recent ice retreat from ^{10}Be that was deposited during previous interglacial periods. Instead, only ages that represent total time of exposure through glacial-interglacial cycles, likely as overestimates, can be reported with confidence.

~~$$I_t = N_z \cdot \rho \cdot z \qquad (4)$$~~

~~$$t = -\frac{1}{\lambda} \cdot \ln\left[1 - \frac{(I - I_t)\lambda}{Q - E\rho N}\right] \qquad (5)$$~~

4.3.1. Model variable selection and key assumptions

The exposure age calculations are dependent on the selected values for the variables in Eq. (1-6~~5~~). We chose a flux value (Q) of 1.3 x 10^5 atoms cm^{-2} yr^{-1} from Taylor Dome (Steig et al., 1995) due to a similar climate to that of the CTAM and an absence of local meteoric ^{10}Be flux data. Soil density (ρ) across the Shackleton Glacier region was approximately 2 g cm^{-3}. While we did not calculate erosion rates, previous studies have estimated rates from rocks of 1 to 65 cm ~~Myr~~Ma^{-1} in Victoria Land (Ivy-Ochs et al., 1995; Margerison et al., 2005; Morgan et al., 2010; Strasky et al., 2009; Summerfield et al., 1999) and 5 to 35 cm ~~Myr~~Ma^{-1} further south in the Transantarctic Mountains (Ackert and Kurz, 2004; Balter-Kennedy et al., 2020; Morgan et al., 2010). Balter-Kennedy et al. (2020) determined that erosion rates for boulders at Roberts Massif which were less than 2 cm ~~Myr~~Ma^{-1}. However, we chose a conservative value of 5 cm ~~Myr~~Ma^{-1} for our analysis of the Shackleton Glacier region. ~~Soil density (ρ) across the Shackleton Glacier region was approximately 2 g cm^{-3}.~~

It is important to note two key assumptions in our variable selection and model development. First, we have assumed a uniform erosion rate across the region. Given the variety of surface features at each location (Table 2), some locations on valley floors, for example, may have increased surface concentrations of meteoric ^{10}Be due to entrapment of wind-blown fine-grained sediments. Locations on hillslopes and valley walls might have higher erosion rates (Morgan et al., 2010; Schiller et al., 2009). We assumed that deflation of fine-grained material had occurred rapidly on the flat surfaces we sampled due to strong winds over the poorly consolidated tills following soil exposure (Lancaster et al., 2010). Due to a deficit of soil erosion data in the CTAM, we calculated exposure ages (Eq. 6) with the 5 cm Ma^{-1} erosion value and without the erosion/deposition term (E=0). Second, we attempted to estimate the background concentrations and initial inventory for each sample collected furthest from the glacier. We hypothesized that these samples were potentially exposed throughout at least the LGM and had negligible inheritance, though this was merely an assumption. With the possibility of overestimating or underestimating the exposure ages, we solved Eq. 6 both with and without estimated initial inventory terms. For all samples, including those without depth profile measurements, we utilized an empirical relationship derived between surface (maximum) meteoric ^{10}Be concentration and measured inventory to estimate surface exposure ages (see Section 5.3.3) (Graly et al., 2010).

Formatted: Font: Bold, Underline

Formatted: Centered, Indent: First line: 0"

5. Results

5.1. Surface concentrations Concentrations of meteoric ^{10}Be and grain sizedepth profile composition

Surface concentrations of meteoric ^{10}Be span more than an order of magnitude in the Shackleton Glacier region and range from 2.9 x 10^8 atoms g^{-1} at Mount Speed to 73 x 10^8 atoms g^{-1} at Roberts Massif (Fig. 4; Table 3). At individual sites where samples were collected at two locations, concentrations are typically highest for the samples furthest from the glacier, with notable exceptions at Roberts Massif and Thanksgiving Valley (Fig 4). This trend is expected since our sampling plan was designed to capture recently exposed soils (near the glacier(s)) and soils which have been exposed throughout the LGM and possibly other glacial periods. The measured inventories (Eq. 2) vary from 0.57 x 10^{11} atoms g^{-1} at Bennett Platform to 1.5 x 10^{11} atoms g^{-1} at Roberts Massif (Table 4). In general, concentrations of meteoric ^{10}Be increase with both distance from the coast and elevation (Fig. 5). There is a stronger relationship with distance from the coast (R^2 = 0.48), compared to elevation (R^2 = 0.39). An exception to this trend is Bennett Platform as both surface samples from Bennett Platform have lower concentrations than expected from the linear regression. If the samples from Bennett Platform are excluded from the linear regression, the R^2 values increase to 0.67 and 0.51 for distance from the coast and elevation, respectively, with p-values < 0.001 for both regressions.

Sediment grain size is similar among the three soil profiles collected from Roberts Massif, Bennett Platform, and Thanksgiving Valley; the soils are primarily comprised of sand-sized particles, with less silt-sized and smaller material (Fig.

5). The proportions of silt and gravel are similar at Roberts Massif, although the majority of the profile is sand-sized. Thanksgiving Valley has the least fine material, while Bennett Platform has a more even grain size distribution. The deepest profile is from Thanksgiving Valley, while the Roberts Massif and Bennett Platform profiles are half the depth. All three profiles are ice-cemented at the bottom and are shallow compared those collected from the McMurdo Dry Valleys (Dickinson et al., 2012b; Schiller et al., 2009; Valletta et al., 2015).

The meteoric ^{10}Be depth profiles differ between Roberts Massif, Thanksgiving Valley, and Bennett Platform. The profile from Roberts Massif has the highest overall concentrations (Fig. 6). Within the profile, the 5-10 cm sampling interval has the highest concentration, followed by the bottom of the profile, then the surface. The profile behavior for Thanksgiving Valley is similar, though the differences in concentrations within both profiles are relatively small. Bennett Platform is the only location where the surface concentration is the highest compared to the remainder of the profile, which decrease with depth (Fig. 6). Although we sampled the entirety of the active layer where particle mobility throughout the soil column occurs, no depth profiles appear to decrease to background levels to calculate an initial meteoric ^{10}Be inventory (Eq. 5). As a result, we are not able to correct the measured inventory for background ^{10}Be nor are we able estimate the inherited ^{10}Be concentration in the soil (Eq. 6).Sediment grain size is similar among the three soil profiles from Roberts Massif, Bennett Platform, and Thanksgiving Valley; the soils are primarily comprised of sand-sized particles, with less silt-sized and smaller material (Fig. 6). The proportions of silt and gravel are similar at Roberts Massif, although the majority of the profile is sand-sized. Thanksgiving Valley has the least fine material, while Bennett Platform has a more even grain size distribution.

5.2. Relationship between meteoric ^{10}Be and NO_3^-

The concentrations of NO_3^- span four orders of magnitude across the seven depth profiles sampled in the Shackleton Glacier region (Fig. S1; Table S2). The lowest concentration is from Mt. Franke at ~1 µg g^{-1}, while the highest concentration is from Roberts Massif at 15 mg g^{-1}. In addition, similar to the meteoric ^{10}Be profiles, the NO_3^- concentrations are highest for the samples which were collected furthest from the coast and at the highest elevations (Table S2). The depth profiles of NO_3^- and meteoric ^{10}Be are compared for Roberts Massif, Bennett Platform, and Thanksgiving Valley (Fig. 6b). In general, the profiles from Roberts Massif and Thanksgiving Valley are similar, where ^{10}Be and NO_3^- behavior similarlylikewise – the concentrations are highest just below the surface in the 5-10 cm interval and are fairly consistent throughout the profile.

Formatted: Font: 10 pt

Formatted: Font: Not Bold

Interestingly, the NO_3^- depth profile mirrors the ^{10}Be profile at Bennett Platform – while ^{10}Be concentrations decrease with depth, the NO_3^- concentration increases with depth.

Since the behavior of NO_3^- and ^{10}Be are similarparallel or proportionately dissimilar (as in the case for Bennett Platform), we further evaluate their relationship. When regressed on log scales, NO_3^- and ^{10}Be have a strong power-law relationship with R^2 values ranging from 0.66 to 0.99 (Fig. 6c). The power-law slope for Roberts Massif and Thanksgiving Valley is positive, while the Bennett Platform has a negative slope. Given this regressed relationship, it is possible to estimate ^{10}Be concentrations with NO_3^- concentrations (see Section 5.3.2).

5.23. Calculated maximum and inheritance-corrected exposure agesRelative exposure age calculations and estimates

5.3.1 "Measured" maximum exposure ages from Roberts Massif, Bennett Platform, and Thanksgiving Valley

We calculated exposure ages for the samples furthest from the glacier for Roberts Massif, Bennett Platform, and Thanksgiving Valley using Eq. 4, both with and without the erosion term (Table 3). The exposure ages with erosion range from 120 ka to 4.15 Ma, and the ages without erosion range from 110 ka to 1.67 Ma for Bennett Platform and Roberts Massif, respectively. Thanksgiving Valley is intermediate with an exposure age of 540 ka with erosion and 500 ka without erosion. Since we are not able to correct for initial inventory nor inheritance, the exposure ages with the erosion term represent maximum ages and the erosion rate we estimated is relatively low compared to the calculated exposure ages, with the exception of Roberts Massif. Moreover, the ages without erosion terms are probably overestimates as well.

Formatted: Font: Not Bold

Formatted: Normal, Indent: First line: 0.5"

Calculated maximum meteoric ^{10}Be exposure ages for Roberts Massif, Bennett Platform, and Thanksgiving Valley range from 0.11 Myr at Bennett Platform to 4.1 Myr at Roberts Massif, assuming no inheritance (Table 3). Bennett Platform is the only location that has exponentially decreasing ^{10}Be concentrations with depth and appears to approach background levels towards the bottom of the 15 cm deep profile. We used the 10-15 cm ^{10}Be concentration value to calculate the inheritance for this location. While ^{10}Be concentrations at Roberts Massif and Thanksgiving Valley did not exponentially decrease in a similar manner, we used the lowest concentration from each of the profiles to calculate the inheritance, which is likely an overestimate. Using Eq. (5), the inheritance-corrected exposure ages are younger and range from 0.04 Myr at Thanksgiving Valley to 0.14 Myr at Roberts Massif (Table 3). These corrected ages are minimum ages.

5.3. Estimated exposure ages for sites without meteoric ^{10}Be depth profiles

5.3.1 2 Maximum and inheritance-corrected estimated“Estimated” maximum exposure ages using NO_3^- concentrationsrelationship

As we suggest in Section 5.2, theMeteoric ^{10}Be and NO_3^- concentrations are correlated in the depth profiles from Roberts Massif, Bennett Platform, and Thanksgiving Valley, with a strong power relationship between the two measurements (R^2 = 0.66 to 0.99) (Fig. 7c). In addition, similar to the meteoric ^{10}Be profiles, the NO_3^- concentrations are highest for the samples which were collected furthest from the coast and at the highest elevations (Table S2). power-law relationship between NO_3^- and meteoric ^{10}Be can be used to estimate ^{10}Be concentrations from NO_3^- concentrations. Since we measured NO_3^- concentrations in all seven depth profiles, we compared the profile concentrations and shape from the four profiles without ^{10}Be depth measurements (Mt. Augustana, Schroeder Hill, Mt. Franke, and Mt. Heekin) to the Roberts Massif, Bennett Platform, and Thanksgiving Valley profiles with both measurements (Fig. S1). Our fundamental principle assumes that NO_3^- profiles which have similar behavior among the sites might have similar ^{10}Be profile behavior as well. The profiles are fairly homogenous and most similar to the profile from Thanksgiving Valley, though Schroeder Hill is most similar to Roberts Massif (Fig. S1). Applying the power-law relationship from Thanksgiving Valley to Mt. Augustana, Mt. Franke and Mt. Heekin, and the relationship from Roberts Massif to Schroeder Hill, we provide estimates of meteoric ^{10}Be concentrations for the entire depth profile (Table S2) and use these concentrations to calculate an estimated inventory using Eq. 2 (Table 4). Further, the estimated inventories are used to estimate exposure ages using Eq. 4, both with and without the erosion term.

The “estimated” inventories (using the NO_3^- power-law relationship) with erosion range from 0.14 x 10^{11} atoms g^{-1} at Bennett Platform to 1.5 x 10^{11} atoms g^{-1} at Roberts Massif (Table 4). The measured and estimated inventories differ by ~3-18%. The estimated exposure ages using the estimated inventory range from 120 ka to 4.54 Ma with erosion, and the ages without erosion range from 110 ka to 1.74 Ma for Bennett Platform and Roberts Massif, respectively (Table 4). We used the relationship between NO_3^- and ^{10}Be to estimate ^{10}Be concentrations for all seven soil profiles (Table 3, Fig. 8). The calculated measured and NO_3^- estimated maximum exposure ages, both with and without erosion, only differ by ~46-200% for Roberts Massif, Bennett Platform, and Thanksgiving Valley, which have full data sets for both parameters. The inheritance-corrected exposure ages have a difference of ~10-35% between the calculated and estimated ages. Since we could cannot not calculate ^{10}Be exposure ages using only ^{10}Be for the profiles from Schroeder Hill, Mt. Augustana, Mt. Heekin, and Mt. Franke, we were are not able to make similar age comparisons. However, we were canable to compare the estimated surface ^{10}Be concentrations using NO_3^- to the measured ^{10}Be concentrations. The percent differences at Schroeder Hill and Mt. Heekin are 4% and 7%, respectively, while Mt. Augustana and Mt. Franke have higher differences of 36% and 40%, respectively (Tables 3 and 4S2).

5.3.32 "Inferred" maximum exposure ages using inventory relationshipMaximum estimated ages inferred using maximum meteoric ^{10}Be concentrations

Similar to our exposure age estimates using NO_3^- concentrations, we used the relationship between the maximum meteoric ^{10}Be concentration in the soil profile and the meteoric ^{10}Be inventory (Graly et al., 2010) to "infer" ^{10}Be inventories and estimate maximum exposure ages (without a correction for inheritance) for all eleven locations, again, with and without erosion (Fig. 7; Table 5Table 4, Fig. 8). As is the case for Roberts Massif and Thanksgiving Valley, the highest concentrations may not always be at the surface for all locations; however, the relationship is sufficiently strong to provide an estimate of the ^{10}Be inventory and thus an age estimate (Fig. 7S1). Compared to the measured inventories from Roberts Massif, Bennett Platform, and Thanksgiving Valley, the inferred inventories differ by ~316-18%130%. The inferred exposure ages with erosion range from 58 ka to >6.5 Ma, and the ages without erosion range from 57 ka to 1.94 Ma for Mt. Speed and Roberts Massif, respectively (Table 4).The estimated inferred maximum exposure ages range from 0.13 Myr at Mt. Speed to >14 Myr at Roberts Massif. With the exception of Roberts Massif, and Thanksgiving Valley, and Mt. Speed, the oldest surfaces are those which we sampled furthest from the glacier, which is consistent with our sampling methodology to capture younger and older soils.. The sample from Roberts Massif collected closest to the glacier has an estimated exposure age that is outside the model limits (>14>6.5 MyrMa). The calculated measured maximum exposure ages and estimated maximum ages from the inferred inventory differ by the inferred exposure ages differ by ~4049-75% for Roberts

~~Massif and Thanksgiving Valley~~with erosion and ~15-75% without erosion. ~~, and the estimated age is half the calculated age for Bennett Platform (Table 4).~~The greatest differences between the ages are at Bennett Platform.

