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Reply

Reply to Carlson (2020) comment on “Deglaciation of the Greenland and Laurentide ice sheets interrupted by glacier advance during abrupt coolings”

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The cosmogenic nuclide exposure dating community has made tremendous strides over the last 25 years. For example, pioneering studies that utilized exposure age calculations in glacial settings had uncertainties in the ~15–20% range (Gosse et al., 1995). Here, this comment and reply discusses the minutiae of exposure age calculations that affect calculated ages by a few percent in select environments. Carlson (2020) questions the rationale on how we re-calculated and presented ^{10}Be ages that were originally reported in Ullman et al. (2016). Here, we highlight 1) what we believe are some key aspects of the Baffin Bay ^{10}Be production-rate calibration dataset, 2) how we re-calculated the ^{10}Be ages of Ullman et al. (2016), 3) how these re-calculated ^{10}Be ages are an improvement with the goal of comparing them to the new ^{10}Be ages of Young et al. (2020), and 4) moving forward, recommendations for calculating ^{10}Be ages in (paleo) ice-sheet environments where isostatic rebound has occurred.

One of the key findings of Young et al. (2020) is that advances of both the Laurentide and Greenland Ice sheets apparently culminated synchronously at ~10.4 ka, 9.3 ka, and 8.2 ka, correlative with known periods of regional abrupt cooling. Ullman et al. (2016) reported that advances of the Labrador sector of the Laurentide Ice Sheet also culminated at ~10.4 ka, 9.3 ka and 8.2 ka. Thus, at face value, these results are supportive of even more widespread synchronous ice-sheet change. As Carlson (2020) notes, Ullman et al. (2016) included a significant correction for the effects of isostatic uplift, and Young et al. (2020), in their effort to compare their results with those of Ullman et al. (2016), removed this correction resulting in younger ^{10}Be ages. These differing approaches highlight the central issue of how to consider the effects of isostatic rebound when calculating ^{10}Be ages. The central questions, however, are 1) do the effects of isostatic rebound need to be considered when calculating ^{10}Be ages, and 2) if so, what is the proper way to make this correction? These topics are of great interest to the cosmogenic-nuclide exposure dating community, and at present, there is no consensus on how to treat these issues.

In recently glaciated terrains, the elevation at which a sample is collected for cosmogenic nuclide analysis has changed through time. Specifically, this location once rested at a lower elevation (resulting in more overriding atmosphere and less nuclide production) and post-glacial isostatic rebound of the crust driven by ice-sheet mass loss has since brought that site to its modern elevation (resulting in less overriding atmosphere and more nuclide production). The concern is that if the effects of isostatic

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rebound are not considered when calculating a ^{10}Be age, one might calculate an age that is too young because the calculation relies on a production rate that is based solely on the modern sample elevation. In reality, this site was subjected to a time-integrated rate of ^{10}Be production that is likely lower than the modern production rate at that sample location.

^{10}Be production-rate calibration datasets are developed to help produce a consistent framework in which to calculate ^{10}Be ages. The idea being that those who have developed a calibration site have considered, or at least tried to, all the sources of uncertainty and corrections that need to be applied in order to produce a baseline reference production rate for that region. It is this baseline reference production rate that can then be used independently to calculate the ^{10}Be ages of unknown sites when paired with a set of guidelines for scaling production rates across space. Then, this reference production rate can be directly compared to, or even combined with, other reference production rates around the globe (e.g. Borchers et al., 2016).

The Baffin Bay production-rate calibration dataset was developed from three independent calibration datasets: one from Baffin Island and two from western Greenland (Young et al., 2013). Because the calibration datasets span a similar time frame and have similar uplift histories as sites of unknown age in Young et al. (2020), we need not correct for post-glacial elevation change (i.e. make an “uplift correction”) when calculating ^{10}Be ages in this region. Any potential variations in nuclide production that the unknown sites may have experienced due to post-glacial uplift is offset by these same variations affecting the production-rate calibration dataset. In other words, if the uplift of the unknown sites is generally similar to that of the calibration sites, the effect is already included (see Young et al., 2013, 2020). Key in the development of the Baffin Bay production-rate calibration, however, is that Young et al. (2013) calculated two separate reference production rates – one with, and one without, a correction for isostatic rebound. How each of these production rates are used warrants further consideration.

