Was Scotland deglaciated during the Younger Dryas?

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Abstract

Recent work has produced data that challenges the canonical view that the Younger Dryas (c.12.9 – 11.7 ka) was a time of glacier expansion across the North Atlantic. Boulders on moraines located within the inner sector of the Scottish Loch Lomond Stadial (≈ Younger Dryas) ice cap yield cosmogenic exposure ages 12.8 – 11.3 ka with a best estimate moraine age of 11.5 ± 0.6 ka. This age contradicts the interpretation that Scotland was completely deglaciated as early as 12,580 cal yr BP and no later than 12,200 cal yr BP. Our data supports the previously accepted scenario, supported by a wide variety of data, that final deglaciation of Scotland did not occur until late in the Loch Lomond Stadial or the early Holocene.

1. Introduction

The Younger Dryas cold event (YD; 12.8 – 11.7 ka) interrupted the overall warming trend of the last deglaciation in the Northern Hemisphere (Alley, 2000). It is commonly attributed to freshwater input to the North Atlantic that forced a re-organization of oceanic circulation and interrupted heat transport to higher latitudes (Broecker et al., 1989; Clark et al., 2001; McManus et al., 2004). Changes in Greenland mean annual temperatures are dominated by large changes in wintertime temperature with summer temperatures displaying a subdued response (Björck et al., 2002; Buizert et al., 2014) due to greatly expanded North Atlantic winter sea ice (Lie and Paasche, 2006). The role of North Atlantic sea ice in modulating the rapid YD climate shifts through increased seasonality (Denton et al., 2005) has been invoked to explain data that challenges the accepted view that the YD was a time of glacier expansion across the North Atlantic (Bromley et al., 2014).

Determining the response of ice masses to rapid climate change is important to fully understand the inter-connected ocean-atmosphere-cryosphere system. The response of ice masses to increased YD seasonality has implications for understanding the extent to which North Atlantic stadials aided or abetted glacier expansion and the spatial variance of any heterogeneous response. In Scotland, the Loch Lomond Stadial (LLS) is approximately equivalent to the YD (YD ≈ LLS). The LLS is widely held to be a time of cooling and renewed ice growth in the Scottish Highlands (the Loch Lomond Readvance [LLR] (Sissons et al., 1973)). Bromley et al. (2014) present radiocarbon ages from the central Highlands of Scotland which they argue provide a minimum age for complete deglaciation of 12,262 ± 85 cal yr BP and most likely by 12,493 - 12,580 cal yr BP. They invoke summer warming caused by heating of a shallow mixed layer in the North Atlantic to reconcile deglaciation of Scotland with the observed stadial stadial conditions of the LLS.

We present new ^{10}Be cosmogenic exposure ages from the site of Bromley et al. (2014) to test the hypothesis that Scotland deglaciated during the early-mid LLS. We review their interpretation in light of this new data and suggest an alternative interpretation to reconcile new and extant data.

2. Setting and Methods

Rannoch Moor (Figure 1) is located within the central Highlands of Scotland and forms an elevated (~400 m) plateau with a total area of ~400 km^2. It is surrounded by mountain peaks rising to ~1000 m. Geomorphological mapping and numerical modeling (Golledge et al., 2008) place Rannoch Moor at the centre of the LLR ice cap. Given this, it has widely been assumed that deglaciation of Rannoch Moor closely equates to final deglaciation of Scotland (Bromley et al., 2014; Lowe and Walker, 1976).

We sampled six granite boulders from the crest of a moraine impounding several core sites of Bromley et al. (2014) (Figure 1). Sample information is summarised in Table 1. Quartz was separated using standard mineral separation techniques (cf. Kohl and Nishiizumi, 1992) and purified by ultrasonicating in 2%HF/HNO_3 to remove remaining contaminants and meteoric ^{10}Be. Samples were spiked with Be carrier and Be extraction followed methods modified from Child et al. (2000). $^{10}Be/^{9}Be$ ratios were measured on the 5MW accelerator mass spectrometer at the Scottish Universities Environmental Research Centre (Xu et al., 2010).