6. Discussion

Meteoric ^{10}Be concentrations and surface exposure ages vary widely across the Shackleton Glacier region and at individual locations. These data provide spot measurements to understand and constrain relative terrestrial exposure ages. While there are not enough data to absolutely ascertain soil ages, these meteoric ^{10}Be and NO_3^- data contribute to growing exposure age measurements, which can inform climate, landscape development, and ecology.

The Shackleton Glacier region soil profiles have the highest meteoric ^{10}Be concentrations (~10^9 atoms g^{-1}) yet measured in Earth's polar regions (Fig. 6a). Though our profiles are shallower than profiles from the MDV and Victoria Land in Antarctica (Dickinson et al., 2012a; Schiller et al., 2009; Valletta et al., 2015) and Sweden and Alaska in the Arctic (Bierman et al., 2014; Ebert et al., 2012), the soils from these previous studies reached background concentrations of ^{10}Be within the top 40 cm, which is close to our maximum depth of 30 cm at Thanksgiving Valley. The Bennett Platform soil profile is most similar to the soil profiles from other regions in Antarctica, as they have decreasing ^{10}Be concentrations with depth, while Thanksgiving Valley and Roberts Massif are relatively homogenous and more similar to profiles from the Arctic.

6.1. Calculated and estimated exposure age validation ~~6.1. Calculated and estimated exposure age validation~~

~~The Shackleton Glacier region soil profiles have the highest meteoric ^{10}Be concentrations (~10^9 atoms g^{-1}) yet measured in Earth's polar regions (Fig. 7a). Though our profiles are shallower than profiles from the MDV and Victoria Land in Antarctica (Dickinson et al., 2012a; Schiller et al., 2009; Valletta et al., 2015) and Sweden and Alaska in the Arctic (Bierman et al., 2014; Ebert et al., 2012), the soils from these previous studies reached background concentrations of ^{10}Be within the top 40 cm, which is close to our maximum depth of 30 cm at Thanksgiving Valley. Bennett Platform is most similar to the soil profiles from other regions in Antarctica, as they have decreasing ^{10}Be concentrations with depth, while Thanksgiving Valley and Roberts Massif are relatively homogenous and more similar to profiles from the Arctic. As a result, our profiles are likely sufficient for inventory and inheritance calculations.~~

Formatted: Font: 10 pt, Bold

Formatted: Indent: First line: 0", Line spacing: Multiple 1.08 li

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Our calculated~~ and ~~, estimated, and inferred exposure ages are consistent with the limited *in-situ* exposure age data from the Shackleton Glacier region (http://antarctica.ice-d.org; Balco, 2020). Exposure ages from glacial erratic boulders using *in-situ* were determined from Roberts Massif, Thanksgiving Valley, and Mt. Franke (Figs. 8 and 9). ~~ ~~From *in-situ* ^{10}Be, ^{26}Al, ^{3}He, and ^{21}Ne data, exposure ages on the northern flank of Roberts Massif range from 1.10 Ma~~~0.33~~ to 3.26~~1.58~~ Ma~~Myr~~ (Balter-Kennedy et al., 2020; ~~ICE-D~~Balco, 2020; http://antarctica.ice-d.org), and our ~~inheritance-corrected calculated age~~measured, estimated, and inferred ages without erosion are 1.67 Ma, 1.74 Ma, and 1.94 Ma, respectively. Our ages, which are likely overestimates, are comparable to these nearby *in-situ* ages at similar elevations (Figs. 8 and 9). The age with the erosion term are greater and outside the range from Balter-Kennedy et al. (2020). This suggests that soil erosion rates are probably low at Roberts Massif, and the initial inventory and ^{10}Be inheritance from previous exposure are likely significantly smaller than the measured inventory. Otherwise, the corrected meteoric ^{10}Be exposure ages would be much greater than the *in-situ* ages.

~~was 0.14 Myr, with a maximum (un-corrected) value of 4.09 Myr. The inheritance-corrected NO_3^- estimated age is 0.17 Myr.~~ To the north, the *in-situ* ages ~~from~~ from erratic boulders at Thanksgiving Valley vary greatly from ~4.3 ~~kyr~~ ka near the glacier to ~~0.45 Myr~~450 ka at higher elevations, though most ages appear to be around 30~~35~~ ka~~yr~~ (Figs. 8 and 9) (Balco, 2020; http://antarctica.ice-d.org~~ICE-D~~).~~, which~~ Our exposure ages are among the higher of that range. In particular, the sample collected closest to Shackleton Glacier has an inferred age two orders of magnitude higher than the *in-situ* age from a nearby glacial erratic (Fig. 9) at the same elevation. Given the location (~100 m from the glacier) and young nearby *in-situ* age (~4.3 ka), this location was likely covered during the LGM and other glacial periods. Therefore, considering the high surface concentration of meteoric ^{10}Be for this sample, it is possible that there is an additional delivery mechanism of ^{10}Be, such as deposition of material deflated from the valley walls or at high elevations, or a large inherited component. However, without additional information, such as a depth profile and drift sequencing, the discrepancy in ages remains an enigma.

~~is close to our inheritance-corrected calculated and NO_3^- estimated ages of ~40 kyr and ~30 kyr, respectively.~~ Closer to the Ross Ice Shelf, the *in-situ* ages from Mt. Franke range from ~29 ka~~kyr~~ to 220~~0.19~~ k~~M~~a. Our estimated age without erosion is at the top that range at 220 ka, though the inferred ages are considerable younger at 94 ka and 72 ka (Table

Formatted: Font: Italic

5). Similar to Roberts Massif, our ages from Mt. Franke ages are comparable to the *in-situ* ages from similar elevations (Fig. 9). Additionally, soil erosion, initial inventory, and inheritance likely minimally influence the measured ^{10}Be inventory. yr, which is similar to our NO_3^- estimated ages, which range from ~18 kyr for the inheritance-corrected age to a maximum age of 0.23 Myr.

The *in-situ* ages are youngest closer to the glacier at nearly all locations along the Shackleton Glacier (Balter et al., 2020; ICE-D), which is the same trend we observed for the meteoric ^{10}Be ages. In addition, the *in-situ* ages and calculated and estimated ages from the Shackleton Glacier region are typically younger at lower elevations and decrease closer to the Ross Ice Shelf (Fig. 8). Similar patterns have been observed in the Beardmore Glacier region. Exposure ages at the head of the Beardmore Glacier at the Meyer Desert are the oldest (up to 5.0 Myr). However, on the western side near the Beardmore Glacier, the ages are only ~10 kyr (Ackert and Kurz, 2004). To the north, ages from Cloudmaker range from ~9 kyr to 15 kyr near the glacier, and ~ 600 to 3 kyr near the Ross Ice Shelf at Mt. Hope (Spector et al., 2017). We argue that while the maximum calculatedmeasured, estimated, and inferred and estimated exposure ages from the Shackleton Glacier region can indicate general trends in exposure ages are similar to *in-situ* agesand are useful in establishing an upper age limit, they are likely an overestimate and most useful from a relative perspective in understanding which surfaces have been exposed for longer than others.e and the inheritance-corrected (minimum) ages are more accurate, as determined by comparison to previous work.

Formatted: Font: 7 pt

6.2. NO_3^- as an efficient inventory and exposure age datingestimation tool

This study is not the first to attempt to use water-soluble NO_3^- to help understand glacial history, but it is the first use NO_3^- concentrations to directly estimate meteoric ^{10}Be concentrations. Previous studies have argued that atmosphere-derived salt concentrations at the surface may correlate with exposure ages and wetting ages in Antarctica (Graham et al., 2002; Graly et al., 2018; Lyons et al., 2016; Schiller et al., 2009). Graly et al. (2018) showed that, in particular, water-soluble NO_3^- and boron exhibited the strongest relationships (R^2 = 0.9 and 0.99, respectively). Lyons et al. (2016) used nitrate concentrations to estimate the amount of time since the soils were last wetted and Graham et al. (2002) attempted to calculate exposure ages using the inventory of nitrate in the soil. Graly et al. (2018) argue that boron is preferable to nitrate due to concerns over related to nitrate mobility under sub-arid conditions (e.g. Frey et al., 2009; Michalski et al., 2005), and given that uncertainties in local accumulation rates and ion transport can result in inaccurate ages when using NO_3^- alone (Graham et al., 2002; Schiller et al., 2009). Based on the results presented here for hyper-arid CTAM ice-free regions and the concerns with boron mobility depending on whether the B species present in the soils is BO_3^{3-} (borate) or H_3BO_3 (boric acid), we conclude that NO_3^- appears suitable for relative age dating and for producing age estimates.

~~Through a coupled approach using both meteoric ^{10}Be and NO_3^- concentrations, we developed a useful model for estimating soil exposure ages.~~ We show that the percent differences between ~~calculated~~ measured ^{10}Be inventories and estimated inventories using NO_3^- ~~and NO_3^- estimated ages~~ are low (see Section 5.3.2~~4.4.~~) and argue that the power-law relationship between meteoric ^{10}Be and NO_3^- can be used to expand our current exposure age database for the TAM; compared to cosmogenic radionuclide analyses, NO_3^- analyses are rapid and cost effective. However, a model using NO_3^- or salts alone is likely insufficient, unless the anion accumulation rates are known (Graham et al., 2002; Schiller et al., 2009). Though the regressions between NO_3^- and ^{10}Be are strong (Fig. 6~~7~~c), each of the three profiles from Roberts Massif, Bennett Platform, and Thanksgiving Valley have different regression coefficients and slopes. In other words, the nature of the relationship between meteoric ^{10}Be and NO_3^- ~~is~~ varies ~~not uniform~~ across the Shackleton Glacier region and varies depending on the location. This is l~~, l~~ikely due to ~~local glacial history and climate, soil development, and geography.~~ differences in NO_3^- and ^{10}Be transport and mobility in different surface environments and under different local climates. To address these uncertainties, some ^{10}Be data, surface samples for all locations and a few depth profiles in particular, are necessary to choose the proper regression to minimize the associated error.

We tested our meteoric ^{10}Be – NO_3^- model with data from Arena Valley in the MDV (Graham et al., 2002) and found that our model is roughly applicable to other TAM ice-free areas. Similar to the Shackleton Glacier region soils, the soils from Arena Valley are hyper-arid with high concentrations of NO_3^- and other salts (Graham et al., 2002). Precipitation in MDV is low at ~5 cm water equivalent each year (Fountain et al., 1999), though NO_3^- and other water-soluble salts at the surface can be wetted and mobilized. The highest NO_3^- concentrations are at 10 cm depth, while ^{10}Be concentrations are highest at the surface and decrease with depth, indicating vertical transport of NO_3^- through time (Graham et al., 2002). The power-law relationship between ^{10}Be and NO_3^- throughout the profile is ~~not as strong~~weaker for the Arena Valley samples compared to Shackleton Glacier samples; there is a stronger~~er~~ power-law correlation in the top 20 cm (R^2 = 0.61) ~~than~~

compared to the bottom 70 cm ($R^2 < 0.01$), though the profile is considerably deeper (110 cm). Using the power-law relationship from Bennett Platform, which mostly closely resembles the profile behavior for Arena Valley given the negative regression slope, the estimated inventory is 5.4 x 10^{10} atoms cm^{-2}. TThe measured inventory is fairly close at 1.3 x 10^{10} atoms cm^{-2}, indicating a moderate model fit. Applying the power-law relationship from Arena Valley, the estimated inventory is 9.2 x 10^9 atoms cm^{-2}, which is ~27% lower than the measured inventory. These results indicate that although the Shackleton Glacier region is nearly 900 km from Arena Valley, the correlation between NO_3^- and meteoric ^{10}Be is widespread in hyper-arid soils. However, as stated previously, some NO_3^- and meteoric ^{10}Be data are needed to ascertain the general profile and slope behavior within the region. Additionally, thoughestimated inventory is 7.22 x 10^9 atoms cm^{-2}, while the calculated inventory is 1.3 x 10^{10} atoms cm^{-2}, and the exposure ages (without erosion and inheritance corrections) are 56 kyr and 87 kyr, respectively. Though our inheritance-corrected NO_3^- estimated ages are validated using *in-situ* data from previous studies, until our estimated exposure dating technique can be tested more broadly, we interpret these ages as relative or estimated ages.the NO_3^- dating tool will need to be further evaluated with additional measurements and erosion, initial inventory, and inheritance corrections.

6.3. Implications for paleoclimate and ice sheet dynamics

Exposure age data from across Antarctica show that a polar desert regime began in the mid-Miocene and has persisted into modern time (Lewis et al., 2008; Marchant et al., 1996; Spector and Balco, 2020; Valletta et al., 2015). Additionally, Barrett (2013) provides a detailed review of studies focused on Antarctic glacial history, particularly centered around the “stabilist vs. dynamicist” debate concerning the overall stability of the EAIS. Interpreting 40+ years of data from published literature, they conclude that the EAIS is stabile in the interior with retreat occurring along the margins, including outlet glaciers (Golledge et al., 2012). Given these findings, we would expect NO_3^- and meteoric ^{10}Be concentrations to be correlated in hyper-arid Antarctic soils, such as those from the Shackleton Glacier region. As stated previously, both constituents are derived from atmospheric deposition with minimal alteration at the surface. The major differences concern transport mechanisms: meteoric ^{10}Be is limited by clay particle mobility and NO_3^- is mobile upon soil wetting. Deviations in the expected relationship between ^{10}Be and NO_3^- can inform surface processes in the TAM.

