Author Responses to Reviewer Comments for

GCHRON-2023-16 | Research article

**Early Holocene ice retreat from Isle Royale in the Laurentian Great Lakes constrained with $^{10}$Be exposure-age dating**

Eric W. Portenga, David J. Ullman, Lee B. Corbett, Paul R. Bierman, and Marc Caffee

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**Comments from RC1:**

Review of Portenga et al. Geochronology 2023

**Major comments**

Two approaches already exist for assigning ages to the moraines on Isle Royale, with this article offering a third and more direct approach by using cosmogenic dating of boulders on the moraines themselves. The first approach is geomorphic in nature. By using the extent of the Highbridge shoreline on Fig. 3 and from the work of Breckenridge (2013) that shows where the lake's outlet is for the Highbridge level, the ice margin location and age within a few hundred years is known on Isle Royale and the south shore of Lake Superior. Thus, the radiocarbon-based chronology in Breckenrdige (2013) is being tested by cosmogenic dating. The Highbridge shoreline ends just east of the eastern-most sampled moraine, and on Fig. 3c the Highbridge shoreline may be in contact with the eastern-most mapped moraine. These data suggest that when the ice margin was adjacent to the youngest moraine mapped, the outlet for the lake was the McMaster outlet on the UP according to figure 7 in Breckenridge (2013) well south of the position shown in Fig 6b. Assuming the 10.8-10.6 cal ka BP age is correct for drawdown of the glacial lake levels, then the geomorphology of the moraines and lake levels in the study area indicates the moraines mapped on Isle Royale had formed before or at the start of the lake drawdown:~10.8 cal yr BP.

**Author Response:** One major component of the geographical extent of existing landforms that is important to recognize about strandlines on Isle Royale (and therefore the relative position of all other landforms, including the moraines we sample in this study) is their anisotropy. All strandlines on Isle Royale older than those associated with post-Minong lake levels, are restricted to northwest-facing slopes and are completely absent from southeast-facing slopes. Thus, interpreting the relationship between strandline ages and moraine ages is not as simple as saying that the age of moraines must be older than the age of Highbridge because Highbridge strandlines extend up-ice of sampled moraines. Rather, it is crucial to recognize in our interpretation of new $^{10}$Be ages that these Highbridge strandlines are on the opposite side of the ridges from where our samples are found. The complete absence of these older strandlines on the southeast-facing slopes implies a longer-lasting presence of ice on Isle Royale, later than previously considered, else older strandlines would also be present on southeast-facing slopes, as is the case with post-Minong and younger strandlines. This is a major component of our interpretation, and one that we feel is supported by our new data.

The second approach is taking advantage of the utility of the basal radiocarbon dates from Lily and Ojibway lakes, which could have been further explored to understand the timing of ice retreat across the island using 14C dating. The basal, bulk dates from gytjja (Flakne, 2003) only record establishment of vegetation in the watershed after the drawdown of the glacial lakes (isolation ages), thus they are very much minimum ages for deglaciation, and some lag estimate needs to be assigned to cover the time gap between ice margin retreat and isolation of the lake. The lake bottom 14C dates give an approximate ice margin retreat rate of 100 m/yr across the island. If assuming a 100 year lag, and the distance east of Lily lake, the moraines would date to ~10.7 ka.

**Author Response:** Per the Reviewer's suggestion, we now include in the Discussion the inferred retreat rate between Lily Lake and Lake Ojibway, but we are uncertain how the Reviewer arrived at a 100 m $yr^{-1}$ retreat rate. We are also uncertain about how the Reviewer arrives at the assumption that the minimum-limiting 14C ages from Lily Lake and Lake Ojibway lags 100 years behind deglaciation. The distance between these lakes is ~42 km and the difference in reported median ages is 900 yrs (Flakne, 2003). This rate (~46 m $yr^{-1}$) is similar to that along the North Shore, but the series of moraines we dated in this study fall geographically between these two lakes. Thus, the retreat rate between these two lakes should be considered a minimum mean retreat rate because it does not account for the periods of time that the ice margin was at a standstill during which the subaqueous IR1 and IR2 moraines (Colman et al., 2020) and the subaerial moraines (this study) were constructed. These points are now included in our Discussion.

The two methods just discussed give ages that are encompassed by the cosmogenic dating result of this article: 9-11.2 ka. However, due to the large uncertainity (2200 years) for the boulders, there is little justification to fine tune an ice margin position at 10.1 ka within eastern Lake Superior basin given it is only the mean age, and the 14C dated lake levels linked to ice margins provide older age estimates for the moraines with less uncertainty.

**Authors' Comments:** We understand that the ±1.1 ka, 1σ standard deviation uncertainty we report is broad; however, there is a large amount of geological and methodological variability that could affect individual ages and/or the dataset as a whole. Yes, accounting for some of these factors (e.g. snow shielding, exhumation) could make our ages older, but some (e.g. inheritance) could make ages younger. The mean age, based on $^{10}$Be data, is the mean age of the dataset and it is what we have available to us to interpret in the context of the existing regional glacial history. We do add language to the first paragraph of the Discussion, however, that hopefully makes it clear to the readers that we know we report a broad uncertainty but that we interpret the mean age that emerges from our dataset. We do make stronger attempts to use wording that lets readers know that the spatial or chronological relationships we present are based on this mean $^{10}$Be age.