Exposure ages were calculated using the CRONUS-Earth online calculator (Wrapper script 2.2, Main calculator 2.1, constants 2.2.1, muons 1.1; http://hess.ess.washington.edu/math/al_be_v22/al_be_calibrate_v22.php; accessed 25/11/2015; Balco et al., 2008). Exposure ages are based on the time-dependent Lm scaling (Lal, 1991; Stone, 2000) and assuming 1 mm ka^{-1} erosion. Our interpretation is not sensitive to choices in scaling scheme or assumed erosion rate. We calibrated exposure ages using two local, independently constrained production rates, the Loch Lomond production rate (LLPR) (Fabel et al., 2012;) and the Glen Roy production rate (GRPR) (Small and Fabel, 2015). These production rates (3.92 ± 0.18 and 4.26 ± 0.21 atoms g^{-1} a^{-1} respectively) agree within uncertainties but also provide upper and lower limits on the range of production rates derived from other high latitude Northern Hemisphere sites (Balco et al., 2009; Goehring et al., 2012; Young et al., 2013).

3. Results

Exposure ages calculated using both local production rates are summarised in Table 2 and Figure 3. Four ages post-date the YD (≈ LLS) termination as defined in the Greenland Ice core records (Rasmussen et al., 2014) regardless of choice of production rate. RMOOR03 produces an age that pre-dates the YD (LLPR) or falls within the YD (GRPR). RMOOR06 produces an age that falls within the YD (LLPR) or post-dates the YD termination (GRPR).

The six samples from Rannoch Moor produce a reduced Chi-square (χ^2_R) of 3.5 indicating that they are not a single population and are influenced by geological uncertainty. The sampled boulders were located on the crests of moraines that retain a steep profile compared to the diffuse profile indicative of significant moraine degradation. Additionally, given the high rainfall in Scotland vegetation is likely to have stabilised moraines very soon after deposition. Consequently, we consider significant exhumation unlikely and interpret the older ages as being the result of nuclide inheritance. The four youngest samples (RMOOR01, 02, 04, 05) agree within their analytical uncertainties (Figure 3) and have a χ^2_R of 0.34 indicating that they are a single population. This lends confidence to our interpretation as it is unlikely any exhumation could result in close clustering of these samples. Given the geomorphological setting and excellent statistical agreement between these ages (cf. Balco, 2011) we consider the best estimate of true moraine age is given by RMOOR01, 02, 04, 05 with a mean age (full uncertainty) of 11.5 ± 0.6 ka (LLPR) or 10.6 ± 0.6 ka (GRPR).

4. Discussion

Regardless of production rate the best estimate moraine age post-dates the minimum deglaciation age proposed by Bromley et al. (2014). A detailed assessment of the relative accuracy of the local production rate calibrations is beyond the scope of this paper. We note that the LLPR is derived from direct age control provided by limiting radiocarbon ages (MacLeod et al., 2011) whereas the GRPR is based on assumed ages of tephra within a varve chronology (MacLeod et al., 2015). Based on this, and to simplify comparison to previously published data, we focus further discussion on the implications of our data calibrated using the LLPR.

Most existing ^{10}Be exposure ages relating to the LLS in Scotland are from satellite ice masses (Ballantyne et al., 2007; Ballantyne et al., 2013; Finlayson et al., 2011; Gheorgiu et al., 2012; Small et al., 2012). These ages paint a complex picture of diachronous glacial maxima (Ballantyne, 2012) suggesting that some LLS glaciers reached their maxima in the early part of the stadial. Given evidence for oscillatory retreat (Ballantyne, 1989, 2002; Golledge, 2010) deglaciation of these ice masses may have occurred during the LLS but constraints on final deglaciation of satellite ice masses are lacking.

Thus far, the best control on the timing of maximum extent of the main ice mass comes from the southern extremity of Loch Lomond where radiocarbon dates of plant macrofossils beneath till suggest overriding by ice 11.9 - 11.6 cal ka (MacLeod et al., 2011). This is within the age range for deglaciation of Rannoch Moor suggested by our data. If Rannoch Moor was the centre of ice dispersal this implies rapid deglaciation from the southern margin to Rannoch Moor, a distance of c. 70 km, within a timeframe constrained by the resolution of our ages. Given evidence for oscillatory ice retreat this scenario seems unlikely. Alternatively, deglaciation was diachronous and the Lomond glacier was not fed from an ice dome over Rannoch Moor but instead from the abundance of high ground to the north of Loch Lomond. This scenario has previously been suggested on the basis of field evidence (Golledge, 2007) and modelling experiments (Golledge et al., 2009).