If we assume an "ideal" situation where an undisturbed hyper-arid soil has accumulated meteoric ^{10}Be (Fig. 3a-b), ^{10}Be concentrations would be highest at the surface and decrease to background levels at depth. None of the profiles we sampled and measured for meteoric ^{10}Be and NO_3^- reached background concentrations. All profiles were sampled until frozen soil was reached (or bedrock at Schroeder Hill) (Fig. S1), demonstrating an active layer much shallower than those from the MDV (Graham et al., 2002; Schiller et al., 2009; Valletta et al., 2015). This suggests that ^{10}Be particles were able to migrate to deeper depths in the past and have relatively recently (within the ^{10}Be half-life) closed off ~20 cm for most the Shackleton Glacier region. Though clay particle translocation by percolating water can explain the correlated behavior of ^{10}Be and NO_3^- at Roberts Massif and Thanksgiving Valley, it is unlikely that the region had sufficient precipitation for significant percolation over the last 14 Ma (Menzies et al., 2006). The concentrations of fine particles in the soil profiles also do not change significantly with depth, as would be expected if large precipitation or melt events were frequent (Fig. 5). Additionally, similar to Arena Valley and Wright Valley in the MDV (Graham et al., 2002; Schiller et al., 2009), NO_3^- concentrations are highest just beneath the surface at Roberts Massif, indicating shallow salt migration under an arid climate. These data suggest that the samples furthest inland at Roberts Massif and Thanksgiving Valley have been undisturbed since at least the middle to late Pleistocene. Although meteoric ^{10}Be and NO_3^- at Bennett Platform are mirrored with a negative power-law slope, we argue that the difference is not due to NO_3^- mobility, but instead ^{10}Be deposition. Bennett Platform was the only location we sampled on a large moraine (Fig. 2c), and as such, we would expect minimal inheritance with ^{10}Be decreasing at depth. This is generally the observed behavior, with significantly higher surface concentrations. The NO_3^- profile behavior is similar to those throughout the Shackleton Glacier region, though the concentrations continue to increase with depth, possibly indicating minor percolation of NO_3^- rich brine. What may be considered the "anomalous" data point is the surface concentration of meteoric ^{10}Be. Even though we sampled a constructional landform, the sample was collected between two boulder lines in a small, local depression (~1 m) (Table 2). It is probably no coincidence that this location also has the greatest proportion of fine-grained material in the soil profile. The two boulder lines impede wind flow and act as a sediment and snow trap, resulting in a higher concentration of meteoric ^{10}Be than expected simply from atmospheric deposition. In this case, an additional deposition term (superseding any erosion) needs to be considered to accurately date the moraine, and the current exposure age we measured is may be an overestimate.

While we were not able to identify and sample common drifts at each location for comparison, the youngest surfaces we sampled are those from the lowest elevations and closest to the Ross Ice Shelf (Fig. 10). This is generally consistent with pervious glacial modeling studies which show that the greatest fluctuations in glacier height during the LGM were along outlet glacier and ice shelf margins (Golledge et al., 2012; MacKintosh et al., 2011; Mackintosh et al., 2014). We have emphasized throughout this paper that erosion and inheritance/initial inventory could not be assessed in this study. However, erosion rates are low throughout Antarctica (Balter-Kennedy et al., 2020; Ivy-Ochs et al., 1995; Morgan et al., 2010) and would not drastically impact our relatively young inferred ages (Fig. 10). Additionally, background concentrations of meteoric ^{10}Be in other Antarctic soil profiles are often approximately one to two order of magnitude lower than surface concentrations (Fig. 6). With these considerations, the Mt. Speed, Mt. Wasko, and Mt. Franke samples were all likely covered by the Shackleton Glacier during the LGM, as well as the lower elevation, closest to the glacier samples from Mt. Heekin, Bennett Platform, and Mt. Augustana may have also been covered. The samples we collected near the head of Shackleton Glacier encompass a range of ages, where lower elevation soils are relatively younger, though the soils from Schroeder Hill and Roberts Massif have likely been exposed since the early Pleistocene (Fig. 10).

Lastly, while we cannot directly evaluate the overall stability of the EAIS during changes in climate, Sirius Group deposits were ~~only~~ observed at Roberts Massif ~~(Fig. 2a)~~ and were ~~either~~ deposited ~~or exposed~~ as the Shackleton Glacier retreated in this region (Fig. 2a). ~~-~~Evidence for a dynamic EAIS is derived primarily from the diamictite rocks (tills) of the Sirius Group, which are found throughout the TAM and include well-documented outcrops in the Shackleton Glacier region, but their age is unknown (Hambrey et al., 2003). Some of the deposits contain pieces of shrubby vegetation, suggesting that the Sirius Group formed under conditions warmer than present with trees occupying inland portions of Antarctica (Webb et al., 1984, 1996; Webb and Harwood, 1991). Sparse marine diatoms found in the sediments were initially interpreted as evidence for formation of the Sirius Group via glacial over riding of the TAM during the warmer Pliocene (Barrett et al., 1992), though it is now argued that the marine diatoms were wind-derived contamination, indicating that the Sirius Group is older (Scherer et al., 2016; Stroeven et al., 1996). We document a large diamictite at site RM2-8 that is underlain by soils with an inferred age of at least 1.9 Ma, possibly greater than 6.5 Ma. These exposure ages suggest that the loose Sirius Group diamict was deposited at Roberts Massif some point after the Pliocene. While these data cannot constrain the age of the formation, we suggest that the Sirius Group diamict formed prior than the Pliocene and was transported during the Pleistocene glaciations.

At sample site RM2-8, where soil collected closest to the Shackleton Glacier, we documented a large diamictite that is underlain by soils estimated to be a maximum of >14 Myr in age. While this soil age is likely an overestimate given previously published *in-situ* ages (Balter-Kennedy et al., 2020), the Sirius Group was not observed near the relatively younger RM2-1 soils, with an inheritance-corrected age of 0.14 Myr. We interpret these sparse data to suggest that either the tills were transported from further inland during previous glacial retreat, or that the Sirius Group formed over an extended period of time. However, considering we did not observe any diamictite on younger soils, these observations support previous studies (e.g. Barrett, 2013; Sugden et al., 1993, 1995; Sugden, 1996), which argue that, at least for the southern Shackleton Glacier region, the Sirius Group likely formed prior to the Pliocene.

Our data support models and previous studies suggesting that EAIS advance and retreat was not synchronous during the LGM and throughout the late Cenozoic (DeConto and Pollard, 2016; Golledge et al., 2013; Marchant et al., 1994; Scherer et al., 2016). Calculated and estimated exposure ages (including both maximum and inheritance-corrected) are youngest near the coast and greatest at the head of the Shackleton Glacier (Fig. 8). The furthest inland sample at Mt. Franke indicates that deglaciation occurred as recently as ~0.02 Myr in the northern portion of the region, although the samples closest to the glacier are likely younger in age and may indicate that deglaciation continued into the late Pleistocene/ early Holocene (Spector et al., 2017). Deglaciation in the southern portion of the region likely occurred earlier, with the furthest inland samples from Roberts Massif, Schroeder Hill, and Bennett Platform exposed since shortly before or after the onset of the last glacial period (~0.10 Myr) (Blunier and Brook, 2001; Clark et al., 2009; Mackintosh et al., 2014). Previous data from Roberts Massif also suggests that much, if not all of this location was ice-free throughout the last glacial period (Balter-Kennedy et al., 2020). However, our inferred maximum estimated ages also indicate that, similar to the more northern locations, the samples collected closest to the glacier are likely younger and were more recently exposed due to ice retreat (Fig. 8).

~~Tributary glaciers in the Shackleton Glacier region appear to behave differently than the Shackleton Glacier itself. This is best demonstrated by the Bennett Platform samples, collected near the tributary Gallup Glacier. Bennett Platform is unique in being the only location we sampled with large lateral moraines and several nearby medial moraines (Fig. 2c). The surface concentration of meteoric ^{10}Be is lower at Bennett Platform than what would be expected from regression models relating concentration with elevation and distance from the coast (Fig. 5). The lower concentrations of ^{10}Be, in turn, result in relatively lower calculated and estimated exposure ages (Fig. 8; Table 3). Specifically, the exposure ages suggest that glacier retreat following termination of the last glacial period was delayed at Bennett Platform.~~

~~We argue that the younger than anticipated exposure age is due to differing glacial dynamics between tributary and major outlet glaciers. Meteoric ^{10}Be concentrations and exposure ages at Mt. Augustana are also lower than anticipated given its distance from the coast and elevation. Similar to Bennett Platform, Mt. Augustana is along a tributary glacier, McGregor Glacier. We did not observe the same large moraines from Bennett Platform, but it is possible that McGregor Glacier and Gallup Glacier behave similarly and have a comparatively delayed response to the transition from glacial to interglacial periods. Previous work in the Royal Society Mountains found that marine and land-terminating glaciers behave asynchronously; although sea-level rise likely induced grounding line retreat in the Ross Sea following the LGM, alpine glaciers have since advanced (Higgins et al., 2000; Jackson et al., 2018). The Shackleton Glacier is marine terminating and likely susceptible to ice shelf stability and sea level rise, while the regional tributary glaciers are likely grounded on bedrock troughs and are resulting more stable with respect to changes in climate. Though the physical properties of Gallup and McGregor Glaciers are unknown during the LGM and previous glacial periods (i.e. cold vs. polythermal, shallow vs. deep grounding), these glaciers possibly represent the dynamics of other tributary glaciers in the CTAM, which may similarly have a delayed response to climate shifts.~~

7. Conclusions

We measured concentrations of meteoric ^{10}Be and NO_3^- in soils from eleven ice-free areas along the Shackleton Glacier, Antarctica, which include the highest measured meteoric ^{10}Be concentrations from the polar regions. ~~Calculated~~ Measured (using meteoric ^{10}Be inventories), estimated (using the power-law relationship between NO_3^- and ^{10}Be), and inferred (using the relationship between maximum ^{10}Be and total inventory) exposure ages were calculated and ranged from

58 ka to >6.5 Ma with an estimated erosion component and 57 ka to 1.9 Ma without erosion. In general, there is high agreement between the three techniques.

The estimated and inferred ages without erosion at Roberts Massif, Thanksgiving Valley, and Mt. Frank are similar to nearby *in-situ* ages from previous studies. maximum and inheritance-corrected (minimum) exposure ages are well-correlated with estimated ages, determined using NO_3^- concentrations and inferred ^{10}Be inventories. In particular, coupling relating NO_3^- concentrations with to ^{10}Be measurements represents results an efficient method to attain a greater number of exposure ages in the CTAM, a region with currently sparse meteoric ^{10}Be data. - However, while the relationship betweenpower-law relationship between NO_3^- and ^{10}Be had either a positive or negative slope depending on the location, the is strong in the Shackleton Glacier region, its widespread applicability has yet to be addressed of this tool needs to be further evaluated. Additionally, though we assumed an erosion rate for the region, some soils in local topographic lows are probably have a positive particle flux.

Since NO_3^- and ^{10}Be are both derived from atmospheric deposition, we would expect their concentration behvaiors to be similar at depth in hyper-arid soils. In general, this was true for Roberts Massif and Thanksgiving Valley, while NO_3^- and ^{10}Be concentrations were mirrored at Bennett Platform. We conclude that much of the upper Shackleton Glacier region has maintained persistent arid-conditions since at least the Pleistocene, though the region was warmer and wetting in the past, as evidenced by frozen soil at the bottom of our depth profiles. The onset of aridity is particularly important in understanding refugia and ecological succession in TAM soils. Since the region has remained hyper-arid and undisturbed for upwards of a few million years, prolonged exposure has resulted in the accumulation of salts at high concentrations in the soils. As such, it is an enigma how soil organisms have persisted throughout glacial-interglacial cycles. However, it is possible that organisms have persisted near the glacier at locations like Mt. Augustana, where glacial advance appears to have been minimal during the LGM, but seasonal summer melt has the potential to solubilize salts.

Overall, our data show that the relatively youngest soils we sampled were at lower elevations near the Shackleton Glacier terminus and lower elevations further inland (typically near the glacier). Our sampling scheme was successful in capturing a range of surface exposure ages which contribute to growing archives in the CTAM. We hope that future studies will address the outstanding issues regarding inheritance dynamics of meteoric ^{10}Be in disturbed environments and particle erosion/deposition rates.

Soil exposure ages are generally youngest at lower elevations and closer to the Ross Ice Shelf, but are also younger closer to the Shackleton Glacier or other tributary glaciers. Though we could only estimate maximum inferred ages, our soil transects likely encompass the LGM transition. Inheritance-corrected calculated and estimated ages at Roberts Massif (~1 km from the glacier) indicate that the Shackleton Glacier was likely present in its current form since at least the Pleistocene in southern portions of the region. More northern samples indicate that towards the glacier terminus, the Shackleton Glacier is more susceptible to changes in climate and has likely retreated in the past. However, tributary glaciers likely had a delayed retreat following the LGM. These data represent a comprehensive analysis of meteoric ^{10}Be to demonstrate the dynamic behavior of CTAM outlet glaciers at glacier termini and stability at glacier heads.

Author Contributions

The project was designed and funded by BJA, DHW, IDH, NF, and WBL. Fieldwork was conducted by BJA, DHW, IDH, NF, and MAD. LBC, PRB, and MAD prepared the samples for meteoric ^{10}Be analysis and MAD analyzed the samples for NO_3^-. MAD wrote the article with contributions and edits from all authors.

Data Availability Statement

The datasets generated for this study are included in the article or supplementary materials.

Competing Interests

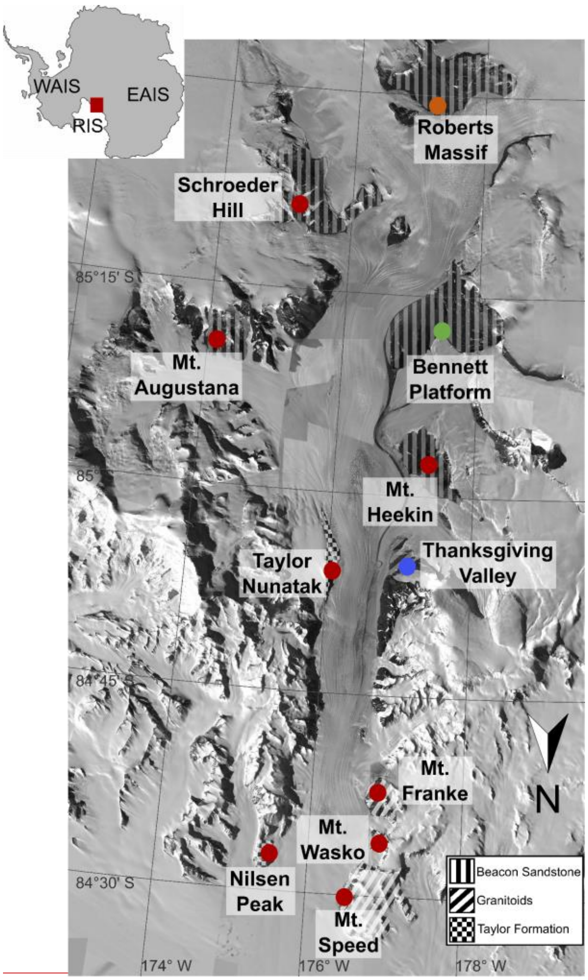
The authors declare that they have no conflict of interest.