Because of the uniquely intertwined relationship between the calibration sites and unknown sites in Baffin Bay, either reference production rate can be used. However, if the production rate that has been adjusted to correct for uplift is selected, the ^{10}Be age of an unknown site ought to be calculated using an uplift-corrected elevation history. This corrected elevation will be lower than the modern sample elevation and reflect the uplift history of that sample site. Failure to make this adjustment would result in ^{10}Be ages that are younger than true age, or corresponding radiocarbon constraints, for example. But, how these reference production rates are applied beyond the immediate Baffin Bay region in locations that do not have their own well-constrained regional ^{10}Be production-rate calibration is unclear. Because a local or regional production-rate calibration should have already accounted for the necessary uncertainties and corrections in order to make the calibration directly comparable to other calibrations, one could perhaps argue that the Baffin Bay calibration that has been adjusted for an uplift correction should be used beyond the Baffin Bay region. In this case, sample elevation history would need to be adjusted for post-glacial uplift.

The ^{10}Be ages in Ullman et al. (2016) were calculated using the northeastern North American production rate (NENA; Balco et al., 2009) and post-glacial uplift corrections for each sample location. The NENA calibration dataset is not adjusted for post-glacial rebound. NENA is also statistically identical to the Baffin Bay calibration dataset that *does not* include an uplift-based adjustment to the reference production rate, and both datasets include the Baffin Island calibration dataset (Clyde River; Briner et al., 2007; Table 1). The other NENA calibration sites also come from locations that have undergone isostatic uplift, one of which is from ~450 km inland of the LGM terminus and experienced considerable uplift. Carlson (2020) rightfully points out that the NENA calibration dataset does not include a correction for isostatic uplift and the original authors considered the potential effects of uplift to determine its effects to likely be no more than a few percent on the production rate. Regardless, it is this uncorrected production rate that was used to calculate the ^{10}Be ages by Ullman et al. (2016), who also used rebound-adjusted sample elevations. The same considerations and corrections applied to the NENA and Baffin Bay production rates must also be considered when calculating the ages at unknown sites within the region. Carlson (2020) recognizes the mistake of the age calculations originally reported and re-cast the original ^{10}Be ages in Ullman et al. (2016) using an “uplift-corrected” NENA production rate to produce updated moraine ages (although the source of the uplift-corrected reference production rate is unknown). So now the question arises over which regional production-rate calibration dataset to use when calculating the Labrador ^{10}Be ages of Ullman et al. (2016) if the goal is to compare with the ages in Young et al. (2020).

To make the ^{10}Be ages of Ullman et al. (2016) directly comparable to those of Young et al. (2020), we chose to re-calculate the Ullman ages with non-uplift-corrected Baffin Bay calibration dataset and use raw (modern) sample elevations. We felt that this approach ensured the best apples-to-apples comparison of ages that would allow us to rigorously compare our chronology with that of Ullman et al. (2016), which was our ultimate goal (not to mention also requested during peer review). Furthermore, the exposure duration of the Labrador sites is more similar to the exposure history of the Baffin Bay calibration sites (8–9.2 ka) than the NENA calibrations sites (mostly 13 ka or older, with one 8 ka site). In any case, if one wanted to calculate the Labrador ^{10}Be ages using rebound-corrected elevations with the Baffin Bay calibration dataset, the uplift-corrected calibration dataset and the uplift-corrected sample elevations would need to be used. Failure to do both would suggest that one thinks the effects of rebound on isotope production are important for one calculation and not the other.

Carlson (2020) reports new moraine ages of 8.1 ± 0.5 ka, 9.1 ± 0.5 ka, and 10.3 ± 0.6 ka using an uplift-corrected NENA calibration dataset and uplift-corrected sample sites (Table 2);

Table 1
Western North Atlantic reference production rates.