Regardless of the pattern of deglaciation the mean age for moraine deposition, based on the youngest ^{10}Be ages from Rannoch Moor, conflicts with the minimum deglaciation age of Bromley et al. (2014). Only at the upper extremity of its uncertainty does our best estimate moraine age overlap with the youngest radiocarbon age (OS-89841) used in their interpretation. It does not overlap with either the mean conservative age or the earliest probable ages for deglaciation of Bromley et al. (2014) (Figure 4).

Considered alongside the age of maximum ice extent from Loch Lomond our data conflicts directly with the interpretation of Bromley et al. (2014) that deglaciation of Scotland was complete by 12,262 ± 85 cal yrs BP and likely by 12,493 - 12,580 cal yr BP. Additionally, the explanation of deglaciation due to increasing summer air temperatures (Bromley et al., 2014) is not supported by chironomid based reconstructions of July air temperature which show a sharp drop in Scottish summer air temperatures at the LLS onset to a minimum value c.12.6 -12.4 ka (Figure 3: Brooks and Birks, 2000; Brooks et al., 2012).

Reconciling conflicting geochronological constraints on deglaciation is necessary to realise the potential of utilising the LLR ice mass as a proxy for terrestrial palaeo-environmental change. One potential explanation stems from the fundamental control accurate knowledge of production rates has on the resulting accuracy of exposure ages. The deglaciation age of Rannoch Moor, constrained by our ^{10}Be data, varies depending on choice of production rate *vis a vis* GRPR or LLPR. Using the GRPR makes the exposure ages younger and thus does not resolve the disparity. However, it highlights uncertainty in constraining local production rates raising the possibility that both the GRPR and LLPR underestimate ^{10}Be production rates in Scotland. The lowest independently constrained production rate is the New Zealand production rate (3.74 ± 0.08 atoms g yr^{-1}) (Putnam et al., 2010). For illustrative purposes a recalibration of the Rannoch Moor samples with this production rate yields a best estimate moraine age of 11.7 ± 0.6 ka and thus fails to reconcile the ^{10}Be data with the radiocarbon ages. Given the range of published Northern Hemisphere production rates we consider it unlikely that both local calibrations underestimate ^{10}Be production such that the ^{10}Be ages could be reconciled with the radiocarbon ages.

An alternative explanation is based on the material dated by Bromley et al. (2014). The interpretation of early deglaciation is based on the youngest ages of plant macrofossils (Figure 4). Dating macrofossils renders the hardwater effect unlikely however the youngest samples are all mixed populations; sub-optimal material as they potentially contain material of varying ages. The resulting ages are averages and may be biased by incorporation of older material. While the state of preservations suggests such reworking was minimal we note that two single macrofossil samples produce ages (11.4 ± 0.1 and 11.7 ± 0.1 ka) in good agreement with the ^{10}Be exposure ages and that the vast majority of the radiocarbon data is in agreement with the ^{10}Be exposure ages (Figure 4).

Incorporation of older material in some mixed population samples provides the simplest explanation to reconcile the data of Bromley et al. (2014) with the new evidence presented here, existing geochronological control on maximum ice extent (MacLeod et al., 2011), numerical modeling experiments (Golledge et al., 2008;

Golledge et al., 2009), and paleo-environmental reconstructions of summer air temperature changes during the LLS (Brooks and Birks, 2000; Brooks et al., 2012). This does not preclude the possibility that significant deglaciation of parts of Scotland occurred during the LLS or that increased seasonality played an important role. However, barring new evidence, the conclusion that Scotland was completely deglaciated during the LLS cannot be supported by the majority of available data.

5. Conclusions

New ^{10}Be exposure from boulders on Rannoch Moor provide direct geochronological constraints on deglaciation of Scotland. Regardless of choice of production rate this deglaciation occurred after the dramatic warming that marks the end of the LLS. While Rannoch Moor has often been assumed to have been the centre of ice dispersal our best estimate age of deglaciation (11.5 ± 0.6 ka) is the same as the age of maximum ice extent at Loch Lomond suggesting that the timing of deglaciation of the Scottish ice mass was highly heterogeneous and that much of it was not fed directly from Rannoch Moor.