Acknowledgments

We thank the United States Antarctic Program (USAP), Antarctic Science Contractors (ASC), Petroleum Helicopters Inc. (PHI), and Marci Shaver-Adams for logistical and field support. We especially thank Dr. Marc Caffe and the Purdue University PRIME Lab for their assistance with AMS measurements. Additionally, we thank Dr. Andrew Christ at University of Vermont for thoughtful discussions and Dr. Sue Welch and Daniel Gilbert at The Ohio State University for help with initial laboratory analyses. We appreciate the detailed and thoughtful suggestions and edits from Dr. Brent Goehring and an anonymous reviewer which have greatly improved this manuscript. This work was supported by NSF OPP grants 1341631 (WBL), 1341618 (DHW), 1341629 (NF), 1341736 (BJA), NSF GRFP fellowship 60041697 (MAD), and a PRIME Lab seed proposal (MAD). Sample preparation and LBC's time supported by NSF EAR 1735676. Geospatial support for this work provided by the Polar Geospatial Center under NSF OPP grants 1043681 and 1559691.

Figures:

Figure 1: Overview map of the Shackleton Glacier region, located in the Queen Maud Mountains of the Central Transantarctic Mountains. The red circles represent our eleven sampling locations, with an emphasis on Roberts Massif (orange), Bennett Platform (green), and Thanksgiving Valley (blue), which have the most comprehensive dataset in this study. The bedrock serves as primary weathering product for soil formation (Elliot and Fanning, 2008; Paulsen et al., 2004). Base maps provided by the Polar Geospatial Center.


WAIS
EAIS
RIS
Roberts Massif
Schroeder Hill
85°15' S
Mt. Augustana
Bennett Platform
Mt. Heekin
Taylor Nunatak
Thanksgiving Valley
84°45' S
N
Mt. Franke
Mt. Wasko
Nilsen Peak
84°30' S
Mt. Speed
Beacon Sandstone
Granitoids
Taylor Formation
174° W
176° W
178° W

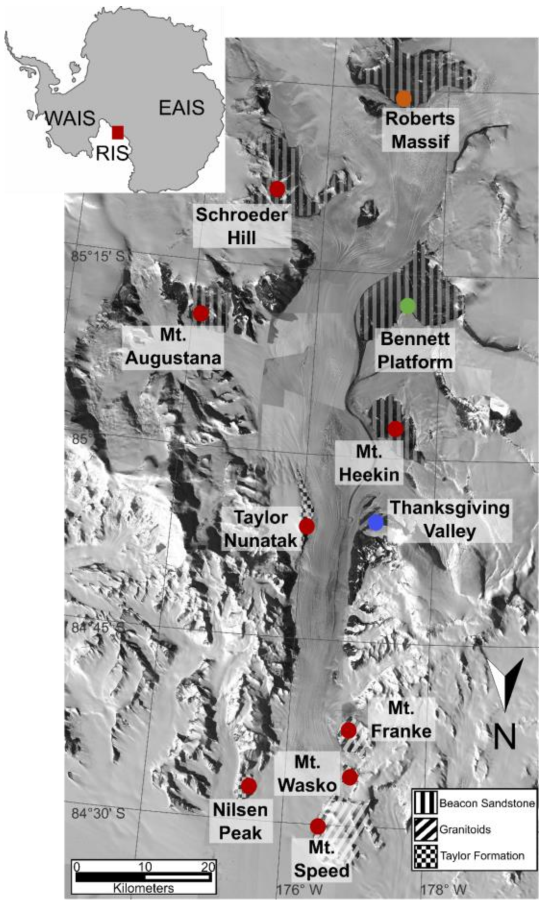

WAIS
EAIS
RIS
Roberts Massif
Schroeder Hill
85°15' S
Mt. Augustana
Bennett Platform
Mt. Heekin
Thanksgiving Valley
Taylor Nunatak
84°45' S
Mt. Franke
N
Mt. Wasko
Nilsen Peak
84°30' S
Mt. Speed
Beacon Sandstone
Granitoids
Taylor Formation
0
10
20
Kilometers
176° W
178° W

Figure 2: The Sirius Group was documented at Roberts Massif near the RM2-8 sampling location (a). Cold-based glacierSmall m-moraines were observed at Roberts Massif (b) and large moraines large polythermal moraines were observed at Bennett Platform (c).

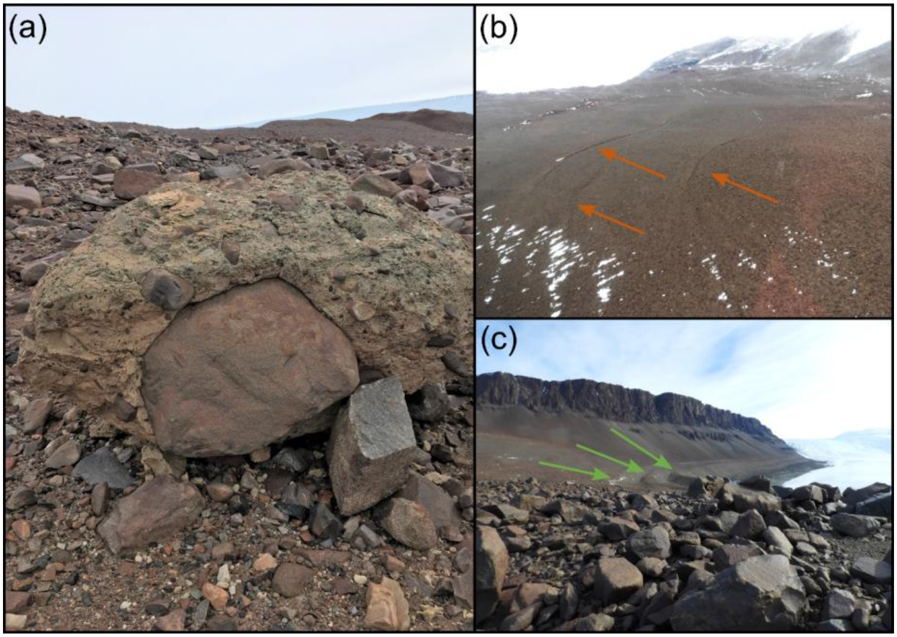


Figure 3: Conceptual diagram of meteoric ^{10}Be accumulation in soils during glacial advance and retreat. In "ideal" conditions, ^{10}Be accumulates in exposed soils and ^{10}Be -concentrations beneath the glacier are negligible at background levels (a). As the glacier retreats, ^{10}Be can begin accumulating in the recently exposed soil and an inventory can be measured to calculate exposure ages. In the case where the glacier has waxed and waned numerous times and the soils already contain a non-negligible ~~background~~ "inheritance" concentration of ^{10}Be, the inventories need to be corrected for ^{10}Be inheritance (c-d) to accurately determine exposure ages.

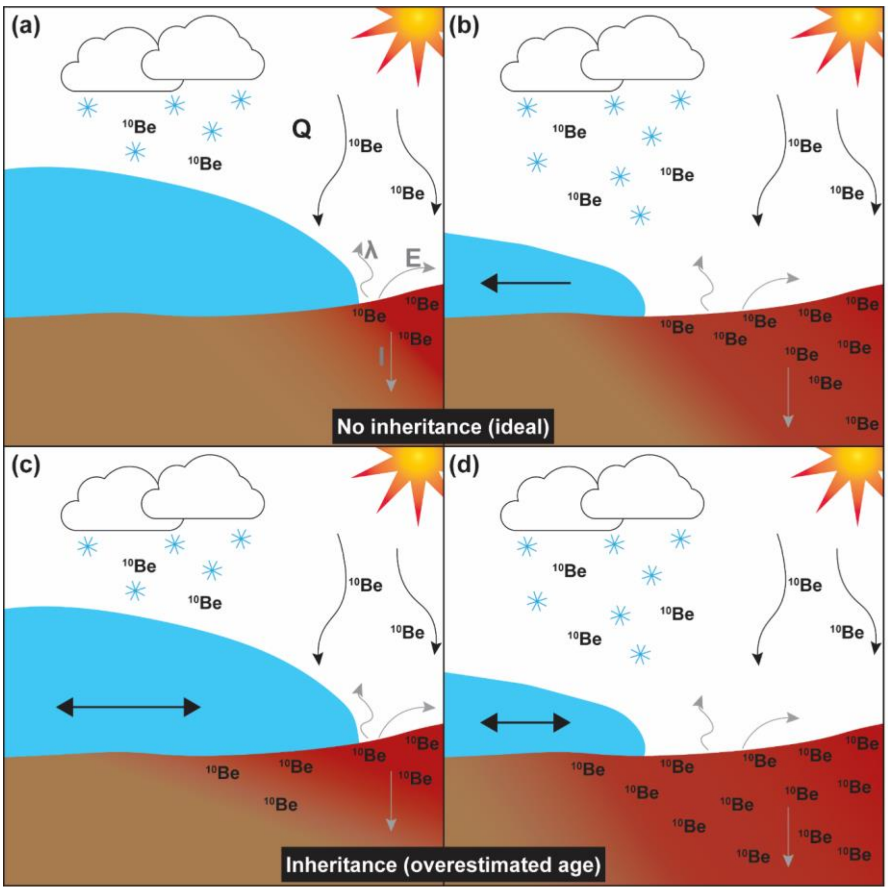
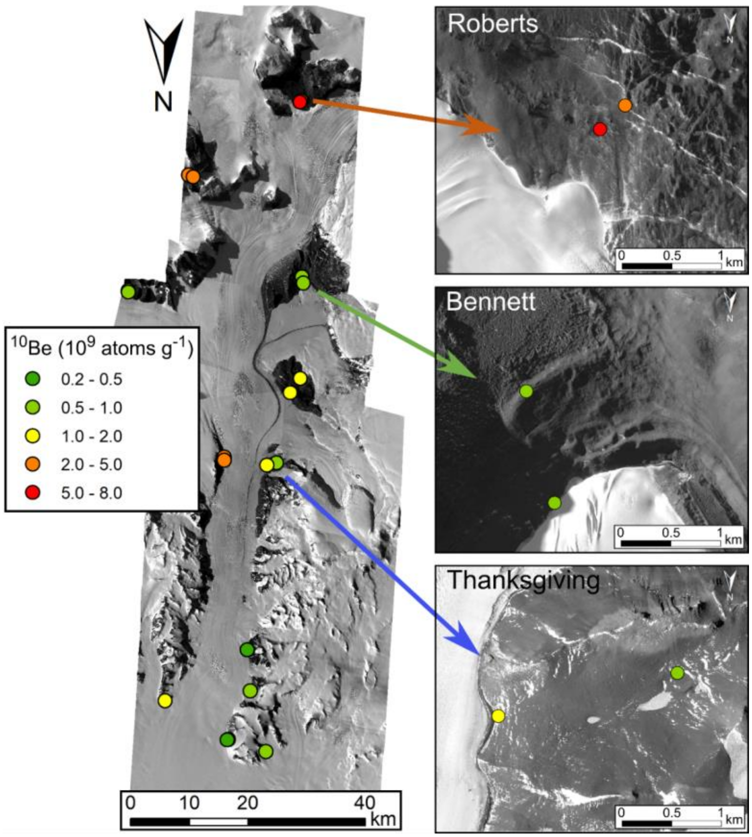


Figure 4: Spatial distribution of surface meteoric ^{10}Be concentrations in the Shackleton Glacier region. Where possible, two samples were collected at each location to represent surfaces closest to the glacier, which might have been glaciated during recent glacial periods, and samples furthest from the glacier that are likely to have been exposed during recent glacial periods. Insets of Roberts Massif ~~(orange)~~, Bennett Platform ~~(green)~~, and Thanksgiving Valley (blue) are included ~~(color scheme consistent throughout),~~ , as these locations serve as the basis for our relative exposure age models. Base maps provided by the Polar Geospatial Center.


N
^{10}Be (10^9 atoms g^{-1})
0.2 - 0.5
0.5 - 1.0
1.0 - 2.0
2.0 - 5.0
5.0 - 8.0
0 10 20 40 km
Roberts
Bennett
Thanksgiving
0 0.5 1 km

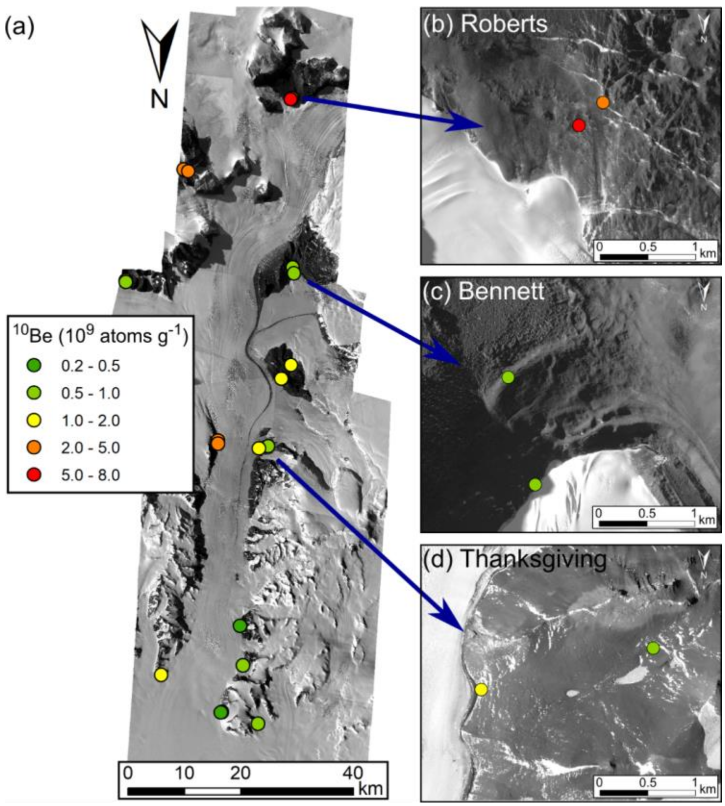

(a)
N
^{10}Be (10^{9} atoms g^{-1})
0.2 - 0.5
0.5 - 1.0
1.0 - 2.0
2.0 - 5.0
5.0 - 8.0
0 10 20 40 km
(b) Roberts
0 0.5 1 km
(c) Bennett
0 0.5 1 km
(d) Thanksgiving
0 0.5 1 km

Figure 5: Concentration of meteoric ^{10}Be with elevation and distance from coast. The solid black lines are linear regressions.