Scaling scheme	Baffin Bay uncorrected	Baffin Bay RSL	Baffin Bay 5G	NENA uncorrected	NENA 5G
St	4.04 ± 0.07	4.26 ± 0.07	4.23 ± 0.07	4.04 ± 0.27	4.09 ± 0.29
Lm	4.04 ± 0.07	4.26 ± 0.07	4.23 ± 0.07	4.04 ± 0.27	4.09 ± 0.29
LSD	0.786 ± 0.007	0.826 ± 0.010	0.819 ± 0.010	0.855 ± 0.068	0.865 ± 0.060

The Baffin Bay and northeastern North America reference production rates (Young et al., 2013; Balco et al., 2009). Both the Baffin Bay and NENA uncorrected rates, and the Baffin Bay RSL rate, are slightly higher that what was reported in their original publications due to an updated treatment of muons (Balco, 2017); the calibration datasets are the same. The Baffin Bay RSL rate is corrected for uplift using local relative sea-level history. Both the Baffin Bay 5G and NENA 5G rates are corrected using elevation and isotope production histories using the ICE-5G glacial isostatic adjustment model (Peltier, 2004; Jones et al., 2019). St and Lm - Lal (1991); Stone (2000); LSD - Lifton et al. (2014).

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Table 2
Labrador moraine ages discussed in the text.

Moraine	Moraine age reported in Ullman et al. (2016); uncorrected NENA calibration and uplift-corrected sample elevations (ka)[a]	Same as previous column, but moraine ages are calculated using a straight mean (ka)	As re-calculated in Young et al. (2020); uncorrected Baffin Bay calibration and raw sample elevations (ka)	Uplift-corrected (RSL) Baffin Bay calibration and uplift-corrected sample elevations (ka)	Uplift-corrected NENA (5G) and uplift-corrected sample elevations (ka)
Sakami	8.2 ± 0.5 (8.1 ± 0.5)	8.09 ± 0.79 (0.88)	7.64 ± 0.74 (0.75)	7.68 ± 0.75 (0.76)	8.00 ± 0.78 (0.88)
North Shore	9.2 ± 0.5 (9.1 ± 0.5)	9.10 ± 0.62 (0.77)	8.83 ± 0.61 (0.63)	8.63 ± 0.59 (0.61)	8.99 ± 0.62 (0.76)
Paradise	10.4 ± 0.6 (10.3 ± 0.6)	10.13 ± 0.69 (0.85)	9.99 ± 0.67 (0.69)	9.63 ± 0.65 (0.68)	10.01 ± 0.68 (0.84)

To ensure consistency, all moraine ages rely on updated reference production rates (see Table 1), use Lm scaling, and we report the more conservative straight mean age ± 1 SD. The error in parentheses includes the production rate uncertainty, which must be considered when comparing to radiocarbon-based chronologies. The external errors for the NENA-based calculations are larger than those for the Baffin Bay-based calculations because of the uncertainties in the production rate (see Table 1). Of these four options, only the latter three rely on consistent calculation methods and, moreover, each is consistent with the Labrador radiocarbon-based chronology (Fig. 1).

[a] Moraine ages reported in Ullman et al. (2016; see original publication for uncertainty details). In parentheses is the recalculated age listed by Carlson (2020).