Our new deglaciation ages conflict with the suggestion that complete deglaciation of Scotland was complete by 12,262 ± 85 cal yrs BP and most likely by 12,493 - 12,580 cal yr BP, an interpretation that also conflicts with existing geochronological and paleoenvironmental data. The uncertainties on our data do not rule out significant deglaciation of Scotland during the late LLS however, given the existing body of work and the new data presented here we conclude that complete deglaciation of Scotland did not occur during the early to mid-LLS as has been suggested.

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Figure Captions and tables

Figure 1. Location map of Rannoch Moor showing the location of the sampled boulders (red stars) and the core sites of Bromley et al. (2014). The cores yielding the youngest radiocarbon ages are labelled. The inset map shows the location of Rannoch Moor within the limits of the Loch Lomond Readvance (Golledge, 2010) and the

location of the site where the maximum extent of glaciation was dated by radiocarbon by MacLeod et al. (2011). The X marks the location where the panorama in Figure 2 was taken. NEXTmap hillshade DEM by Intermap Technologies.

Figure 2. Photographs of sampled moraine (A) from position X (Figure 1) showing location of sampled boulders. RMOOR01 is located behind the moraine crest. Examples of sampled boulders RMOOR01 (B), RMOOR04 (C), and RMOOR06 (D).

Figure 3. Camel plots of cosmogenic exposure ages presented here as calibrated using; Top, Glen Roy production rate (GRPR), and bottom, Loch Lomond production rate (LLPR). Individual probabilities (thin lines) are shown with the four ages yielding the lowest χ^2_R shown with solid lines. The cumulative probability is shown with the red line. Uncertainties used to generate individual probability curves are 1σ analytical uncertainties.

Figure 4. ^{10}Be ages plotted alongside radiocarbon ages from Bromley et al. (2014). Filled triangles represent exposure ages used in the interpretation. Open triangles represent exposure ages interpreted as resulting from nuclide inheritance. The radiocarbon ages have been sub-divided into those obtained from single macrofossils and those obtained from mixed populations. The young ages used to support early deglaciation are highlighted with dashed boxes. The shaded box shows the best estimate age for moraine deposition (11.5 ± 0.6 ka) The conservative deglaciation age (12,262 ± 85 cal yr BP) and the most likely deglaciation age (12,493 – 12, 580 cal yr BP) of Bromley et al. (2014) are shown by dashed lines A and B respectively. The ages are shown alongside a chironomid derived record of summer air temperature (Brooks

and Birks, 2000) and the NGRIP $\delta^{18}O$ record (Rasmussen et al., 2014). Note some of the radiocarbon uncertainties are smaller than the symbols.

Table 1. Sample location, chemistry data and measured $^{10}Be/^{9}Be$ for Rannoch Moor samples.

Sample	Lat.	Long.	Altitude (m)	Thick. (cm)	Shielding[a]	Boulder Dimensions (m)	Qtz Mass (g)	Be Spike[b] (µg)	$^{10}Be/^{9}Be$[c] (10^{-15})	uncert ($x10^{-15}$)
RMOOR01	56.635	-4.778	327	1.6	0.9989	2.5 x 1.9 x 1.0	49.19	247.9	193.07	3.32
RMOOR02	56.635	-4.781	326	1.2	0.9998	2.5 x 2.0 x 1.4	43.48	247.7	174.65	2.90
RMOOR03	56.634	-4.781	329	1.2	0.9998	2.7 x 2.1 x 1.4	32.63	246.6	147.87	2.78
RMOOR04	56.634	-4.779	329	1.2	0.9998	3.0 x 2.8 x 1.2	38.55	247.8	158.47	3.12
RMOOR05	56.634	-4.777	326	3	0.9997	2.6 x 1.4 x 1.0	50.21	251.3	195.02	3.43
RMOOR06	56.634	-4.775	323	1.5	0.9997	3.6 x 3.4 x 1.6	47.65	248.7	200.60	3.74

[a] Calculated using CRONUS calculator (Balco et al. 2008), available at (http://hess.ess.washington.edu/math/general/skyline_input.php).

[b] ^{9}Be spike concentration of 849 ± 12 µg/g.

[c] Relative to NIST_27900 with $^{10}Be/^{9}Be$ taken as 2.79×10^{-11}. Background correction of $3.68 \pm 0.54 \times 10^{-15}$ applied to all samples.

Table 2. ^{10}Be concentrations, uncertainties, and exposure ages from Rannoch Moor samples.