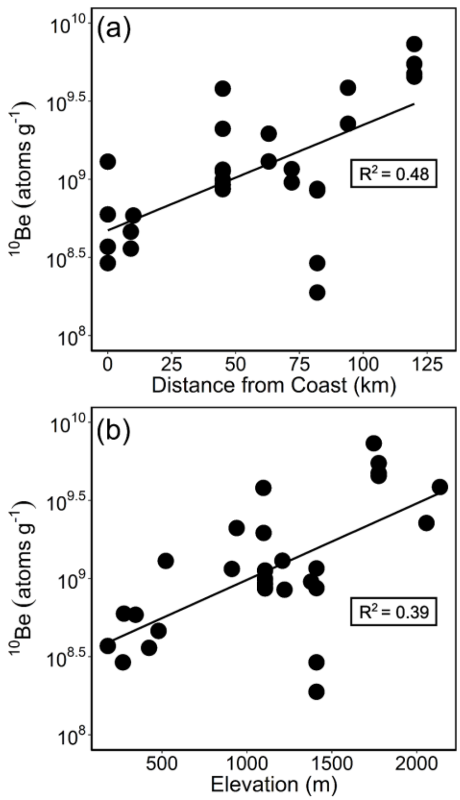
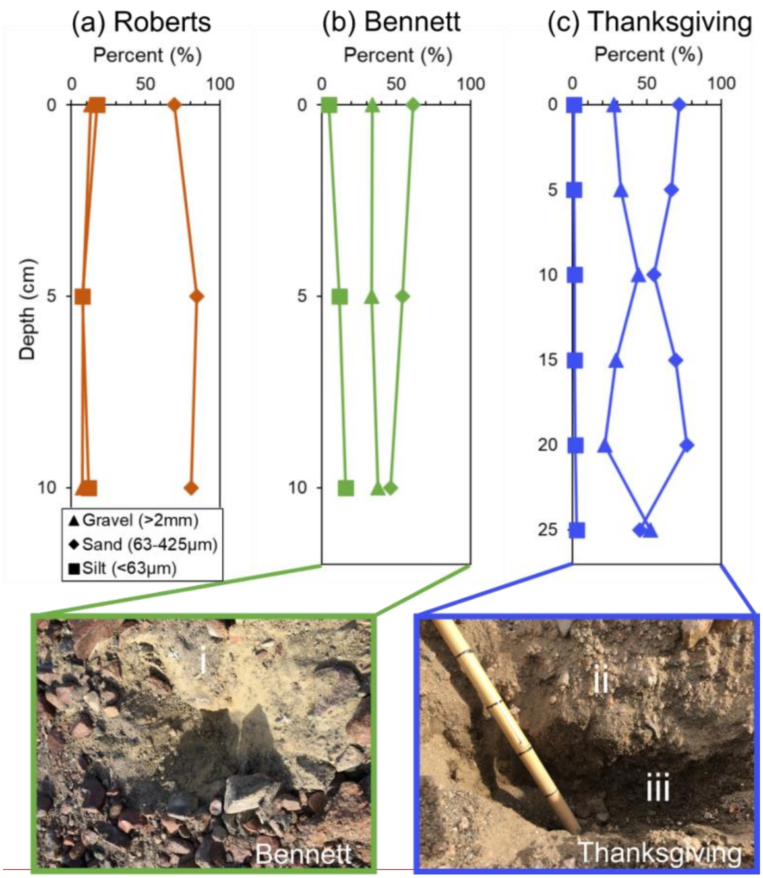


Figure 56: The grain size composition of soil profiles collected from Roberts Massif (a, orange), Bennett Platform (b, green), and Thanksgiving Valley (c, blue). The soil pits from Bennett Platform and Thanksgiving Valley are also shown with distinct soil horizons.


(a) Roberts
(b) Bennett
(c) Thanksgiving
Percent (%)
Percent (%)
Percent (%)
Depth (cm)
Gravel (>2mm)
Sand (63-425µm)
Silt (<63µm)
i
Bennett
ii
iii
Thanksgiving

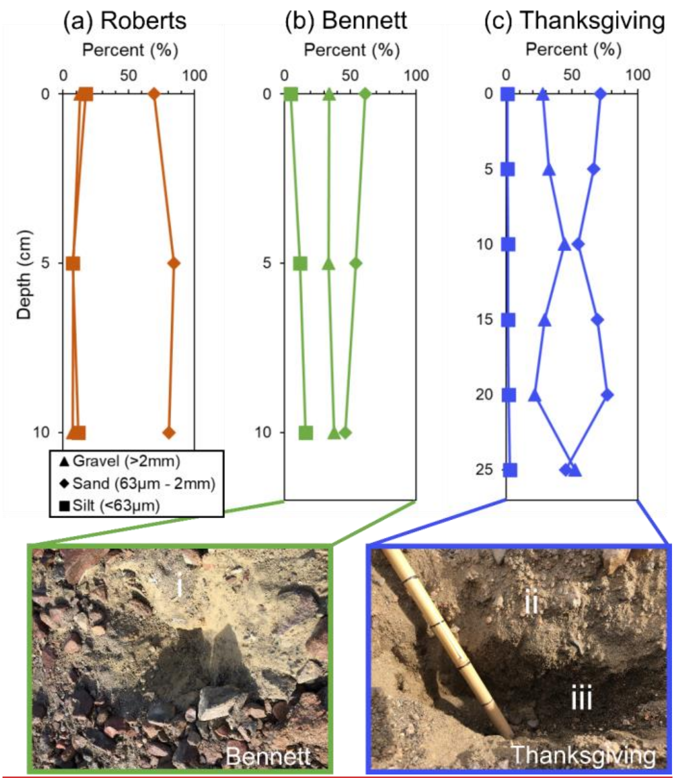
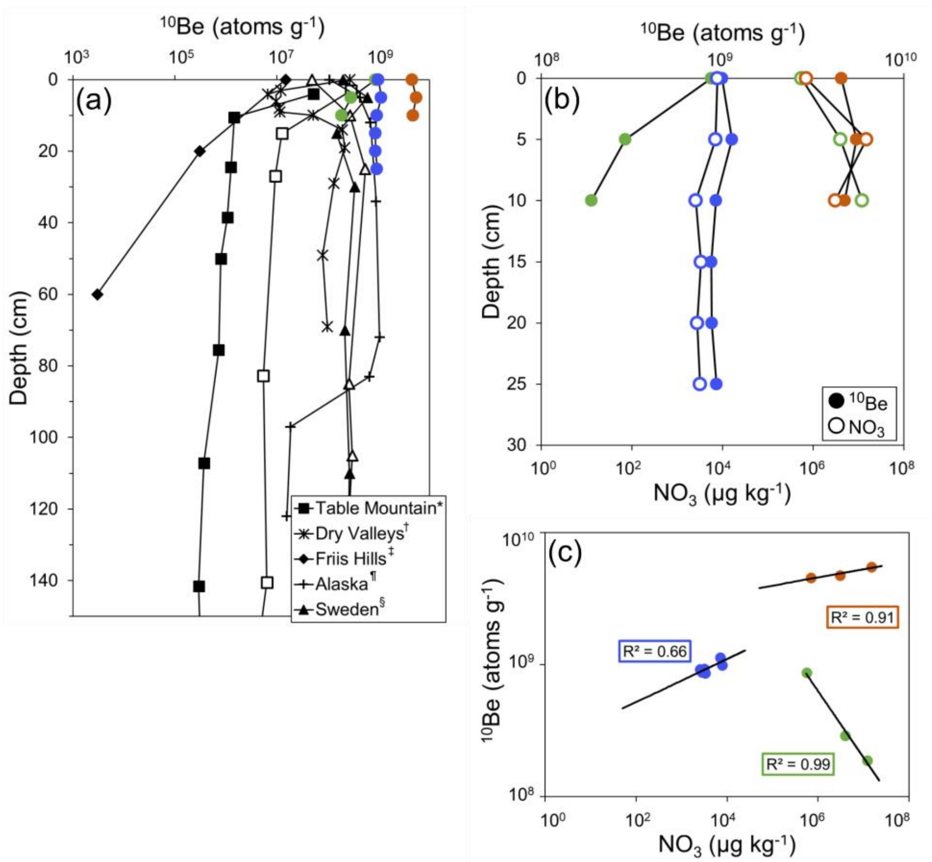
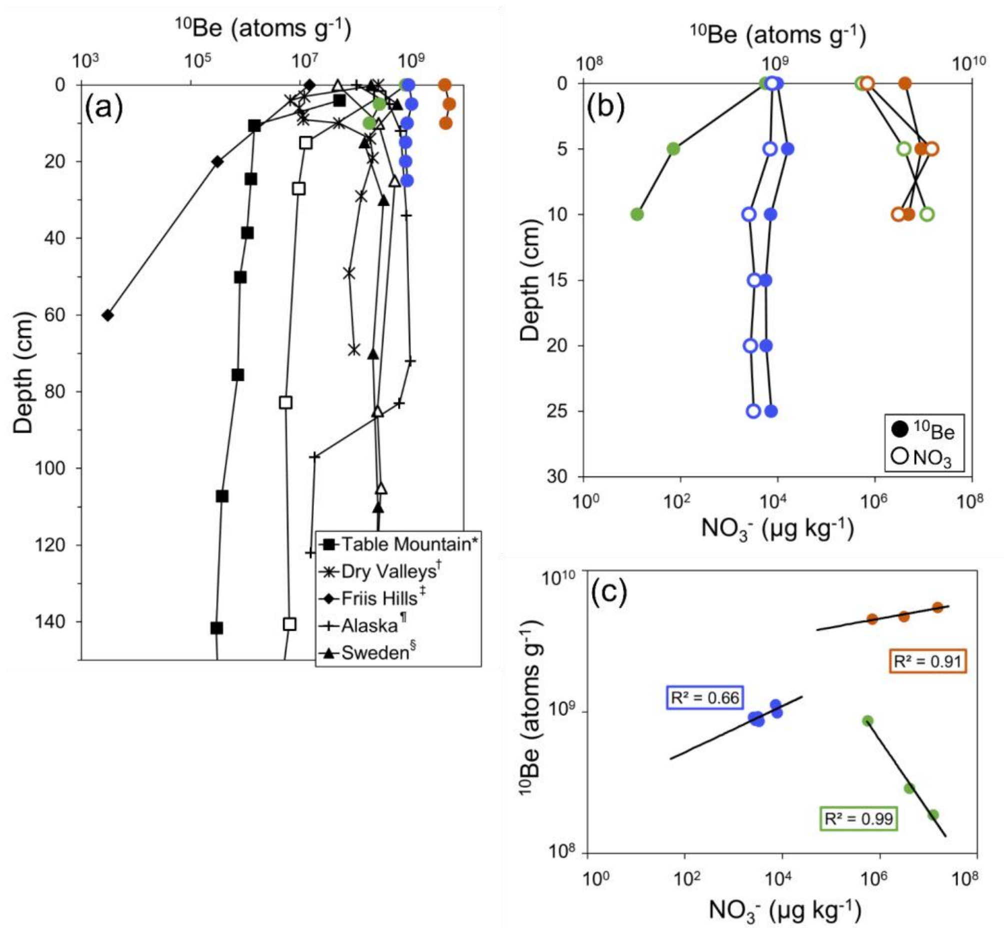

(a) Roberts
(b) Bennett
(c) Thanksgiving
Percent (%)
Depth (cm)
Gravel (>2mm)
Sand (63µm - 2mm)
Silt (<63µm)
i
Bennett
ii
iii
Thanksgiving

Figure ~~7~~6: Soil profiles of meteoric ^{10}Be concentrations for Roberts Massif (orange), Bennett Platform (green), and Thanksgiving Valley (blue) compared to profiles from the Antarctic (Dickinson et al., 2012*; Schiller et al., 2009†; Valletta et al., 2015‡) and Arctic (Bierman et al., 2014¶; Ebert et al., 2012§) (a). The ^{10}Be concentration profiles were also compared to NO_3^- concentration profiles (b) and a power function was fit to the data (c).

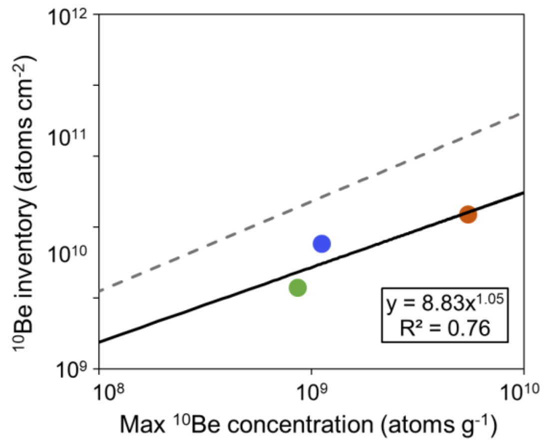


(a)
^{10}Be (atoms g^{-1})
10^3 10^5 10^7 10^9
Depth (cm)
0 20 40 60 80 100 120 140
Table Mountain*
Dry Valleys†
Friis Hills‡
Alaska¶
Sweden§
(b)
^{10}Be (atoms g^{-1})
10^8 10^9 10^{10}
Depth (cm)
0 5 10 15 20 25 30
^{10}Be
NO_3
10^0 10^2 10^4 10^6 10^8
NO_3 (µg kg^{-1})
(c)
^{10}Be (atoms g^{-1})
10^{10} 10^9 10^8
R^2 = 0.66
R^2 = 0.91
R^2 = 0.99
10^0 10^2 10^4 10^6 10^8
NO_3 (µg kg^{-1})



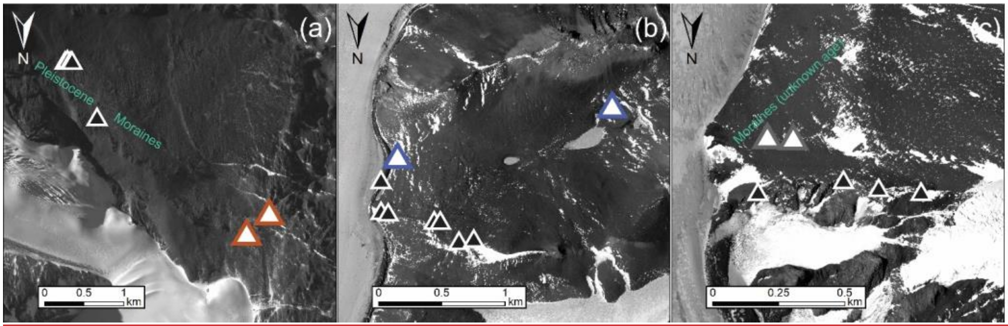
10Be (atoms g-1)
(a)
Depth (cm)
Table Mountain*
Dry Valleys†
Friis Hills‡
Alaska¶
Sweden§
(b)
10Be
NO3
NO3- (μg kg-1)
(c)
R² = 0.91
R² = 0.66
R² = 0.99

Figure 7: Relationship between the measured maximum (or surface) meteoric ^{10}Be concentration and the calculated inventory (Eq. 2). This relationship is used to infer ^{10}Be inventories given a maximum or surface concentration (Graly et al., 2010). The solid black line is the power relationship between concentration and inventory, while the dashed grey line is the regression from Graly et al. (2010).



