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Comment on 'Was Scotland deglaciated during the Younger Dryas?' by Small and Fabel (2016)

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The course of climatic events in Scotland and the broader North Atlantic region during the glacial termination has important implications for our understanding of the causes and mechanisms of abrupt climate change but remains in debate. One example is the timing of the late-glacial 'Loch Lomond Readvance' (LLR), during which an ice cap and numerous cirque glaciers were nourished in the Scottish Highlands. Exactly when the LLR occurred and culminated has been disputed for several decades and has been addressed via several different types of chronologic evidence (e.g., Lowe and Walker 1976; Golledge et al., 2007; MacLeod et al., 2011; Bromley et al 2014). Recently, Small and Fabel (2016) presented a suite of six ^{10}Be surface-exposure ages from moraine ridges on Rannoch Moor, central Scottish Highlands, that questioned whether two different dating techniques – ^{10}Be and ^{14}C – yield the same result for the timing of final deglaciation of the Scottish ice cap. In that study, Small and Fabel (2016) concluded that the ^{10}Be data show deglaciation occurred at the close of the Younger Dryas (YD) stadial (~11.6 kyr), as much as a millennium later than the scenario presented by Bromley et al. (2014) based on minimum-limiting ^{14}C data. While the issue of which, if either, is a more reliable age for deglaciation cannot be resolved fully in a short note, we comment on several points raised by Small and Fabel (2016) and suggest a means to resolve this question.

Interpretation of the deglaciation of the central Scottish Highlands hinges critically on the relative merits and treatment of two different chronometers. A key issue that Small and Fabel (2016) did not elaborate on is why the original radiocarbon data reported by Bromley et al. (2014), based on macrofossils primarily of terrestrial plant species, were discounted. While they argue that the "resulting ages are averages and may be biased by incorporation of older material", we note that Small and Fabel (2016) provide no evidence for where this older material may have originated. They acknowledge that a hardwater effect is unlikely and that reworking of well-preserved macrofossils probably was minimal, so what other specific source of old carbon is plausible for this site? Unless an explicit type and amount of contamination can be demonstrated, the most reasonable view is that ^{14}C ages represent a minimum age for the first vegetation to colonise the deglaciated landscape of Rannoch Moor. We note the radiocarbon data set consists of 13 cores that yield 32 radiocarbon dates that are in correct stratigraphic order, are reproducible, and agree with prior studies (Lowe and Walker, 1976; Walker and Loew, 1977, 1979). Since these are minimum age estimates, the oldest ^{14}C ages indicate deglaciation occurred prior to 12.5 kyr (Bromley et al., 2014) (Fig. 1), well before the ~11.6 kyr age inferred by Small and Fabel (2016) from ^{10}Be exposure ages.

Rather than invoking old-carbon contamination, which is unlikely for samples comprising cleaned terrestrial macrofossils and for which there is no evidence, we propose instead that the discrepancy highlighted by Small and Fabel (2016) results from their treatment of the ^{10}Be data and calculated ages. Three lines of evidence support this alternative scenario. First, we note that the complete set of six ^{10}Be ages (hereafter '6-sample' data set) presented by Small and Fabel (2016) constitutes a non-normal distribution encompassing much of the YD stadial. The reported ages span a range of ~1500 years, which, whether using the Loch Lomond or Glen Roy production rates (Small and Fabel, 2016), actually overlaps with the minimum-limiting ^{14}C age for deglaciation reported by Bromley et al. (2015). However, Small and Fabel (2016) eliminated the oldest two ^{10}Be ages (i.e., those most closely aligned with the ^{14}C ages), constituting 33% of their data set. Although the oldest ^{10}Be concentration might be considered a statistical outlier (falling outside the 95% confidence interval of the entire distribution), there is no reason to assume the second-oldest sample is an outlier. It is indistinguishable from the rest of the population at 95% confidence. Indeed, inclusion of sample RMOOR06 results in a χ^2 value that is consistent with that of a normally distributed population. Therefore, we conclude that, without justifiable geological or statistical reasons to reject sample RMOOR06, Small and Fabel (2016) based their climatic interpretation of the Rannoch Moor ^{10}Be ages on an arbitrarily reduced data set.

Second, after reducing their dataset to include only the youngest samples (hereafter '4-sample' data set), Small and Fabel (2016) suggested that choosing any range of production rate values, including that of Putnam et al. (2010), would give ages that are inconsistent with the ^{14}C evidence. In fact, with no samples removed, the 6-sample dataset of Small and Fabel (2016) actually shows general agreement with the ^{14}C data set for most currently available production-rate estimates, with the greatest degree of chronologic overlap achieved when using 'lower' production rate values such as those reported by Putnam et al. (2010) from New Zealand (Fig. 1), Kaplan et al. (2011) from Patagonia, Claude et al. (2014) from Switzerland, Fenton et al. (2011) from northern Norway, and Kelly et al. (2015) and Martin et al. (2015) from Perú. For example, as shown in Figure 1, the 6-sample ^{10}Be age distribution encompasses the entire period represented by the oldest replicable ^{14}C ages of Bromley et al. (2014), regardless of confidence interval, when calculated using the New Zealand production rate for Lm scaling (Putnam et al., 2010).