The cosmogenic dating method requires many corrections and assumptions to ensure the most accurate age assignment for a sample because of the complexity of the dating process. So, it seems odd that the multiple corrections that are explored in the sensitivity analysis are dismissed in part based on what other authors have done nearby, and that the age corrections fall within the error associated with preferred age. If corrections were made using snow cover and possibly a different calculator, the mean age may more closely match ages already established by the two methods previously described above. From my perspective based on the available chronology in the region, the mean deglacial age from boulders in this article (10.1 ka) is too young based on my reasoning in the previous paragraphs. It is surprising that the correction for snow cover was not made. Of course, the meteorological data for the past 60 years may not perfectly match the past 10,000 years, but as the authors state, heavy snowfall is normal for this region, and from my perspective, some reasonable attempt seems better than ignoring the problem altogether. By being consistent with the approach used by Lowell et al. (2021) seems like weak reasoning for the preferred methodology, especially when the radiocarbon chronology from Isle Royale offers reasonable bracketing power for the moraines suggesting the moraines are older. Thus, by not doing some of the corrections or using a newly released calculator in order to maintain a similar methodology with other studies seems to be an approach that weakens the rigour of the method, and its ability to independently test the results (i.e., 14C) from other studies. And what if in the future, the approach used in other articles turns out to be less rigorous?

**Author Response:** We appreciate the reviewer's concern that we did not make more corrections to our dataset than we could have, but we did not just dismiss many of these options because others did; we dismissed many of these options because we showed that they either weren't significant or that we did not have reasonable justification for doing so. We also do not present a preferred age; we present the mean exposure age based on our $^{10}$Be data. The reviewer is correct that making some additional corrections may indeed place our mean age in closer agreement with previously established ages; however, we do not believe we have the justification for doing so, as we describe in Appendix B and as we elaborate on further in responses to subsequent Reviewers, all of whom self-identify as being very familiar with the $^{10}$Be exposure-age dating method. We prefer to interpret our data as they are, rather than making unjustifiable corrections to make them fit some pre-existing expectation of what the data should be. As other Reviewers note, they appreciate our exploration of how ages would shift with different corrections or approaches to exposure age calculations, but overall, they agree that our approach is sound. Subsequent reviewers focus their critiques on our approach on issues related to moraine topographical degradation/erratic exhumation and issues of snow cover, and we address these issues below.

**Minor Comments:**
The article would read much better if the first-person phrases (allow us, we suggest, we hypothesize, etc.) are removed. The reader knows who the authors are.

**Author Response:** First-person articles are not uncommon in the literature. Our choice may be stylistic, but it is not against *Geochronology*'s standards. We did, however, review the manuscript for consistent voice, and we made appropriate wording edits in the Methods to reduce first-person language.

Missing from the introduction is a more complete deglaciation history of the Superior basin, starting with the uncertainty of how far the ice receded before the Marquette readvance. This is relevant for any meltwater routing associated with that time period, and perhaps for explaining the author's oldest erratic on Isle Royale (12.4 ka), whose older age is not discussed.

**Author Response:** The Reviewer makes this point in their comment re: Line 63 (see below), and we address the issue of ice margin position prior to the Marquette Readvance there. The older age of the oldest sample (IR-18-06) is not a statistical outlier (see our comment to RC3 re: Lines 220-221).

Line 62, not sure ice grew in the area vs. advanced, and recent work by Lowell et al. 2021 shows that the ice margin (different lobes) along the North Shore was in constant recession during the YD, so perhaps that is a more relevant finding for this part of the world vs other areas (Carlson 2010). Study location contains more review text. Section 2 could be reduced and relevant text moved to section 1.

**Author Response:** We change our wording from "growth" to "advance" here and elsewhere

**Technical Comments:**
Strings of references within the text should be arranged in chronological order (oldest first) vs. alphabetical.

**Author Response:** Copernicus guidelines state that in-text citations can be in alphabetical order (https://www.geochronology.net/submission.html#references)

Line 72, for glacial Lake Agassiz and other formal lake names, 'glacial' is not capitalized as it is an adjective.

**Author Response:** All usage of 'glacial' as an adjective have been changed to lowercase

Line 11, moraines, like the island have been dated with minimum 14C ages from bracketing lakes. Change 'previous' to 'directly'.

**Author Response:** Done

Line 31, include recent Lake Agassiz paper by Fisher and Breckenridge, 2022 QSR.

**Author Response:** Done

Line 60, add BP as the date is based on 14C ages. Similarly elsewhere in the text. Also, for this complex sentence remove reporting method and add it as a separate sentence.

**Author Response:** All 14C ages are now reported as "cal ka BP" We moved the reporting method sentence to the end of the previous paragraph where it seems to be a better fit so as not to disrupt the narrative.

Line 63, relevance here is how far ice first retreated before it readvanced, perhaps it was only a short distance from the southern shore of the lake.

**Author Response:** It is unclear how far ice retreated prior to the Marquette Readvance, but it is thought to be moderate, and not far. We now cite Hobbs and Breckenridge (2011), who explain that this advance is thought to have been moderate from pre-Marquette Readvance ice positions, at least to the Grand Marais I and Marks Moraines.