Formatted: Centered

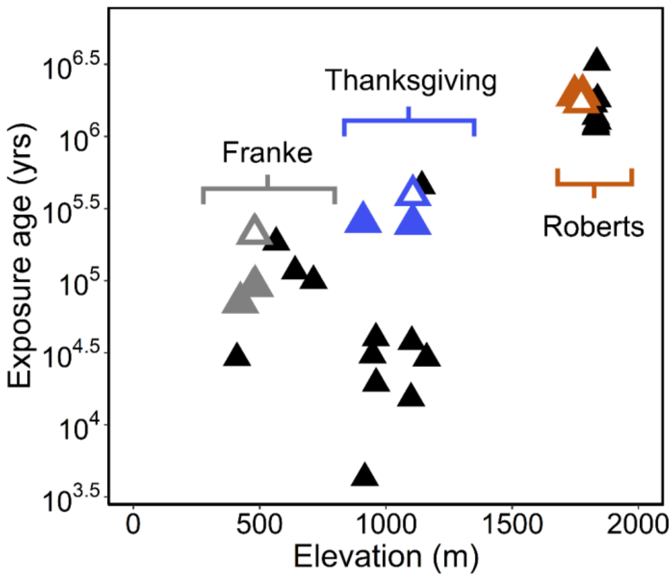
Figure 8: *In-situ* exposure age measurements from glacial erratic boulders (black filled triangles) (http://antarctica.ice-d.org; Balco, 2020; Balter-Kennedy et al., 2020) in relation to the meteoric ^{10}Be sample locations from Roberts Massif (a, orange), Thanksgiving Valley (b, blue), and Mt. Franke (c, grey). Pleistocene-age moraines described by Balter-Kennedy et al. (2020) are labeled at Roberts Massif. We identified moraines of an unknown age at Mt. Franke.



Formatted: Font: (Default) Times New Roman, 10 pt, Fo color: Auto

Formatted: Font: 12 pt, Not Bold

Figure 9: Estimated (using NO_3^-) meteoric ^{10}Be exposure ages (open colored triangles) and inferred (using maximum ^{10}Be concentration) exposure ages (closed colored triangles) without erosion compared to *in-situ* ages from ICE-D and Balter-Kennedy et al. (2020) (solid triangles) against elevation. All *in-situ* ages were measured from glacial erratic boulders.



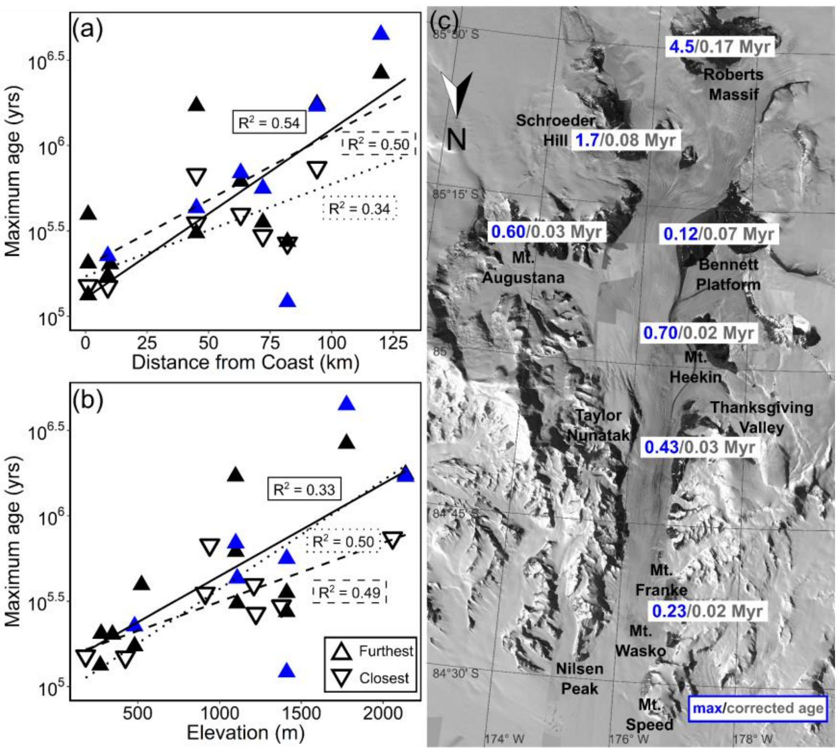
Formatted: Font: (Default) Times New Roman, 10 pt, Bo
Font color: Auto

Formatted: Heading 2

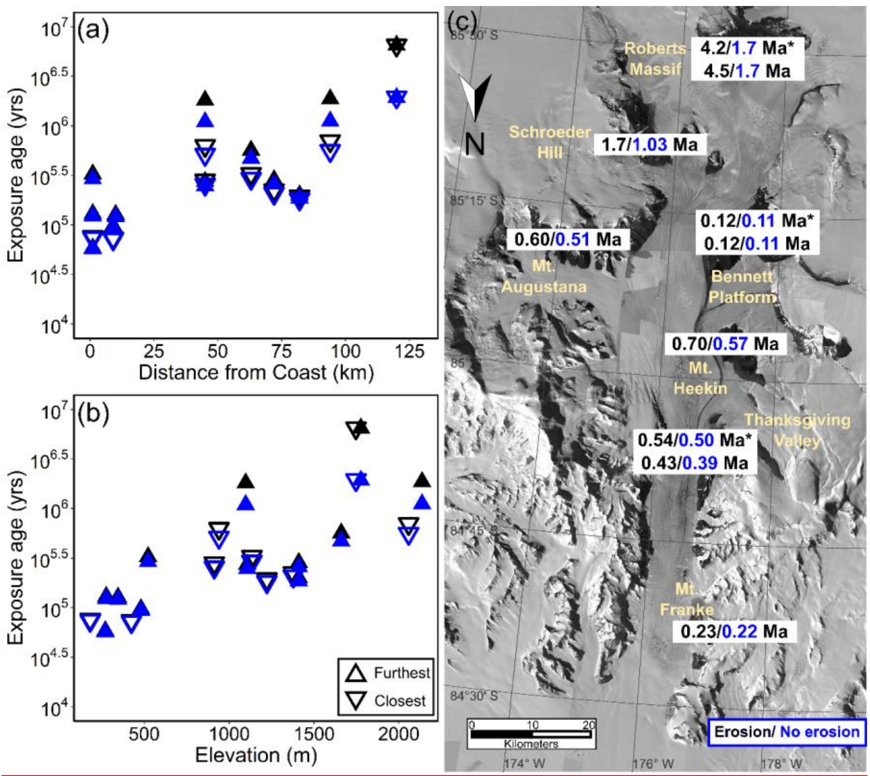
Formatted: Font: Bold

Formatted: Centered

Figure 810: Estimated Inferred surface exposure agesmaximum age versus distance from the coast (a) and elevation (b), with (blue) and without (black) a assumed erosion rate. The blue triangles represent the maximum age estimates using the relationship between NO_3^- and ^{10}Be, black and white triangles represent maximum age estimates using inferred ^{10}Be inventories. Upward facing triangles are samples collected furthest from the glacier, while downward triangles are samples collected closest to the glacier. Sample RM2-8 (Roberts Massif, closest to glacier) is outside the range. Linear regression lines are plotted for the three datasets where the solid line is for the NO_3^- estimate, the dashed line is the inferred estimate for samples furthest from the glacier, and the dotted line is the inferred estimate for samples closest to the glacier. The estimated maximum surface exposure ages using NO_3^- concentrations are included in panel (c). Values with asterisks (*) are ages calculated using the measured meteoric ^{10}Be ages (blue) and inheritance-corrected ages (grey) using the NO_3^- concentrations are overlaid on a map of the Shackleton Glacier region (c).concentrations in depth profiles.



(a)
Maximum age (yrs)
10^5
$10^{5.5}$
10^6
$10^{6.5}$
R^2 = 0.54
R^2 = 0.50
R^2 = 0.34
0 25 50 75 100 125
Distance from Coast (km)
(b)
Maximum age (yrs)
R^2 = 0.33
R^2 = 0.50
R^2 = 0.49
Furthest
Closest
500 1000 1500 2000
Elevation (m)
(c)
85°30' S
85°15' S
84°45' S
84°30' S
N
4.5/0.17 Myr
Roberts Massif
Schroeder Hill
1.7/0.08 Myr
0.60/0.03 Myr
Mt. Augustana
0.12/0.07 Myr
Bennett Platform
0.70/0.02 Myr
Mt. Heekin
Taylor Nunatak
Thanksgiving Valley
0.43/0.03 Myr
Mt. Franke
0.23/0.02 Myr
Mt. Wasko
Nilsen Peak
Mt. Speed
max/corrected age
174° W
176° W
178° W


(a)
Exposure age (yrs)
Distance from Coast (km)
(b)
Exposure age (yrs)
Elevation (m)
Furthest
Closest
(c)
Roberts Massif
4.2/1.7 Ma*
4.5/1.7 Ma
N
Schroeder Hill
1.7/1.03 Ma
0.12/0.11 Ma*
0.12/0.11 Ma
0.60/0.51 Ma
Mt. Augustana
Bennett Platform
0.70/0.57 Ma
Mt. Heekin
Thanksgiving Valley
0.54/0.50 Ma*
0.43/0.39 Ma
Mt. Franke
0.23/0.22 Ma
Kilometers
Erosion/ No erosion
174° W
176° W
178° W

Tables:

Table 1: Geographic data of samples collected from eleven ice-free areas along the Shackleton Glacier. Distance from the coast (aerial) was measured post-collection using ArcMap 10.3 software. Samples of the format "X-1" are samples collected furthest from the glacier in the transect.

Location	Sample name	Latitude	Longitude	Elevation (m)	Distance from coast (km)
Mt. Augustana	AV2-1	-85.1706	-174.1338	1410	72
Mt. Augustana	AV2-8	-85.1676	-174.1393	1378	72
Bennett Platform	BP2-1	-85.2121	-177.3576	1410	82
Bennett Platform	BP2-8	-85.2024	-177.3907	1222	82
Mt. Franke	MF2-1	-84.6236	-176.7353	480	9
Mt. Franke	MF2-4	-84.6237	-176.7252	424	9
Mt. Heekin	MH2-1	-85.0299	-177.2405	~~1098~~1660	63
Mt. Heekin	MH2-8	-85.0528	-177.4099	~~1209~~1134	63
Mt. Speed	MSP2-1	-84.4819	-176.5070	270	0
Mt. Speed	MSP2-4	-84.4811	-176.4864	181	0
Mt. Speed	MSP4-1	-84.4661	-177.1224	276	0
Mt. Wasko	MW4-1	-84.5600	-176.8177	345	10
Nilsen Peak	NP2-5	-84.6227	-176.7501	~~522~~670	0
Roberts Massif	RM2-1	-85.4879	-177.1844	1776	120
Roberts Massif	RM2-8	-85.4857	-177.1549	1747	120
Schroeder Hill	SH3-2	-85.3597	-175.0693	2137	94
Schroeder Hill	SH3-8	-85.3569	-175.1621	2057	94
Thanksgiving Valley	TGV2-1	-84.9190	-177.0603	1107	45
Thanksgiving Valley	TGV2-8	-84.9145	-176.8860	912	45
Taylor Nunatak	TN3-1	-84.9227	-176.1242	1097	45
Taylor Nunatak	TN3-5	-84.9182	-176.1282	940	45

Table 2: Surface features of the sample locations.

Location	Sample name	Sample description
Mt. Augustana	AV2-1	Up valley from Gallup Glacier (tributary glacier); at valley floor; surface covered by cobbles and pebbles; red-stained sandstones nearby; frozen ground at bottom of depth profile
Mt. Augustana	AV2-8	At toe of Gallup Glacier; surface covered primarily by boulders; mainly sand between boulders
Bennett Platform	BP2-1	On larger moraine; local depression between two boulder lines, up valley from McGregor Glacier (tributary glacier); at valley floor
Bennett Platform	BP2-8	At toe of McGregor Glacier (tributary glacier); surface covered primarily by boulders; mainly sand between boulders
Mt. Franke	MF2-1	Bottom of wide valley floor; near small moraine; frozen soil at bottom of profile
Mt. Franke	MF2-4	Bottom of wide valley floor; near small moraine
Mt. Heekin	MH2-1	On high-elevation saddle; surface covered by sparse small boulders, cobbles, and pebbles; poorly consolidated till; frozen ground at bottom of profile
Mt. Heekin	MH2-8	At toe of Baldwin Glacier (tributary glacier) on valley floor; two ponds nearby; surface covered by loose rocks and sand; poorly consolidated till; possible polygonal surface nearby
Mt. Speed	MSP2-1	Steep slope; large granite boulders; scree
Mt. Speed	MSP2-4	Near cliff by Shackleton Glacier; large granite boulders; scree
Mt. Speed	MSP4-1	Spur on level with glacier; frozen soil near 5 cm depth
Mt. Wasko	MW4-1	Steep slope; large granite boulders; scree; nearby snowpack
Nilsen Peak	NP2-5	On ridge; near large snow patch
Roberts Massif	RM2-1	Near thin moraine; red-stained sandstones nearby with etches; frozen ground at bottom of depth profile
Roberts Massif	RM2-8	Near thin moraine and Sirius Group diamict; large boulders nearby with unconsolidated sediment
Schroeder Hill	SH3-2	Red-stained sandstone; poorly consolidated till; bedrock at bottom of profile
Schroeder Hill	SH3-8	Red-stained sandstone; poorly consolidated till;
Thanksgiving Valley	TGV2-1	Lightly uphill on valley wall; poorly consolidated till; frozen ground at bottom of depth profile; polygonal surface nearby
Thanksgiving Valley	TGV2-8	At the toe of Shackleton Glacier; near thin moraines, surface covered primarily large boulders
Taylor Nunatak	TN3-1	On ridge; surface covered by small boulders with underlaying silt; frozen ground at bottom of depth profile
Taylor Nunatak	TN3-5	Valley floor; nearby snow patches; few glacial erratics; surface covered primarily by small boulders and cobbles with underlaying silt

Table ~~2~~3: Concentration of meteoric ^{10}Be in Shackleton Glacier region surface soils and depth profiles from Roberts Massif, Bennett Platform, and Thanksgiving Valley.