While we commend Small and Fabel (2016) for testing the robustness of their interpretations using different ^{10}Be production rates, we note that we were unable to replicate the average 4-sample ^{10}Be age reported by the authors when using the New Zealand production rate (Putnam et al., 2010) and Lm scaling. When employing the raw data and techniques reported by Small and Fabel (2016) [i.e., utilizing the online CRONUS calculator with the New Zealand production rate for the Lm scaling scheme, and the data set presented in Tables 1 and 2 of Small and Fabel (2016) as input], we determined an arithmetic mean age of 12,000 ± 180 yr (± 1σ) for their four preferred ages, whereas they reported a 'best estimate' moraine age of 11,700 ± 600 yr. Thus, although these two values overlap within the uncertainty of the ^{10}Be ages, there appears to be an offset of 2–3% that is not readily explained. Similarly, we cannot account for the three-fold difference in the uncertainty of the mean age between our recalculation (± 180 yr) and that reported by Small and Fabel (2016) (± 600 yr).

Third, the local ^{10}Be production rate is insufficiently constrained to determine the age of LLR glacial landforms at the required resolution. We note that of the two local Scotland production rates employed in Small and Fabel (2016), the 'LLPR' is unpublished and not yet available for review (references trace back to Fabel et al. (2012), where the rate is cited as 'in preparation'), and the GRPR is based on a landform with no direct dating, but is instead dependent upon an assumed correlation with undated tephra layers in a distal sedimentary deposit. As these two rates differ from one another by 8%, and because the non-directly dated GRPR site (Small and Fabel, 2015) produces a rate 9–12% higher than published production-rate values determined from radiometrically dated landforms in both hemispheres (e.g., Putnam et al., 2010; Fenton et al., 2011; Kaplan et al., 2011; Claude et al., 2014; Kelly et al., 2015; Martin et al., 2015), we consider that the issue of production-rate values in Scotland merits further attention and that ^{10}Be ages in this region should be considered accordingly, not used to discount robust radiocarbon chronologies.

We also note, however, that if one includes in the moraine age calculation sample RMOOR06 (hereafter '5-sample' data set), which is statistically indistinguishable from the four younger samples, the arithmetic mean age and corresponding 1σ uncertainty determined using the Putnam et al. (2010) production rate and Lm scaling (all calculated with the online CRONUS calculator to maintain consistency) becomes 12,100 ± 400 yr, which, within dating uncertainty, is indistinguishable from the suggested minimum ^{14}C age of 12.5 kyr (at 90% confidence) for deglaciation of Rannoch Moor (Bromley et al., 2014) (Fig. 1). Therefore, we suggest that, until the local production rate is fully resolved, use of the Putnam et al. (2010) rate at Rannoch Moor can reconcile the ^{10}Be data of Small and Fabel (2016) with the ^{14}C data set (Bromley et al., 2014). Given that several recent production-rate calibrations determined from directly, radiometrically dated landforms located at different latitudes, altitudes, and geomagnetic settings are indistinguishable from one another (Putnam et al., 2010; Fenton et al., 2011; Kaplan et al., 2011; Claude et al., 2014; Kelly et al., 2015; Martin et al., 2015), we see this as a systematic agreement.

Only with careful, reproducible reconstructions of past glacier behaviour, using a well-calibrated toolset, can the mechanisms driving the LLR event be determined convincingly. While we urge the palaeoclimate community to prioritise this endeavour, however, we caution against treating glacier records as secondary or supporting data to less-direct proxies or model output. For example, Small and Fabel (2016) emphasise the disagreement between the Rannoch ^{14}C record and output from numerical modelling experiments (Golledge et al., 2008, 2009) as additional support for their argument that the ^{14}C data must be incorrect. Yet this logic is circular since the model in question was forced with a scaled version of the GRIP δ^{18}O-inferred temperature record, and thus a late-YD age for deglaciation would be expected. Similarly, Small and Fabel (2016) discount the climatic interpretations of Bromley et al. (2014) on the basis that they do not align with regional chironomid-inferred temperature records (Brooks and Birks, 2000; Brooks et al., 2012). In response, we suggest that, whatever the cause of this discrepancy, the single best indicator of past glacier behaviour is the glacier record itself. After all, glaciers are highly sensitive physical indicators of atmospheric temperature (Oerlemans, 2001, 2005; Zemp et al., 2015), as highlighted by the iconic response of glaciers worldwide to modern warming. We look forward to the additional data and discussion needed to resolve the decades-long debate about the timing of glacier advance and retreat in Scotland and the North Atlantic region.

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Fig. 1. (Top) Sum-probability curve for the oldest replicable ^{14}C ages from Rannoch Moor, from Bromley et al. (2014). Horizontal blue lines represent 68%, 90%, and 95% confidence intervals of the population. Since these are minimum ages, the thick red bar indicates the oldest probable age for the start of plant growth (at both 90% and 95% confidence), which occurred after deglaciation. (Bottom) Probability density function of ^{10}Be ages from Small and Fabel (2016) calculated with the Putnam et al. (2010) production rate for Lm scaling. Thin black lines represent Gaussian approximations of individual ^{10}Be ages (1σ analytical error). Thick dashed curve is the summed probability curve for the entire distribution, with no samples excluded. Thick black curve is the summed probability distribution with the oldest age excluded, while vertical blue line is the mean age for that group. One-, two-, and three-sigma error ranges for the complete 6-sample data set, as well as the reduced 5-sample data set, are represented by horizontal purple bars. Statistics are inset. Chi-square statistics are evaluated at the 95% confidence level, where the $\chi_{expected}$ is the value expected for a normally distributed data set and the $\chi_{experimental}$ is the value determined for this data set. The Younger Dryas chronozone is delineated with blue shading. Recalculating the ^{10}Be surface-exposure ages of Small and Fabel (2016) in this way results in a distribution that is within uncertainty of the oldest replicable ^{14}C ages of Bromley et al. (2014) (thick red bar). The ^{14}C ages indicate plant growth and the ^{10}Be ages indicate nuclide accumulation at this site during the Younger Dryas interval, both of which require deglaciation prior to this time.

Figure 1
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