Line 66, elaborate a bit on what these alternative interpretations are and how this work addresses them.

**Author Response:** We discussed this point prior to initial submission. The "alternative interpretations" relate to the position of the LIS margin during the Marquette Readvance, which we do present to the readers in the Introduction. Adding in all relevant details would significantly deviate from the narrative presented in this study and beyond what the readership of *Geochronology* needs to know about what our new $^{10}$Be data tell us about ice retreat from Isle Royale. We prefer to cite relevant literature here and focus more on the details that will be important for interpreting our new $^{10}$Be dataset and placing it in the context of regional ice retreat *since* the Marquette Readvance.

Line 73, add arrows to figure 2, for routing of Lake Agassiz drainage, and perhaps clarify when drainage was from Lake Agassiz. Also, note that it was not the Superior Lobe that uncovered the eastern outlets of Lake Agassiz, but the Superior Lobe did also have to retreat to permit this drainage.

**Author Response:** Arrows showing the paths of meltwater routing from Lake Agassiz are shown in Figure 2 (blue arrows from Lake Nipigon to Lake Superior). If the Superior Lobe must have retreated for meltwater to drain from Lake Agassiz to Lake Superior via these outlets between Lake Nipigon and Lake Superior, then it must have uncovered outlets as the manuscript reads.

Line 74-77, provide available age constraints for these events so that your results can be compared to them.

**Author Response:** Many of these outlets are undated and only interpreted as being associated with different lake levels between Duluth and post-Minong, all of which overlap in age from ~10.8-10.6 cal ka BP. All of these associations are from Breckenridge (2013), which we cite.

Figure 2 caption has plenty of information not included in the text regarding possible ice margins. The text could be slightly expanded to included implications of the various ice margins.

**Author Response:** The caption for Figure 2 was reviewed for text missing from the main text and vice versa. The caption was edited accordingly, mostly relocating text to the main manuscript. Stylistic revisions were made for brevity.

Line 96, not the middle of the lake.

**Author Response:** Changed 'in the middle of' to 'within'

Red diamicton and lacustrine sediments are also found in the Thunder Bay area related to the local bedrock and not sourced from Lake Agassiz.

**Author Response:** Yes, and we say as much in Line 108, "Red varves are…sourced from red clay, till, and bedrock…" The original work by Farrand suggests a bedrock source and the till and clay sources are identified by Breckenridge et al. Both are cited. To address this comment, we do add in the qualifier "and/or" to this list to highlight to the reader that the source of red varves may be one of the items in this list, or multiple.

Line 125, 'shallow rise', do you mean low-relief? Shallow implies close to the water surface.

**Author Response:** We mean 'shallow rise' because there is a shallow bathymetrical rise northeast of Isle Royale where Mothersill and Fung (1972) identify gray varves directly overlying pre-Marquette Readvance till.

Line 126, clarify what these ridges are. Till, bedrock etc.

**Author Response:** Clarified that these are bedrock ridges

Line 137, slope aspect relationship with elevation has not been introduced. Also, the phrase of 'ice covered southeast-facing slopes' is similarly confusing as wouldn't there also be ice on the northwest facing slopes?

**Author Response:** Per a subsequent Reviewer's suggestion, this section on the location of strandlines and their slope-aspect relationships have been moved later into the Discussion. But to respond to the question raised here, our answer is no, that ice on the northwest facing slopes retreated further than on southeast facing slopes, such that when proglacial lakes occupied western Lake Superior, strandlines only formed on the ice-free side of Isle Royale's ridges.

Line 140, the island and its landforms have been dated from the minimum limiting ages from lake bottoms, and regional relationships. Add 'directly' before 'dated'. Also, basal 14C dates from both lake cores are minimum bulk ages, with at least a few meters of lacustrine clay beneath the gyttja. Thus, these are isolation ages, very much minimum ages for deglaciation, as they simply date establishment of vegetation after drawdown of the glacial lakes.

**Author Response:** We clarify here that the moraines themselves have never been directly dated.

Line 168, 'drift' is an antiquated term now, use till plain instead, assuming it is till deposits you are referring to.

**Author Response:** Maps used by the National Park Service still refer to drift, and we had just followed suit. We now change 'drift' to 'till'

Figure 4: This spatial association indicates that lake level had not fallen from the Highbridge level until ice had retreated east of the easternmost mapped moraine. Thus, according to Fig. 4, only 1 or 2 boulders were submerged in the lake.

**Author Response:** Until we obtained our ages for the Mt. Desor moraine, there existed the possibility that ice had retreated to the easternmost mapped moraine, northeast of our sample sites prior to Highbridge (as indicated in Breckenridge, 2013). Our own LiDAR analysis suggests that if the ice margin had retreated this far during glacial Lake Duluth stage, a few meters of land would be exposed subaerially and any shorelines formed at this time were simply not extensive enough or preserved well enough to be identified at Duluth strandlines in Breckenridge's (2013) analysis. We thought it was necessary to at least consider whether exposure ages could be affected by subaqueous exposure and attenuation of $^{10}$Be production through proglacial lakes; however, the Reviewer's comment helped us recognize that we perhaps spend too much time considering whether initial erratic exposure was subaqueous or subaerial. Because we already conclude that subaqueous exposure would be minimal in the Methods (Line 175), we omitted the comparison of the mean exposure ages of the five lowest elevation versus the five highest elevations in the Discussion. This helps focus the narrative in the Discussion.