Sample name	**Sample mass (g)**	**Mass of ^{9}Be added (µg)***	**AMS Cathode Number**	**Uncorrected $^{10}Be/^{9}Be$ ratio (10^{-11})****	**Uncorrected $^{10}Be/^{9}Be$ ratio uncertainty (10^{-13})****	**Background-corrected $^{10}Be/^{9}Be$ ratio (10^{-11})*****	**Background-corrected $^{10}Be/^{9}Be$ ratio uncertainty (10^{-13})*****	**^{10}Be concentration (10^{9} atoms g^{-1})**	**^{10}Be concentration uncertainty (10^{7} atoms g^{-1})**
AV2-1	0.499	394.3	151135	2.201	1.143	2.201	1.143	1.162	0.604
AV2-8	0.500	400.2	151137	1.786	1.067	1.785	1.067	0.955	0.571
BP2-1, 0-5	0.499	401.2	151147	1.616	1.055	1.615	1.055	0.868	0.567
BP2-1, 5-10	0.499	399.2	151148	0.353	0.748	0.352	0.748	0.188	0.400
BP2-1, 10-15	0.496	400.2	151149	1.573	1.894	1.573	1.894	0.848	1.021
BP2-8	0.498	400.2	151550	0.542	0.448	0.541	0.448	0.291	0.241
MF2-1	0.505	398.2	151554	3.713	3.444	3.712	3.444	1.956	1.815
MF2-4	0.501	398.2	151555	2.448	1.395	2.447	1.396	1.300	0.741
MH2-1	0.498	399.2	151138	0.864	0.820	0.863	0.820	0.462	0.439
MH2-8	0.499	395.3	151139	0.681	0.847	0.680	0.847	0.360	0.449
MSP2-1	0.499	403.2	151556	0.539	0.464	0.538	0.464	0.291	0.250
MSP2-4	0.502	402.2	151557	0.693	0.673	0.692	0.674	0.370	0.361
MSP4-1	0.499	400.2	151566	1.112	1.117	1.111	1.117	0.596	0.598
MW4-1	0.498	400.2	151564	1.093	0.662	1.092	0.662	0.586	0.356
NP2-5	0.496	402.2	151565	2.391	1.200	2.391	1.200	1.295	0.650
RM2-1, 0-5	0.502	399.2	151558	8.541	4.116	8.541	4.116	4.538	2.187
RM2-1, 5-10	0.499	398.2	151559	8.853	8.411	8.852	8.411	4.721	4.485
RM2-1, 10-15	0.500	400.2	151560	13.70	8.460	13.70	8.460	7.327	4.524
RM2-8	0.498	401.2	151561	10.17	15.27	10.17	15.27	5.475	8.221
SH3-2	0.497	398.2	151551	7.191	3.129	7.190	3.129	3.850	1.675
SH3-8	0.501	398.2	151552	4.270	3.351	4.269	3.351	2.267	1.780
TGV2-1, 0-5	0.498	398.2	151140	1.860	2.431	1.859	2.431	0.993	1.299

TGV2-1, 5-10	0.500	398.2	151141	1.731	1.589	1.731	1.589	0.921	0.846
TGV2-1, 10-15	0.497	393.3	151142	1.635	1.377	1.634	1.377	0.864	0.728
TGV2-1, 15-20	0.502	399.2	151143	1.645	1.776	1.645	1.777	0.874	0.944
TGV2-1, 20-25	0.498	403.2	151144	1.711	0.852	1.710	0.852	0.925	0.461
TGV2-1, 25-30	0.497	399.2	151145	2.148	2.071	2.147	2.071	1.152	1.112
TGV2-8	0.499	399.2	151146	2.106	2.185	2.105	2.185	1.125	1.168
TN3-1	0.500	401.2	151562	7.092	5.903	7.091	5.903	3.802	3.165
TN3-5	0.500	401.2	151563	3.926	5.694	3.925	5.694	2.105	3.053

*^{9}Be was added through commercial SPEX carrier with a concentration of 1000 µg mL^{-1}.

**Isotopic analysis was conducted at PRIME Laboratory; ratios were normalized against standard 07KNSTD3110 with an assumed ratio of 2850 x 10^{-15} (Nishiizumi et al., 2007). Blank ^{10}Be/^{9}Be ratio values averaged 8.152 ± 1.884 x 10^{-15}.

Table 34: Exposure ages calculated from Eq. (1-6) and estimated ages using NO_3^- concentration data.

Exposure ages calculated from Eq. (1-5) and estimated ages using NO_3^- concentration data.

Location	**Measured inventory (10^{11} atoms)**	**Measured exposure age with *E* (Ma)**	**Measured exposure age without *E* (Ma)**	**Estimated inventory (10^{11} atoms)***	**Estimated exposure age with *E* (Ma)***	**Estimated exposure age without *E* (Ma)***
Augustana	-	-	-	0.580	0.601	0.505
Bennett	0.135	0.115	0.106	0.143	0.122	0.113
Franke	-	-	-	0.268	0.232	0.217
Heekin	-	-	-	0.646	0.703	0.571
Roberts	1.47	4.15	1.67	1.51	4.54	1.74
Schroeder	-	-	-	1.05	1.66	1.03
Thanksgiving	0.570	0.535	0.495	0.465	0.426	0.394
*Estimations derived from linear relationship between NO3- concentration and meteoric 10Be concentration						

Formatted: Font: (Default) Times New Roman, 10 pt, Font color: Auto
Formatted: Font: 10 pt
Formatted: Heading 2
Formatted: Font: 13 pt
Formatted: Font: Bold
Formatted: Centered
Formatted Table
Formatted: Font: Bold
Formatted: Font: Bold
Formatted: Font: Bold
Formatted: Font: Bold
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered

Table 45: Estimated exposure ages using relationship between maximum ^{10}Be concentration and inventory in Figure S1 (Bierman et al., 2014).

Sample name	**Inferred inventory (10^{11} atoms)**	**Inferred exposure age with *E* (Ma)**	**Inferred exposure age without *E* (Ma)**
AV2-1	0.38	0.285	0.258
AV2-8	0.33	0.224	0.207
BP2-1	0.31	0.200	0.186
BP2-8	0.31	0.195	0.181
MF2-1	0.21	0.097	0.094
MF2-4	0.18	0.074	0.072
MH2-1	0.59	0.565	0.469
MH2-8	0.42	0.328	0.292
MSP2-1	0.16	0.058	0.057
MSP2-4	0.18	0.076	0.074
MSP4-1	0.24	0.129	0.123
MW4-1	0.24	0.127	0.121
NP2-5	0.42	0.326	0.291
RM2-1	1.24	>6.5*	1.93
RM2-8	1.50	>6.5*	1.94
SH3-2	1.07	1.87	1.11
SH3-8	0.67	0.702	0.560
TGV2-1	0.34	0.274	0.248
TGV2-8	0.38	0.282	0.255
TN3-1	1.06	1.81	1.09
TN3-5	0.62	0.628	0.512

*Outside of model range

Formatted: Font: Bold
Formatted: Centered
Formatted Table
Formatted: Font: Bold
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered
Formatted: Centered

References

Ackert, R. P. and Kurz, M. D.: Age and uplift rates of Sirius Group sediments in the Dominion Range, Antarctica, from surface exposure dating and geomorphology, Glob. Planet. Change, 42(1–4), 207–225, doi:10.1016/j.gloplacha.2004.02.001, 2004.

Anderson, J. B., Shipp, S. S., Lowe, A. L., Wellner, J. S. and Mosola, A. B.: The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: a review, Quat. Sci. Rev., 21, 49–70, doi:10.1016/S0277-3791(01)00083-X, 2002.

Augustin, L., Barbante, C., Barnes, P. R. F., Barnola, J. M., Bigler, M., Castellano, E., Cattani, O., Chappellaz, J., Dahl-Jensen, D., Delmonte, B., Dreyfus, G., Durand, G., Falourd, S., Fischer, H., Flückiger, J., Hansson, M. E., Huybrechts, P., Jugie, G., Johnsen, S. J., Jouzel, J., Kaufmann, P., Kipfstuhl, J., Lambert, F., Lipenkov, V. Y., Littot, G. C., Longinelli, A., Lorrain, R., Maggi, V., Masson-Delmotte, V., Miller, H., Mulvaney, R., Oerlemans, J., Oerter, H., Orombelli, G., Parrenin, F., Peel, D. A., Petit, J. R., Raynaud, D., Ritz, C., Ruth, U., Schwander, J., Siegenthaler, U., Souchez, R., Stauffer, B., Steffensen, J. P., Stenni, B., Stocker, T. F., Tabacco, I. E., Udisti, R., van de Wal, R. S. W., van den Broeke, M., Weiss, J., Wilhelms, F., Winther, J. G., Wolff, E. W. and Zucchelli, M.: Eight glacial cycles from an Antarctic ice core, Nature, 429(6992), 623–628, doi:10.1038/nature02599, 2004.

Balco, G.: Technical note: A prototype transparent-middle-layer data management and analysis infrastructure for cosmogenic-nuclide exposure dating, Geochronology, in review(2), 169–175, doi:10.5194/gchron-2020-6, 2020.

Balco, G., Stone, J. O. H., Sliwinski, M. G. and Todd, C.: Features of the glacial history of the Transantarctic Mountains inferred from cosmogenic 26 Al, 10 Be and 21 Ne concentrations in bedrock surfaces, Antarct. Sci., 26(6), 708–723, doi:10.1017/S0954102014000261, 2019.

Balter-Kennedy, A., Bromley, G., Balco, G., Thomas, H. and Jackson, M. S.: A 14.5-million-year record of East Antarctic Ice Sheet fluctuations from the central Transantarctic Mountains, constrained with cosmogenic 3He, 10Be, 21Ne, and 26Al, Cryosph., 14(8), 2647–2672, doi:10.5194/tc-2020-57, 2020.

Barrett, P. J., Adams, C. J., McIntosh, W. C., Swisher, C. C. and Wilson, G. S.: Geochronological evidence supporting Antarctic deglaciation three million years ago, Nature, 359, 816–818, 1992.

Bierman, P. R., Corbett, L. B., Graly, J. A., Neumann, T. A., Lini, A., Crosby, B. T. and Rood, D. H.: Preservation of a Preglacial Landscape Under the Center of the Greenland Ice Sheet, Science (80-.)., 344, 402–405, doi:10.4159/harvard.9780674430501.c21, 2014.

Bromley, G. R. M., Hall, B. L., Stone, J. O., Conway, H. and Todd, C. E.: Late Cenozoic deposits at Reedy Glacier, Transantarctic Mountains: implications for former thickness of the West Antarctic Ice Sheet, Quat. Sci. Rev., 29(3–4), 384–398, doi:10.1016/j.quascirev.2009.07.001, 2010.

Brook, E. J., Kurz, M. D., Ackert, R. P., Denton, G. H., Brown, E. T., Raisbeck, G. M. and Yiou, F.: Chronology of taylor glacier advances in Arena Valley, Antarctica, using in situ cosmogenic 3He and 10Be, Quat. Res., 39(1), 11–23, doi:10.1006/qres.1993.1002, 1993.

Brook, E. J., Brown, E. T., Kurz, M. D., Ackert, R. P., Raisbeck, G. M. and Yiou, F.: Constraints on age, erosion, and uplift of Neogene glacial deposits in the Transantarctic Mountains determined from in situ cosmogenic 10Be and 26Al, Geology, 23(12), 1063–1066, doi:10.1130/0091-7613(1995)023<1063:coaeau>2.3.co;2, 1995.

Brown, E. T., Edmond, J. M., Raisbeck, G. M., Bourlès, D. L., Yiou, F. and Measures, C. I.: Beryllium isotope geochemistry in tropical river basins, Geochim. Cosmochim. Acta, 56(4), 1607–1624, doi:10.1016/0016-7037(92)90228-B, 1992.

Bruno, L. A., Baur, H., Graf, T., Schlüchter, C., Signer, P. and Wieler, R.: Dating of Sirius Group tillites in the Antarctic Dry Valleys with cosmogenic 3He and 21Ne., 1997.

Cary, S. C., McDonald, I. R., Barrett, J. E. and Cowan, D. A.: On the rocks: The microbiology of Antarctic Dry Valley soils, Nat. Rev. Microbiol., 8(2), 129–138, doi:10.1038/nrmicro2281, 2010.

Claridge, G. G. C. and Campbell, I. B.: Origin of nitrate deposits., 1968a.

Claridge, G. G. C. and Campbell, I. B.: Soils of the Shackleton glacier region, Queen Maud Range, Antarctica, New Zeal. J. Sci., 11(2), 171–218, 1968b.

Clark, P. U., Dyke, A. S., Shakun, J. D., Carlson, A. E., Clark, J., Wohlfarth, B., Mitrovica, J. X., Hostetler, S. W. and McCabe, A. M.: The Last Glacial Maximum, Science (80-.)., 325, 710–714, doi:10.1126/science.1172873, 2009.

Collins, G. E., Hogg, I. D., Convey, P., Sancho, L. G., Cowan, D. A., Lyons, W. B., Adams, B. J., Wall, D. H. and Green, T. G. A.: Genetic diversity of soil invertebrates corroborates timing estimates for past collapses of the West Antarctic Ice Sheet, Proc. Natl. Acad. Sci. U. S. A., 117(36), 22293–22302, doi:10.1073/pnas.2007925117, 2020.

Convey, P., Gibson, J. A. E., Hillenbrand, C. D., Hodgson, D. A., Pugh, P. J. A., Smellie, J. L. and Stevens, M. I.: Antarctic terrestrial life - Challenging the history of the frozen continent?, Biol. Rev., 83(2), 103–117, doi:10.1111/j.1469-185X.2008.00034.x, 2008.

Diaz, M. A., Li, J., Michalski, G., Darrah, T. H., Adams, B. J., Wall, D. H., Hogg, I. D., Fierer, N., Welch, S. A., Gardner, C. B. and Lyons, W. B.: Stable isotopes of nitrate, sulfate, and carbonate in soils from the Transantarctic Mountains, Antarctica: A record of atmospheric deposition and chemical weathering, Front. Earth Sci., 8(341), doi:10.3389/feart.2020.00341, 2020.

Dickinson, W. W., Schiller, M., Ditchburn, B. G., Graham, I. J. and Zondervan, A.: Meteoric Be-10 from Sirius Group suggests high elevation McMurdo Dry Valleys permanently frozen since 6 Ma, Earth Planet. Sci. Lett., 355–356, 13–19, doi:10.1016/j.epsl.2012.09.003, 2012a.

Dickinson, W. W., Schiller, M., Ditchburn, B. G., Graham, I. J. and Zondervan, A.: Meteoric Be-10 from Sirius Group suggests high elevation McMurdo Dry Valleys permanently frozen since 6 Ma, Earth Planet. Sci. Lett., 355–356, 13–19, doi:10.1016/j.epsl.2012.09.003, 2012b.

Ebert, K., Willenbring, J., Norton, K. P., Hall, A. and Hättestrand, C.: Meteoric 10 Be concentrations from saprolite and till in northern Sweden: Implications for glacial erosion and age, , doi:10.1016/j.quageo.2012.05.005, 2012.

Elliot, D. H. and Fanning, C. M.: Detrital zircons from upper Permian and lower Triassic Victoria Group sandstones, Shackleton Glacier region, Antarctica: Evidence for multiple sources along the Gondwana plate margin, Gondwana Res., 13, 259–274, doi:10.1016/j.gr.2007.05.003, 2008.

Fountain, A. G., Lewis, K. J. and Doran, P. T.: Spatial climatic variation and its control on glacier equilibrium line altitude in Taylor Valley, Antarctica., 1999.

Fraser, C. I., Nikula, R., Ruzzante, D. E. and Waters, J. M.: Poleward bound: Biological impacts of Southern Hemisphere glaciation, Trends Ecol. Evol., 27(8), 462–471, doi:10.1016/j.tree.2012.04.011, 2012.