Young et al. (2020) recalculated these moraine ages to be 7.64 ± 0.74 ka, 8.83 ± 0.61 ka, and 9.99 ± 0.67 ka using the uncorrected Baffin Bay calibration dataset with no uplift correction applied to each sample elevation (we also prefer to report a straight mean vs an error-weighted mean for ^{10}Be ages resulting in more conservative uncertainty values). Carlson (2020) argues that his approach yields ages that satisfy the existing radiocarbon constraints from Labrador (Dyke, 2004; Ullman et al., 2016). However, a closer look at these radiocarbon constraints reveal that, within uncertainties, our re-calculation of the Ullman et al. (2016) ^{10}Be ages are equally compatible with the existing radiocarbon constraints (Dyke, 2004, Fig. 1). Therefore, the existing Labrador radiocarbon constraints cannot be used to argue that one approach to calculating ^{10}Be ages is more valid than the other. Carlson (2020) also states that relative sea level (RSL) history overestimates the amount of isostatic rebound because these records exclude the gravitational attraction of former ice sheets. Instead, Carlson (2020) suggests that only a full Earth model, such as ICE-5G (Peltier, 2004), should be used. In the development of the Baffin Bay ^{10}Be production-rate calibration, Young et al. (2013) used highly localized relative sea-level histories for each calibration dataset (Long et al., 2006; Briner et al., 2007) to estimate that the effects of isostatic rebound potentially have a 5.1% effect on ^{10}Be production. Using the ICE-5G model to correct for isostatic rebound at the Baffin Bay ^{10}Be calibration sites would result in a 4.7% correction (Peltier, 2004; Jones et al., 2019, Table 1). At least in Baffin Bay and using localized RSL history, these two approaches yield near-identical corrections.

Nobody is suggesting that isostatic rebound does not exist, nor dispute that the amount of uplift in the Labrador region likely