Line 271, add topic sentence to explain purpose of the figure.

**Author Response:** After re-reading the figure caption for Figure 5, it seems the first sentence is clear that this figure is a distribution of $^{10}$Be ages from Isle Royale.

Line 281, also include retreat rate across Isle Royale based on the lake dates, ~100m/yr.

**Author Response:** The retreat rate across Isle Royale based on the lake dates is ~45 m/yr and is now incorporated into our discussion of ice retreat rates. We are uncertain where the suggested ~100 m $yr^{-1}$ value comes from.

Lines 301-303, provide a reference for the association between red varves and Lake Agassiz drainage vs. fluvial drainage from north shore of Lake Superior.

**Author Response:** Done

Line 312, missing are age constraints from the Agassiz literature for when meltwater from Lake Agassiz began flowing through the Nipigon outlets (Fig. 6c) into Lake Superior.

**Author Response:** Done

Line 342, typo at end of line.

**Author Response:** Fixed

Line 352, insert 'a' before 'large'.

**Author Response:** The comment on 'large lakes' has been removed per another Reviewer's comments because doing work on islands is also useful in marine settings.

Fig. 2b, typo in second line of legend. Add arrows for meltwater routing from Lake Agassiz.

**Author Response:** Fixed

Fig 3, are there uncorrelated strandlines mapped? Provide 1 sigma age range for the two 14C dates from the lakes as that is how you present the cosmogenic ages. Orange text on blue background is not legible on print.

**Author Response:** Yes. They are shown as white lines, which are visible in Panels B and C. Orange lines and text changed to dark gray. 2σ ages for 14C sites are now provided in the figure.

Fig. 4, great figure, but add Lake Ojibway too.

**Author Response:** Thank you. Lake Ojibway is added to the figure.

Fig. 6, some of the text is very small.

**Author Response:** We have edited the figure in an attempt to improve readability, as all Reviewers commented on this figure.

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**Comments from RC2:**

In this manuscript, Portenga et al. date the recession of the Laurentide Ice Sheet from the central Lake Superior basin. Their new $^{10}$Be exposure ages from moraines on Isle Royale have an average exposure of 10.1 ± 1.1 ka. Considering their $^{10}$Be ages in combination with minimum-limiting $^{14}$C ages from lake sediments on the island and other constraints from Lake Superior sediments, the authors propose that the deglaciation of southern Lake Superior occurred several hundred years later than previously thought.

Overall, I think this paper will be a solid contribution to the glacial history of the Great Lakes region. Since I'm not as familiar with the LIS retreat chronology in this part of the world, I'll mostly focus my comments on the $^{10}$Be dating. The authors discuss several factors that could affect their chronology, including snow cover and GIA, as well as their choice of calculator, production rate, and scaling scheme. The authors show in the appendix that changing one of these factors does not significantly alter the calculated $^{10}$Be ages. I'm on board with their choice of calculator, production rate, and scaling scheme. I'm also a wary of GIA corrections that don't also include an atmospheric redistribution model (which I don't believe is included in the iceTEA calculator), so leaving the ages uncorrected for GIA in the main text makes sense to me.

However, the boulders that the authors sampled are quite small (Table 1) – some of them barely peek out of the cover on the forest floor (Fig. A1). Seeing this, it makes me wonder if a combination of snow cover and boulder exhumation during moraine degradation could be making the $^{10}$Be ages a bit too young. The modeling by Putkonen and Swanson (2003) suggests that smaller moraines may be less susceptible to significant moraine degradation, but I don't see any detailed information about the moraine topography in this manuscript. Showing some topographic profiles of the moraines themselves in the appendix and discussing this factor as a potential influence on the $^{10}$Be ages would be helpful. Even better, can you quantify how much sediment shielding would be needed to substantially change your interpretation of the $^{10}$Be ages (especially if it's considered in conjunction with snow cover)?

**Author Response:** With regards to boulder size and age, we agree that based on their size, the smaller erratics in this study would be ignored completely in an alpine environment, for example, but we would disagree that these are "barely peeking out" from the forest floor as we found handfuls of erratics that were flush with the forest floor. Sampled erratics that are low-lying (< ~50 cm) are still large in their length and width axes (Table 1). This is the nature of doing $^{10}$Be work in the continental Midwest. One of the authors of this study (D. Ullman) has perhaps the most experience sampling for $^{10}$Be in the Great Lakes region and his previous work (Ullman et al., 2015) demonstrates that reasonable interpretations can come from low-lying erratics; DU was present for fieldwork and helped guide sampling efforts. After three days of traversing these moraines, including the undated moraine east of Mt. Desor and the numerous smaller moraines mapped in the vicinity, these were the largest quartz-bearing erratics present that did not show indications of flipping or sliding from higher elevations.