Frey, M. M., Savarino, J., Morin, S., Erbland, J. and Martins, J. M. F.: Photolysis imprint in the nitrate stable isotope signal in snow and atmosphere of East Antarctica and implications for reactive nitrogen cycling., 2009.

Gasson, E., DeConto, R. M., Pollard, D. and Levy, R. H.: Dynamic Antarctic ice sheet during the early to mid-Miocene, Proc. Natl. Acad. Sci. U. S. A., 113(13), 3459–3464, doi:10.1073/pnas.1516130113, 2016.

Golledge, N. R., Fogwill, C. J., Mackintosh, A. N. and Buckley, K. M.: Dynamics of the last glacial maximum Antarctic ice-sheet and its response to ocean forcing, Proc. Natl. Acad. Sci. U. S. A., 109(40), 16052–16056, doi:10.1073/pnas.1, 2012.

Golledge, N. R., Levy, R. H., McKay, R. M., Fogwill, C. J., White, D. A., Graham, A. G. C., Smith, J. A., Hillenbrand, C. D., Licht, K. J., Denton, G. H., Ackert, R. P., Maas, S. M. and Hall, B. L.: Glaciology and geological signature of the Last Glacial Maximum Antarctic ice sheet, Quat. Sci. Rev., 78, 225–247, doi:10.1016/j.quascirev.2013.08.011, 2013.

Graham, I., Ditchburn, R. G., Claridge, G. G. G., Whitehead, N. E., Zondervan, A. and Sheppard, D. S.: Dating Antarctic soils using atmospheric derived 10Be and nitrate, R. Soc. New Zeal. Bull., 35, 429–436, 2002.

Graly, J. A., Bierman, P. R., Reusser, L. J. and Pavich, M. J.: Meteoric 10Be in soil profiles - A global meta-analysis, Geochim. Cosmochim. Acta, 74, 6814–6829, doi:10.1016/j.gca.2010.08.036, 2010.

Graly, J. A., Licht, K. J., Druschel, G. K. and Kaplan, M. R.: Polar desert chronologies through quantitative measurements of salt accumulation, Geology, 46(4), 351–354, doi:10.1130/G39650.1, 2018.

Gulick, S. P. S., Shevenell, A. E., Montelli, A., Fernandez, R., Smith, C., Warny, S., Bohaty, S. M., Sjunneskog, C., Leventer, A., Frederick, B. and Blankenship, D. D.: Initiation and long-term instability of the East Antarctic Ice Sheet, Nature, 552(7684), 225–229, doi:10.1038/nature25026, 2017.

Hambrey, M. J., Webb, P. N., Harwood, D. M. and Krissek, L. A.: Neogene glacial record from the Sirius Group of the Shackleton Glacier region, central Transantarctic Mountains, Antarctica, GSA Bull., 115(8), 994–1015, doi:10.1130/B25183.1, 2003.

Ivy-Ochs, S., Schluchter, C., Kubik, P. W., Dittrich-Hannen, B. and Beer, J.: Minimum 10Be exposure ages of early Pliocene for the Table Mountain plateau and the Sirius Group at Mount Fleming, Dry Valleys, Antarctica, Geology, 23(11), 1007–1010, 1995.

Jones, R. S., Mackintosh, A. N., Norton, K. P., Golledge, N. R., Fogwill, C. J., Kubik, P. W., Christl, M. and Greenwood, S. L.: Rapid Holocene thinning of an East Antarctic outlet glacier driven by marine ice sheet instability, Nat. Commun., 6(8910), 9910, doi:10.1038/ncomms9910, 2015.

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.: Middle to Late Pleistocene stability of the central East Antarctic Ice Sheet at the head of Law Glacier, Geology, 45(11), 963–966, doi:10.1130/G39189.1, 2017.

Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U. C., Knie, K., Rugel, G., Wallner, A., Dillmann, I., Dollinger, G., von Gostomski, C. L., Kossert, K., Maiti, M., Poutivtsev, M. and Remmert, A.: A new value for the half-life of 10Be by Heavy-Ion Elastic Recoil Detection and liquid scintillation counting, Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms, 268(2), 187–191, doi:10.1016/j.nimb.2009.09.020, 2010.

Lancaster, N., Nickling, W. G. and Gillies, J. A.: Sand transport by wind on complex surfaces: Field studies in the McMurdo Dry Valleys, Antarctica, J. Geophys. Res., 115(F3), F03027, doi:10.1029/2009JF001408, 2010.

Lewis, A. R., Marchant, D. R., Ashworth, A. C., Hedenäs, L., Hemming, S. R., Johnson, J. V., Leng, M. J., Machlus, M. L., Newton, A. E., Raine, J. I., Willenbring, J. K., Williams, M. and Wolfe, A. P.: Mid-Miocene cooling and the extinction of tundra in continental Antarctica, Proc. Natl. Acad. Sci. U. S. A., 105(31), 10676–10680, doi:10.1073/pnas.0802501105, 2008.

Lyons, W. B., Deuerling, K., Welch, K. A., Welch, S. A., Michalski, G., Walters, W. W., Nielsen, U., Wall, D. H., Hogg, I. and Adams, B. J.: The Soil Geochemistry in the Beardmore Glacier Region, Antarctica: Implications for Terrestrial Ecosystem History, Sci. Rep., 6, 26189, doi:10.1038/srep26189, 2016.

MacKintosh, A., Golledge, N., Domack, E., Dunbar, R., Leventer, A., White, D., Pollard, D., Deconto, R., Fink, D., Zwartz, D., Gore, D. and Lavoie, C.: Retreat of the East Antarctic ice sheet during the last glacial termination, Nat. Geosci., 4(3), 195–202, doi:10.1038/ngeo1061, 2011.

Mackintosh, A. N., Verleyen, E., O'Brien, P. E., White, D. A., Jones, R. S., McKay, R., Dunbar, R., Gore, D. B., Fink, D., Post, A. L., Miura, H., Leventer, A., Goodwin, I., Hodgson, D. A., Lilly, K., Crosta, X., Golledge, N. R., Wagner, B., Berg, S., van Ommen, T., Zwartz, D., Roberts, S. J., Vyverman, W. and Masse, G.: Retreat history of the East Antarctic Ice Sheet since the Last Glacial Maximum, Quat. Sci. Rev., 100, 10–30, doi:10.1016/j.quascirev.2013.07.024, 2014.

Marchant, D. R., Denton, G. H., Swisher, C. C. and Potter, N.: Late Cenozoic Antarctic paleoclimate reconstructed from volcanic ashes in the Dry Valleys region of southern Victoria Land, Geol. Soc. Am. Bull., 108(2), 181–194, doi:https://doi.org/10.1130/0016-7606(1996)108%3C0181:LCAPRF%3E2.3.CO;2, 1996.

Margerison, H. R., Phillips, W. M., Stuart, F. M. and Sugden, D. E.: Cosmogenic 3He concentrations in ancient flood deposits from the Coombs Hills, northern Dry Valleys, East Antarctica: interpreting exposure ages and erosion rates, Earth Planet. Sci. Lett., 230(1–2), 163–175, doi:10.1016/J.EPSL.2004.11.007, 2005.

McHargue, L. R. and Damon, P. E.: The global beryllium 10 cycle, Rev. Geophys., 29(2), 141–158, doi:10.1029/91RG00072, 1991.

Menzies, J., van der Meer, J. J. M. and Rose, J.: Till-as a glacial "tectomict", its internal architecture, and the development of a "typing" method for till differentiation, Geomorphology, 75, 172–200, doi:10.1016/j.geomorph.2004.02.017, 2006.

Michalski, G., Bockheim, J. G., Kendall, C. and Thiemens, M.: Isotopic composition of Antarctic Dry Valley nitrate: Implications for NOy sources and cycling in Antarctica, Geophys. Res. Lett., 32(13), 1–4, doi:10.1029/2004GL022121, 2005.

Morgan, D., Putkonen, J., Balco, G. and Stone, J.: Quantifying regolith erosion rates with cosmogenic nuclides 10 Be and 26 Al in the McMurdo Dry Valleys, Antarctica, J. Geophys. Res., 115, F03037, doi:10.1029/2009JF001443, 2010.

Nishiizumi, K., Imamura, M., Caffee, M. W., Southon, J. R., Finkel, R. C. and McAninch, J.: Absolute calibration of 10Be AMS standards, Nucl. Instruments Methods Phys. Res. B, 258, 403–413, doi:10.1016/j.nimb.2007.01.297, 2007.

Paulsen, T. S., Encarnación, J. and Grunow, A. M.: Structure and timing of transpressional deformation in the Shackleton Glacier area, Ross orogen, Antarctica, J. Geol. Soc. London., 161(6), 1027–1038, doi:10.1144/0016-764903-040, 2004.

Pavich, M. J., Brown, L., Klein, J. and Middleton, R.: 10Be accumulation in a soil chronosequence, Earth Planet. Sci. Lett., 68, 198–204, doi:10.1016/0012-821X(84)90151-1, 1984.

Pavich, M. J., Brown, L., Harden, J., Klein, J. and Middleton, R.: 10Be distribution in soils from Merced River terraces, California, Geochim. Cosmochim. Acta, 50, 1727–1735, doi:10.1016/0016-7037(86)90134-1, 1986.

Pollard, D. and DeConto, R. M.: Modelling West Antarctic ice sheet growth and collapse through the past five million years, Nature, 458(7236), 329–332, doi:10.1038/nature07809, 2009.

Reich, M. and Bao, H.: Nitrate deposits of the Atacama Desert: A marker of long-term hyperaridity, Elements, 14(4), 251–256, doi:10.2138/gselements.14.4.251, 2018.

Scherer, R. P., DeConto, R. M., Pollard, D. and Alley, R. B.: Windblown Pliocene diatoms and East Antarctic Ice Sheet retreat, Nat. Commun., 7(1), 1–9, doi:10.1038/ncomms12957, 2016.

Schiller, M., Dickinson, W., Ditchburn, R. G., Graham, I. J. and Zondervan, A.: Atmospheric 10 Be in an Antarctic soil: Implications for climate change, J. Geophys. Res., 114(F1), 1–8, doi:10.1029/2008jf001052, 2009.

Spector, P. and Balco, G.: Exposure-age data from across Antarctica reveal mid-Miocene establishment of polar desert climate, Geol. Soc. Am. | Geol., 1, doi:10.1130/G47783.1, 2020.

Spector, P., Stone, J., Cowdery, S. G., Hall, B., Conway, H. and Bromley, G.: Rapid early-Holocene deglaciation in the Ross Sea, Antarctica, Geophys. Res. Lett., 44(15), 7817–7825, doi:10.1002/2017GL074216, 2017.

Steig, E., Stuiver, M. and Polissar, P.: Cosmogenic isotope concentrations at Taylor Dome, Antarctica, Antarct. J. United States, 30, 95–97, 1995.

Stevens, M. I. and Hogg, I. D.: Long-term isolation and recent range expansion from glacial refugia revealed for the endemic springtail Gomphiocephalus hodgsoni from Victoria Land, Antarctica, Mol. Ecol., 12(9), 2357–2369, doi:10.1046/j.1365-294X.2003.01907.x, 2003.

Stone, J.: A rapid fusion method for separation of beryllium-10 from soils and silicates, Geochim. Cosmochim. Acta, 62(3), 555–561, doi:10.1016/S0016-7037(97)00340-2, 1998.

Strasky, S., Di Nicola, L., Baroni, C., Salvatore, M. C., Baur, H., Kubik, P. W., Schlüchter, C. and Wieler, R.: Surface exposure ages imply multiple low-amplitude Pleistocene variations in East Antarctic Ice Sheet, Ricker Hills, Victoria Land, Antarct. Sci., 21(1), 59–69, doi:10.1017/S0954102008001478, 2009.

Stroeven, A. P., Prentice, M. L. and Kleman, J.: On marine microfossil transport and pathways in Antarctica during the late Neogene: Evidence from the Sirius Group at Mount Fleming, Geology, 24(8), 727–730, doi:10.1130/0091-7613(1996)024<0727:ommtap>2.3.co;2, 1996.

Summerfield, M. A., Stuart, F. M., Cockburn, H. A. P., Sugden, D. E., Denton, G. H., Dunai, T. and Marchant, D. R.: Long-term rates of denudation in the Dry Valleys, Transantarctic Mountains, southern Victoria Land, Antarctica based on in-situ-produced cosmogenic 21Ne, Geomorphology, 27(1–2), 113–129, doi:10.1016/S0169-555X(98)00093-2, 1999.

Talarico, F. M., McKay, R. M., Powell, R. D., Sandroni, S. and Naish, T.: Late Cenozoic oscillations of Antarctic ice sheets revealed by provenance of basement clasts and grain detrital modes in ANDRILL core AND-1B, Glob. Planet. Change, 96–97, 23–40, doi:10.1016/j.gloplacha.2009.12.002, 2012.

Valletta, R. D., Willenbring, J. K., Lewis, A. R., Ashworth, A. C. and Caffee, M.: Extreme decay of meteoric beryllium-10 as a proxy for persistent aridity, Sci. Rep., 5, 17813, doi:10.1038/srep17813, 2015.

Webb, P. N. and Harwood, D. M.: Late Cenozoic glacial history of the Ross embayment, Antarctica, Quat. Sci. Rev., 10(2–3), 215–223, doi:10.1016/0277-3791(91)90020-U, 1991.

Webb, P. N., Harwood, D. M., McKelvey, B. C., Mercer, J. H. and Stott, L. D.: Cenozoic marine sedimentation and ice-volume variation on the East Antarctic craton, Geology, 12(5), 287–291, doi:10.1130/0091-7613(1984)12<287:cmsaiv>2.0.co;2, 1984.

Webb, P. N., Harwood, D. M., Mabin, M. G. C. and McKelvey, B. C.: A marine and terrestrial Sirius Group succession, middle Beardmore Glacier-Queen Alexandra Range, Transantarctic Mountains, Antarctica, Mar. Micropaleontol., 27(1–4), 273–297, doi:10.1016/0377-8398(95)00066-6, 1996.

Welch, K. A., Lyons, W. B., Whisner, C., Gardner, C. B., Gooseff, M. N., Mcknight, D. M. and Priscu, J. C.: Spatial variations in the geochemistry of glacial meltwater streams in the Taylor Valley, Antarctica, Antarct. Sci., 22(6), 662–672, doi:10.1017/S0954102010000702, 2010.

Willenbring, J. K. and von Blanckenburg, F.: Meteoric cosmogenic Beryllium-10 adsorbed to river sediment and soil: Applications for Earth-surface dynamics, Earth-Science Rev., 98(1–2), 105–122, doi:10.1016/j.earscirev.2009.10.008, 2010.

You, C. F., Lee, T. and Li, Y. H.: The partition of Be between soil and water, Chem. Geol., 77(2), 105–118, doi:10.1016/0009-2541(89)90136-8, 1989.