Sample	^{10}Be conc. (at g^{-1})	uncert	Exposure Age [GRPR] (ka)[a]	Exposure Age [LLPR] (ka)[a]
RMOOR01	63780	1513	10.42 ± 0.59 (0.25)	11.29 ± 0.59 (0.27)
RMOOR02	65073	1534	10.60 ± 0.60 (0.25)	11.49 ± 0.59 (0.27)
RMOOR03	72794	1878	11.84 ± 0.68 (0.31)	12.83 ± 0.68 (0.34)
RMOOR04	66488	1746	10.80 ± 0.62 (0.29)	11.70 ± 0.62 (0.31)
RMOOR05	63988	1536	10.57 ± 0.60 (0.26)	11.46 ± 0.60 (0.28)
RMOOR06	68674	1699	11.25 ± 0.64 (0.28)	12.20 ± 0.64 (0.31)

[a] Calculated using CRONUS calculator; Wrapper script 2.2, Main calculator 2.1, Constants 2.2.1, Muons 1.1 (Balco et al. 2008). See Section 2 for details of local production rates. Ages assume 1 mm ka^{-1} erosion, no inheritance, and density of 2.65 g cm^{-3}. Analytical uncertainties reported in parentheses.

*Figure 1
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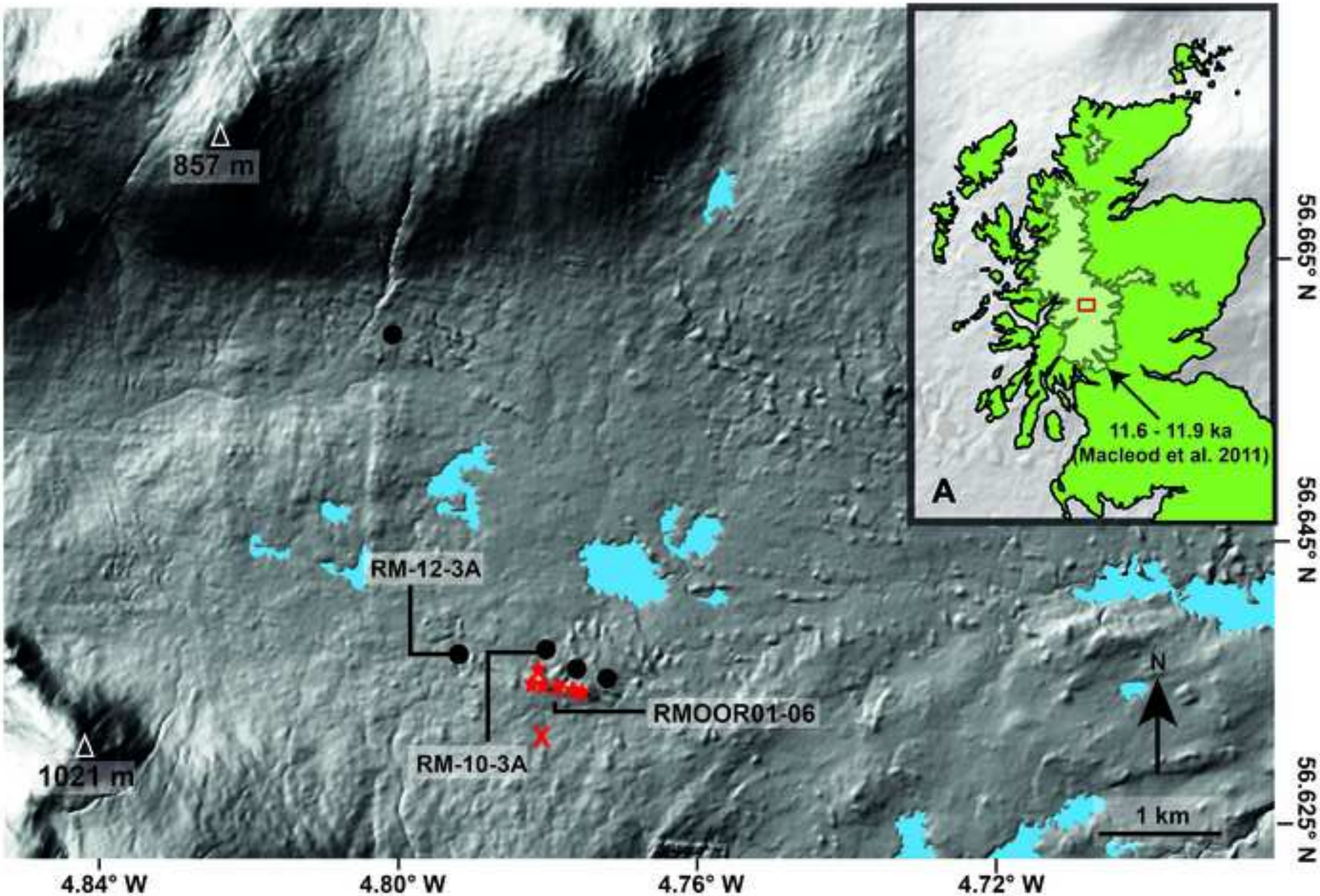