We note that the smallest erratic (i.e. the erratic with the least height above the forest floor, IR-18-02) yields the 2$^{nd}$ oldest age of the dataset. We recognize that this is not proof that little exhumation of moraines occurred, and we are thankful for the Reviewer for pointing us towards Putkonen and Swanson's (2003) work. The erratics in this study were collected from moraines that are small (<10-30 m) and the remain relatively sharp-crested. We now provide a figure (new Figure 4) that shows four topographic profiles based on LiDAR data, each of which traverses the moraines we sampled. Two of these profiles X and Y are 2.5 km in length and span the frontal and lateral crests of the Mt. Desor moraines, respectively. The frontal crests are quite prominent above the local valley floor, whereas the lateral crests, which most of our samples come from, are small yet still distinct from the underlying bedrock ridge.

With regards to snow cover, we reiterate the concerns laid out to RC1, that we cannot know how well 70 years of snowfall data at one station on Isle Royale's northeast side is reflective of snowfall and snow density cover of all of Isle Royale throughout the Holocene (length of data record is <0.7% of the total duration possible snowfall time since the mean age of deglaciation we present in this study (~10.1 ka). We could incorporate a snow-shielding correction to our data, but it would be nothing more than a guess based on no reasonable evidence.

Given this, I think the most reasonable way to interpret the $^{10}$Be ages is that they provide a minimum age for the moraines. Squaring this slightly different interpretation with the age constraints from the Isle Royale lake strandlines and basal lake sediments shouldn't be that difficult of a task.

**Author Response:** We agree with the Reviewer that if exhumation or snow cover were the only two phenomena unaccounted for that the mean exposure age would be better interpreted as a minimum mean exposure age because correcting for exhumation and snow cover "adds in" missing $^{10}$Be production and the corrected exposure ages would be older than reported. However, there also exists the possibility that some of the $^{10}$Be measured from erratics is inherited from some previous exposure, which leads to corrected exposure ages that would be younger than we report. Since we are unable to account for the degree of exhumation, the true amount of snow cover, or whether erratics have inherited $^{10}$Be, we feel the mean age is best left as is, without qualifiers. We include a reference to Briner et al. (2016; Geophys. Res. Let., doi: 10.1002/2016GL070100) to demonstrate these possibilities.

**Minor comments**

Figure 1: Nice figure with a lot of information. In both panels, it would be great if you made the LIS margins a different color than the water bodies.

**Author Response:** We revised this figure, and we believe the ice sheet margins and lake colors are now different enough for visibility purposes.

Line 62: This sentence would read a bit better if the "a brief period of ice…" clause was moved somewhere before the long string of citations and $^{14}$C calibration notes.

**Author Response:** We moved the "a brief period of ice…" clause before the first list of citations and just included our citation to Carlson (2010) in that list. Reading this sentence should now be less awkward.

Line 66: What are the alternative interpretations for the $^{14}$C ages and stratigraphy? Consider adding more detail here, especially as these dates are important for interpreting your $^{10}$Be ages.

**Author Response:** Please see our response to Reviewer 1 comment about Line 66.

Figure 2: IR1 and IR2 abbreviations are not defined in the caption. Typo in key for panel B: "asediment"

**Author Response:** IR1 and IR2 are now defined and the typo is fixed.

Line 88: "overly" should be changed to "overlie."

**Author Response:** Done

Line 141: Specify that the basal ages from Flakne 2003 are on bulk sediments.

**Author Response:** Done

Figure 3: Nice maps. In panel C, are the second and third moraines from the east mapped as one deposit? It looks kind of strange. Also, please add a scale bar to panel C.

**Author Response:** The 2$^{nd}$ and 3$^{rd}$ moraines from the east are indeed mapped as one deposit, kind of like conjoined boomerangs at the northeast end! Scale bar is now added.

Table 2: Exposure age for IR-18-07 is missing a .0 on the end. In the caption, the reader is referred to Supplementary Material. Should this be "appendix B" instead?

**Author Response:** Both issues are now fixed.

Line 287: Unless I'm thinking about this incorrectly, if the ice is standing still to build the moraines, that means that 100 m $a^{-1}$ is a minimum retreat rate, not a maximum. Relatedly, any thoughts on why the ice margin retreat rate south of Isle Royale was faster than in the north?

**Author Response:** This mistake is on our part. The Reviewer is correct, and we change the wording here to clarify this is a minimum retreat rate.

Line 324: Missing period at the end of 10.1 ± 1.1 ka sentence.

**Author Response:** We are not seeing this issue, but we will verify all periods are in place.

Figure 6: Typos on "deposition" in keys of panels C and D. Also, the uncertainty on your $^{10}$Be ages in panel C does not match what's in rest of the manuscript text. At least one typo in the caption: "across end."

**Author Response:** Thanks for the keen eye. All issues are now fixed.

Line 345: I'm left wanting a bit more specificity in this section. For example, rather than saying that you "further clarify the relationship between the position of the ice margin, meltwater drainage pathways, and spatial patterns in lake-bottom stratigraphy," it would be clearer to say what these relationships actually are.

**Author Response:** Our "Implications" section has been revised to be more specific and hopefully more satisfying.

Line 352: should be "large lakes" not "large lake."

**Author Response:** Correct, and following a suggestion from Reviewer 4 (RC5), we removed this clause altogether because focusing on islands can help tie together chronologies in marine settings, too.