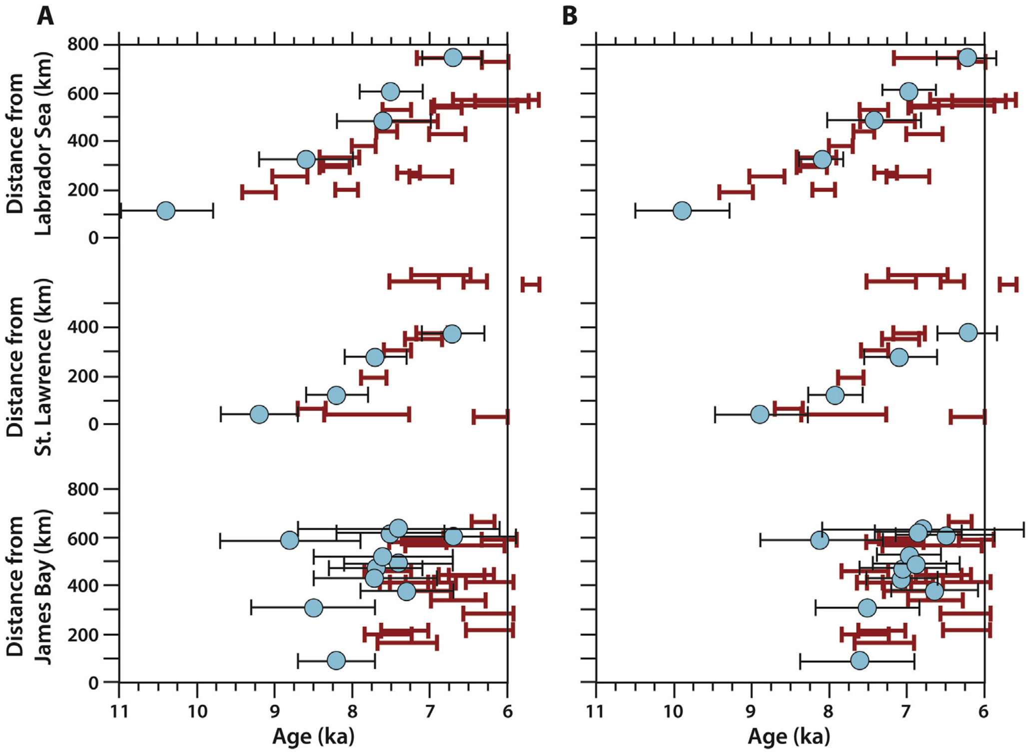

Fig. 1. Modified from Fig. 7 in Ullman et al. (2016). (A) Relation between existing radiocarbon constraints (red symbols; calibrated ages; 2-sigma uncertainties) and ^{10}Be ages (blue symbols) as calculated in Ullman et al. (2016; Table 2); uncorrected NENA production-rate calibration dataset and uplift-corrected sample elevations. (B) Same as A, but ^{10}Be ages (mean ± 1SD with production rate uncertainty of 1.8% propagated in quadrature for moraine age; error for singular erratics is the reported analytical uncertainty with the production rate uncertainty propagated through) are calculated with the uncorrected Baffin Bay production-rate calibration dataset and no correction for isostatic rebound as presented in Young et al. (2020); ^{10}Be ages are consistent with the radiocarbon constraints. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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exceeded the amount of uplift that occurred at the NENA and Baffin Bay ^{10}Be calibration sites. For example, Carlson (2020) points to marine limits of almost 290 m, 150 m, and 140 m associated with the Sakami, Paradise, and North Shore moraines. These marine limits are higher than the marine limits encountered at the Baffin Bay calibration sites, which are up to 60 m, and they are also higher than the amount of uplift experienced at the NENA calibration sites. Yet, there is a mathematically appropriate way to make this calculation where the effects of uplift that are being considered in the sites of unknown age should also be considered in the production-rate calibration dataset you are using. In fact, Young et al. (2020) completed this exercise with the Ullman et al. (2016) dataset and used the uplift-corrected Baffin Bay calibration dataset combined with the uplift-corrected sample elevations to calculate moraine ages 7.68 ± 0.75 ka, 8.63 ± 0.59 ka, and 9.61 ± 0.65 ka. These ages are nearly identical to the ^{10}Be ages of 7.64 ± 0.74 ka, 8.83 ± 0.61 ka, and 9.99 ± 0.67 ka calculated with the uncorrected Baffin Bay calibration and raw sample elevations and therefore would also be consistent with the existing radiocarbon constraints (Fig. 1).

Here, we re-cast the NENA calibration dataset to include an uplift-correction using ICE-5G resulting in reference production rate that is 1.2% higher than the uncorrected NENA reference production rate (Table 1). Using this 5G-corrected NENA calibration dataset, and the uplifted-corrected elevations listed in Ullman et al. (2016), we calculate moraine ages of 8.00 ± 0.78 ka, 8.99 ± 0.62 ka, and 10.01 ± 0.68 ka (Table 2); it is this combination of an uplift-corrected NENA calibration dataset and uplift corrected sample elevations that must be used in conjunction if one is to apply an uplift correction and use the NENA calibration dataset. However, we emphasize that the re-calculation of the Ullman et al. (2016) ^{10}Be ages presented in Young et al. (2020; no uplift correction to either the calibration or unknown sites) results in ^{10}Be ages that remain consistent with the existing Labrador radiocarbon constraints. Thus, in this case, we see no reason why the NENA calibration dataset should be preferred over the Baffin Bay calibration dataset for unknown sites in Labrador.

It remains an open question in the exposure dating community whether uplift should be considered at all because the effects of uplift are counteracted by atmospheric processes (Staiger et al., 2007), albeit this correction is difficult to quantify. Regardless, for this reason, the effects of uplift could be considered a maximum possible correction. Perhaps a better approach moving forward is to develop a ^{10}Be production rate calibration dataset in environments that have experienced significant amounts of isostatic uplift, or benchmark the effects of uplift on ^{10}Be ages against calibration data instead of against records of climate variability. An additional approach could consider whether a broader swath of ^{10}Be calibration data suggest that the effects of uplift are significant. Indeed, one such exercise assessing uncorrected calibration data in ice-proximal vs. ice-distal settings does not reveal significant differences in inferred production rates and suggests that isostatic and atmospheric processes may have offsetting effects (Balco, 2020). Moving forward, we prefer the more straightforward approach of using production-rate calibration datasets that are not corrected for the effects of uplift and applying these same methods to similar sites of unknown age. Yet, if corrections for isostatic rebound are to be made, these same corrections ought to be considered in the production-rate calibration dataset if the calibration site is from an isostatically depressed location.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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