*Figure 2
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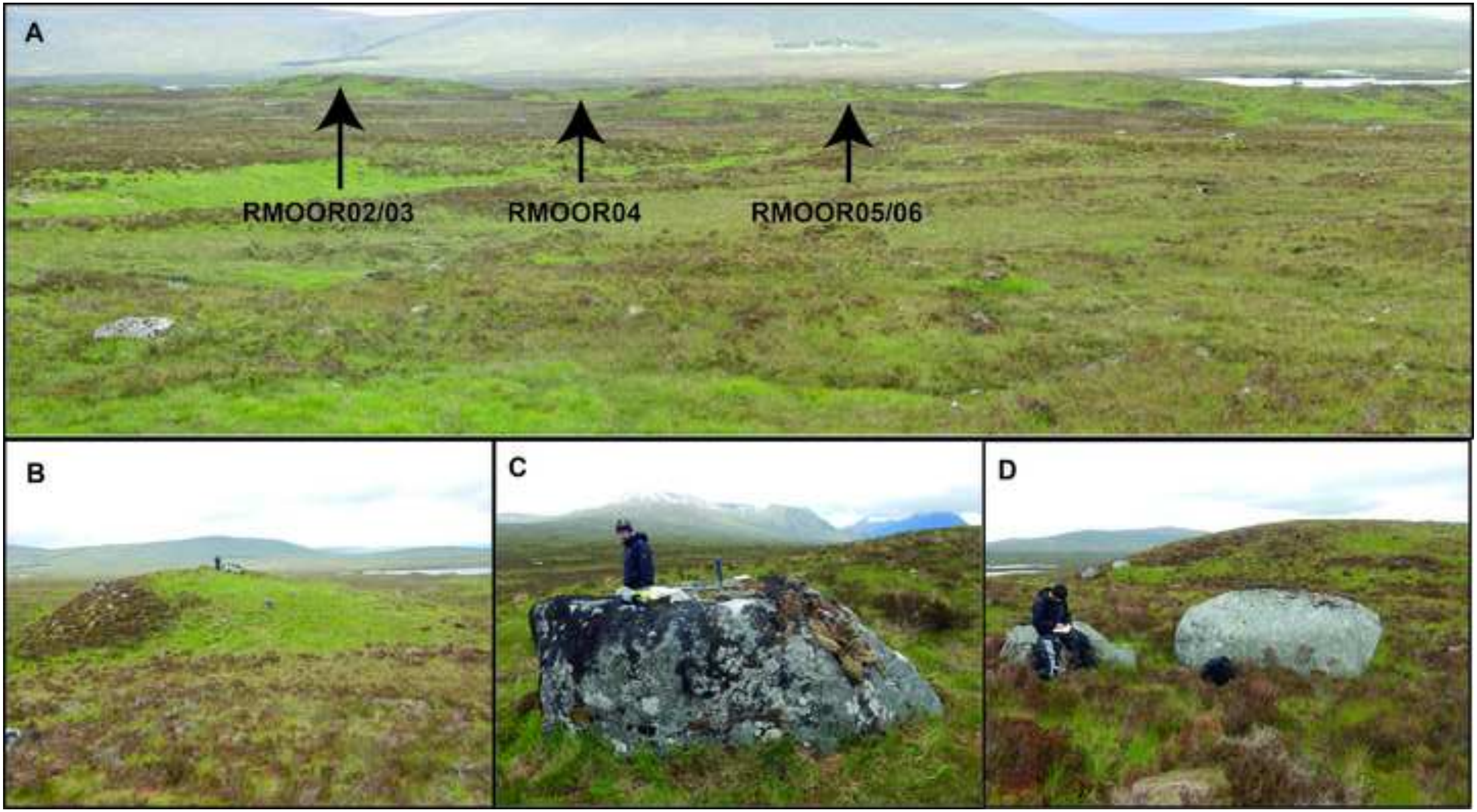