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**Comments from RC3:**

This manuscript presents cosmogenic exposure ages (n=11) from glacial landforms previously mapped on Isle Royale in Lake Superior to constrain the timing and nature of deglaciation from the Marquette Readvance associated with the Younger Dryas. These data yield an average exposure age of 10.1 ± 1.1 ka, and the authors infer that this ice margin position was abandoned later than previously thought, based on existing minimum-limiting radiocarbon ages. They hypothesize that the lake-terminating ice front retreated at different rates north and south of Isle Royale, due to the lake basin topography (as previously suggested by Colman et al., 2020). There are limited accessible locations to assess ice margins that are marine- or lake-terminating.

These conclusions contribute to the regional understanding of the nature and timing of ice retreat and the occupation of different meltwater drainages.

As for the $^{10}Be$ dataset, I have similar concerns to referee #2. I wonder if exhumation may play a role in the slightly younger ages. It would benefit the authors to acknowledge this possibility in the text (perhaps as referee #2 suggests, discussing the more conservative interpretation that these are minimum ages). It would also benefit the paper to include topographic profiles/images of sampled landforms and quantify the sensitivity of the presented ages to sediment cover as part of these appendices. Another possibility could be applying a landscape diffusion model to think about the timing of moraine degradation (see Ceperley et al., 2019).

**Author Response:** We agree with RC2 and RC3 that given the uncertainties of exhumation and snow cover, the mean exposure age of our dataset could be interpreted as a minimum mean exposure age for Isle Royale's moraines; however, we reiterate that there also exists the potential for inherited nuclides, which would counteract the effects of correcting for snow cover or exhumation. Unfortunately, we are unable to justifiably account quantitatively for any of these phenomena based on the data we have, and so the mean age of erratics presented in this study remains the most reasonable age estimate for deglaciation. It is because of these issues, however, that we report the standard deviation of the n = 10 samples (excluding 1 outlier) as the uncertainty and not a narrower measure, such as standard error, even though we could statistically be justified in using the latter (it would be a precision not an accuracy assessment).

We are familiar with Ceperley et al.'s (2019) landscape diffusion model and author EP has discussed that work with Ceperley in the field while visiting the Arnott (MIS3) and Almond (LGM) moraines. Our understanding of their work is that Ceperley et al. were primarily concerned with the age of the Arnott Moraine (is it LGM or older?) and they used landscape diffusion modelling to show that it was likely emplaced during MIS3, not LGM. Part of the success of Ceperley et al.'s work is owed to the presence the Almond Moraine (LGM), a few km away. Ceperley et al. modelled topographic diffusion of the *Almond* Moraine under the weathering conditions that the Arnott Moraine would have experienced during the 34 kyr of exposure the authors interpret for the moraine. Diffusion-based predictions of the Almond moraine matched the present-day topography of the Arnott moraine, and the authors used this to support their interpretation that the Arnott Moraine was emplaced during MIS3. The moraines we sampled in this study are significantly smaller than those in on the Wisconsin mainland and there are no younger moraines on Isle Royale for us to use as a benchmark of a "fresh" moraine cross section in a landscape diffusion model similar to Ceperley et al.'s.

We now include a figure that shows the size of the moraines sampled in this study, and we cite Putkonen and Swanson's (2003) work to support our assumption of minimal exhumation. We also use IR-18-02 to argue for minimal exhumation because it is the lowest-lying sample (25 cm high) and yet it yields the 2nd oldest age of the dataset.

I am not deeply familiar with the regional stratigraphy/chronology and there are several instances in the text that would benefit from clarification when referencing the myriad existing regional datasets. Paying this set up due attention will aid in supporting the hypothesized order of events. Streamlining the Lake Superior Basin deglaciation history in Section 1 (and moving some of this from Section 2 to 1 as referee #1 suggests) will help set up the timeline of events referenced in the discussion and highlight areas/periods of time in need of further investigation. This could begin with a brief overview from the LGM and then focus in on the final deglaciation from the Marquette readvance and clarify the goals of the investigation. Section 2 can then introduce the subregional datasets (the island geomorphological interpretations, radiocarbon ages, and the rich subaqueous datasets) that directly impact the interpretation of the $^{10}$Be ages.

**Author Response:** We follow the advice of the Reviewers and reorganize material in both Sections 1 and 2, and in doing so, we strive to balance being streamlined and concise while also providing enough detail in each section so the reader has a clearer sense of what the background for this work is (in Section 1) and has a more focused overview of the existing chronology and datasets around Isle Royale that we use to interpret our new $^{10}$Be dataset (in Section 2). We thank the Reviewer for their suggestion on what an appropriate outline for the Introduction could be and follow those suggestions.

Minor/In-line comments:
Figures are immensely helpful! Maps need to include the vertical scale in the text or legend. A citation of the basemap is good practice as well.

**Author Response:** We now include a citation to the basemap, as is required for Copernicus publications. As all Reviewers commented, the map figures are too cluttered and text is too small. To address the issue of the vertical scale, we will include in the caption the following elevations: modern Lake Superior lake elevation, deepest depth in Lake Superior, and highest elevation of basemap.

Figure 1: Orange text is hard to read

**Author Response:** Orange text is changed to dark gray

Lines 59-64: This detail seems out of place and might be moved toward the end of this section when the study location and state-of-knowledge are introduced.

**Author Response:** We have moved this detail to the end of the previous paragraph.

Lines 133-138: This discussion of strandline position (north- vs south-facing, etc.) needs clarification and seems very detailed for Section 2. This might be able to move to Section 5 (~Line 262 when this is referenced again).

**Author Response:** We thank the Reviewer for the suggestion and have moved these lines to the Discussion. This also helps address Reviewer 1's concerns that there was too much detail in Section 2.

Lines 138-140: Images and/or topographic profiles would be immensely helpful.

**Author Response:** We provide a new Figure 4, which shows four different topographic profiles across the crests of the Sugar Mtn. and Mt. Desor moraines.

Lines 141ff: This paragraph would make more sense with a concise deglacial history is developed in Section 1.

**Author Response:** We believe our revisions to the Introduction have helped this paragraph make more sense to the reader.

Lines 173-174: Reference existing interpretations that support this claim (dated lake levels?), citations

**Author Response:** The analysis of the timing of lake level drawdown at ~10.8–10.6 cal ka BP was carried out in Breckenridge (2013), which is cited.

Lines 220-221: There needs to be a discussion of the statistical significance of the outlier, i.e., does it fall outside of the second standard deviation of the population mean? This should be included in the appendices and acknowledged here.

**Author Response:** Initially, we relied on output from Balco et al.'s (2008) exposure-age calculator, which uses a $\chi^2$ goodness of fit test to prune outliers; however, the documentation for this "outlier-pruning" process is informal. This guided us to consider the statistics of the dataset in other ways. We now demonstrate that the dataset, inclusive of all samples, passes a Shapiro-Wilk W test for normality, which allows us to inspect outliers using Chauvenet's Criterion, which has been used in many $^{10}Be$ exposure-age studies to assess the presence of outliers (Clark et al., 2009; Rinterknect et al., 2006; Ullman et al., 2015). This more formalized assessment of data also identifies the young age of IR-18-11 as an outlier. We now include the results of the Shapiro-Wilk W test and Chauvenet's Criterion in this manuscript to demonstrate that the age of IR-18-11 is not similar to the others. We maintain that there is no field evidence for burial, exhumation, spallation, rolling, or tipping at this site and that it the the erratic's out-of-sequence age (relative to the geography of all other samples) is justification for not including it in our mean age calculation.

Lines 280ff: Tying in more of the existing subaqueous geomorphological interpretations (Colman et al., 2020 and references therein) may help strengthen and clarify the hypothesis proposed in this paragraph. Are there notable similarities or differences in interpreted subaqueous landforms north and south of the island that support/refute your hypothesis? The discussion in Colman et al., 2020 about (relative) calving rates/the effect of the basin bathymetry during deglaciation may help with the narrative.

**Author Response:** This paragraph has been rewritten and reorganized, along with other paragraphs in the Discussion, which should help focus each part of our interpretation, including our proposal that patterns and rates of ice retreat north of Isle Royale differed from those south of the island. As suggested by the Reviewer, we return to Colman et al.'s (2020) interpretation of high rates of ice retreat due to calving in our interpretation of the ice retreat rate south of Isle Royale as being a minimum average ice retreat rate.

Line 313: Portage and Allouez outlets are not included in maps. It appears that the Portage outlet is to the southwest (Breckenridge, 2013, Fig.2), and if so, is there a typo here? "...drained across eastern(?) Lake Superior basin via the Portage and Allouez outlets.".

**Author Response:** This comment is disregarded per the Reviewer's self-correction (RC4; see below)

Lines 319-323: This tense seems strange/colloquial when describing the extent of the LIS margin?

**Author Response:** We revised the first half of this sentence to remove some redundancies, to streamline the sentence, and to (hopefully) remove any colloquial language.

Figure 6: Needs larger font sizes. Some interpretive text in figure caption (varve descriptions) should move to main text.

**Author Response:** We revised the figure so that all fonts are now 10-pt or larger. To minimize cluttering, we removed references in the figure panels because they are redundant to the figure caption. Text from the figure caption was moved into our revised Discussion section.

Line 352: Nix "in large lake", targeting island glacial deposits can be useful in marine environments as well!

**Author Response:** Of course we do not want to forget the usefulness of islands in marine settings, so the large lake phrase has been removed!

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**Comments from RC4 (a comment from RC3 on their own review):**

Please disregard comment on Line 313! (larger font size in Figure 6 would solve this confusion)

**Author Response:** Done

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**Comments from RC5:**

This manuscript presents new $^{10}$Be surface exposure ages from moraines on Isle Royale located in Lake Superior to constrain the timing of Laurentide Ice Sheet deglaciation across the basin. The authors conclude later retreat from the southern island relative to the northern shore of Lake Superior through a combination of their new $^{10}$Be ages (mean age & standard deviation: 10.1±1.1 ka), radiocarbon ages from lakes on Isle Royale, and the presence of red and gray varves which suggest changes in sediment source and timing. Implications of this restructured ice margin relate to meltwater pathways and lake-bottom stratigraphy.

As with the previous two reviewers, I am less familiar with the detailed stratigraphy of the study area so I will speak to the $^{10}$Be chronology. As has been pointed out, the authors argue that certain areas for geologic uncertainty do not change the results enough to alter their interpretations. This claim is supported by an age standard deviation of ~11% (line 228) and all sensitivity tests changing the age to a lesser degree (0.4 - 6.7%). I see no major concern with this logic, however, I do worry about emphasizing so much of the interpretation off a data set with 11% uncertainty.

**Authors' Response:** As mentioned in responses to other Reviewers, we make a better point to explain why we report a 1.1 ky uncertainty around our mean age, particularly in the Discussion. Throughout the rest of the Discussion, revisions have been made to highlight how well the mean age we report fits within the existing chronology. We suggest that rather than focusing on the uncertainty in our mean age (which are inherent in many $^{10}$Be datasets), readers should focus on how well these new data fit within the existing spatial and chronological knowledge of the western Lake Superior basin. We strived to make revisions to the Discussion that would better guide the reader to this conclusion, and we hope we have been successful in doing so.

A lot is mentioned of the LIS retreating to Lake Nipigon by ~10.6 ka (Leydet et al., 2018; Lowell et al., 2021), yet the ages west of Lake Nipigon from those studies (Pillar: 10.5±0.4 ka (Lowell); Kaiashk: 11.3±1.0 ka (Lowell); Lake Nipigon: 11.2±0.6 ka (Leydet - age reported here with standard deviation)) are statistically indistinguishable from that on Isle Royale (10.1±1.1 ka). A point is made between lines 240-244 that the low-elevation Isle Royale samples (10.4±1.1ka) are indistinguishable with those at higher elevations (9.8±1.0 ka). Yet, there is a smaller range between the Isle Royale TCN mean age (10.1±1.1 ka) and the discussed Lake Nipigon ages (~10.6 ka) which are interpreted as reflecting earlier retreat.

**Author Response:** In an effort to not over-interpret our data, we remove the comparison of exposure ages of erratics that may have been exposed subaerially versus subaqueously in the Discussion. We make this decision in part because we already established that there should be minimal difference in $^{10}$Be production rates between potentially subaerial v. potentially subaqueous erratics in the Methods, and in part to highlight that our ages come from a uniform population that reflect the mean $^{10}$Be timing of ice retreat from Isle Royale. Again, we recognize that the broad uncertainty we report overlaps other existing datasets.

There is likely an argument to be made that the presence of red varves in Lake Nipigong (as shown in Fig. 6b,c) are evidence of ice-free conditions, but the age uncertainties need to be treated similarly across all data sets mentioned. The precision of this surface exposure ages alone might not be at a point where such fine-scale differences can be distinguished. An acknowledgment of the uncertainty in combination with the strong regional evidence will strengthen the interpretations further.

**Author Reponse:** We would like to clarify that it is (1) the similarity of the new $^{10}$Be ages we report for Isle Royale and the estimated age of the IR2 moraine formation (~10.5–10.2 ka; Colman et al., 2020), (2) the geographic continuity of the Isle Royale moraines and the IR2 moraine, and (3) the presence of red varves only southwest of IR2 that allows us to propose a new ice margin across the Lake Superior basin based on the presence or absence of red varves. It is not necessarily the similarity in age of different exposure-age datasets. Within any reported uncertainties, it would be nearly impossible to make any sense of what is happening across the region here without the context of landform position and/or stratigraphy. We make wording revisions in both the Introduction and the Discussion to help us make these points more clearly.

Line comments:
Fig. 2 - the solid black lines indicated the Marquette Readvance are sometimes difficult to distringuish between the Lake Superior shoreline. Consider using a different color.

**Author Response:** We changed the color of the shorelines to blue and the color of the ice margin to white, which we hope addresses the visibility concerns raised here.

Line 104 - how was the ~10.6 ka age determined? The referenced data sets do not match this age. Is it taken from the minimum age range of the Leydet et al. (2018) Lake Nipigon data but using the standard deviation in place of their reported standard error? If so, that needs to be explicitly stated.

**Author Response:** The ages come from $^{10}Be$ data published in both Lowell et al. (2021) for sites west of Lake Nipigon and Leydet et al. (2018) for sites between Thunder Bay and Black Bay. In double-checking our calculations for this value, we recognize that the mean from these n = 10 sites is 10.7 ka, and we will amend this for the revised manuscript. We will also add these $^{10}Be$ sites to Figure 6B.

Line 220 - what statistical method is used to identify the outlier in Balco et al.'s (2008) calculator. Needs to be stated.

**Author Response:** Please see our response to RC3's comment re: Lines 220-221

Line 284-287 - Unless I'm mistaken, the ~100 m/yr rate represents a mean retreat rate over the time interval of 600 years (which doesn't account for uncertainty in the reported ages). If periods of standstill are considered, then the rate of retreat during that time would exceed 100 m/yr which could therefore not represent a maximum rate.

**Author Response:** We clarify that these are mean retreat rates and that the ~100 m $yr^{-1}$ retreat rate is a minimum mean retreat rate.

Line 297 - This (~270 m $yr^{-1}$) is also a mean retreat rate.

**Author Response:** This is now clarified