*Figure 3
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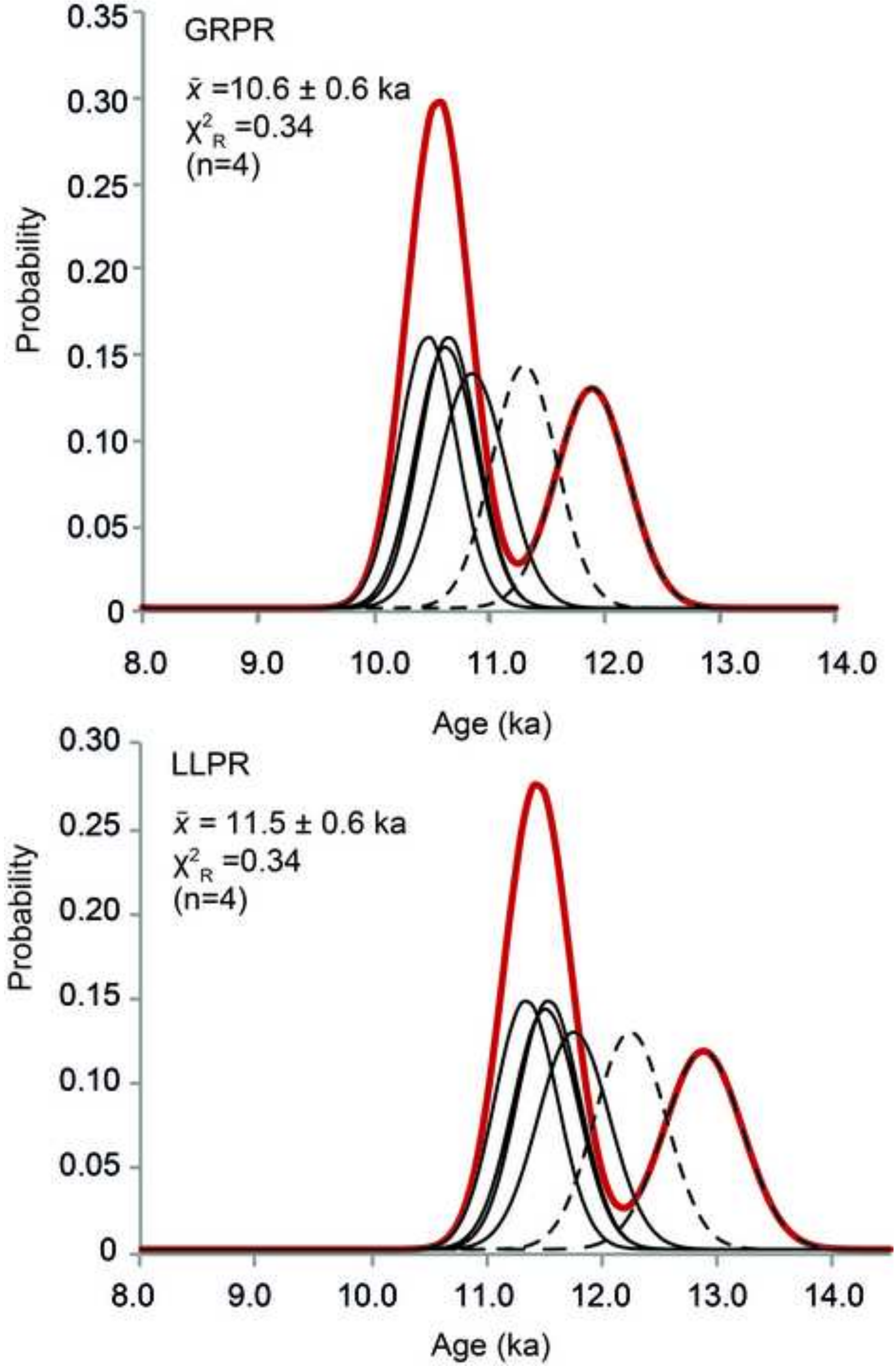
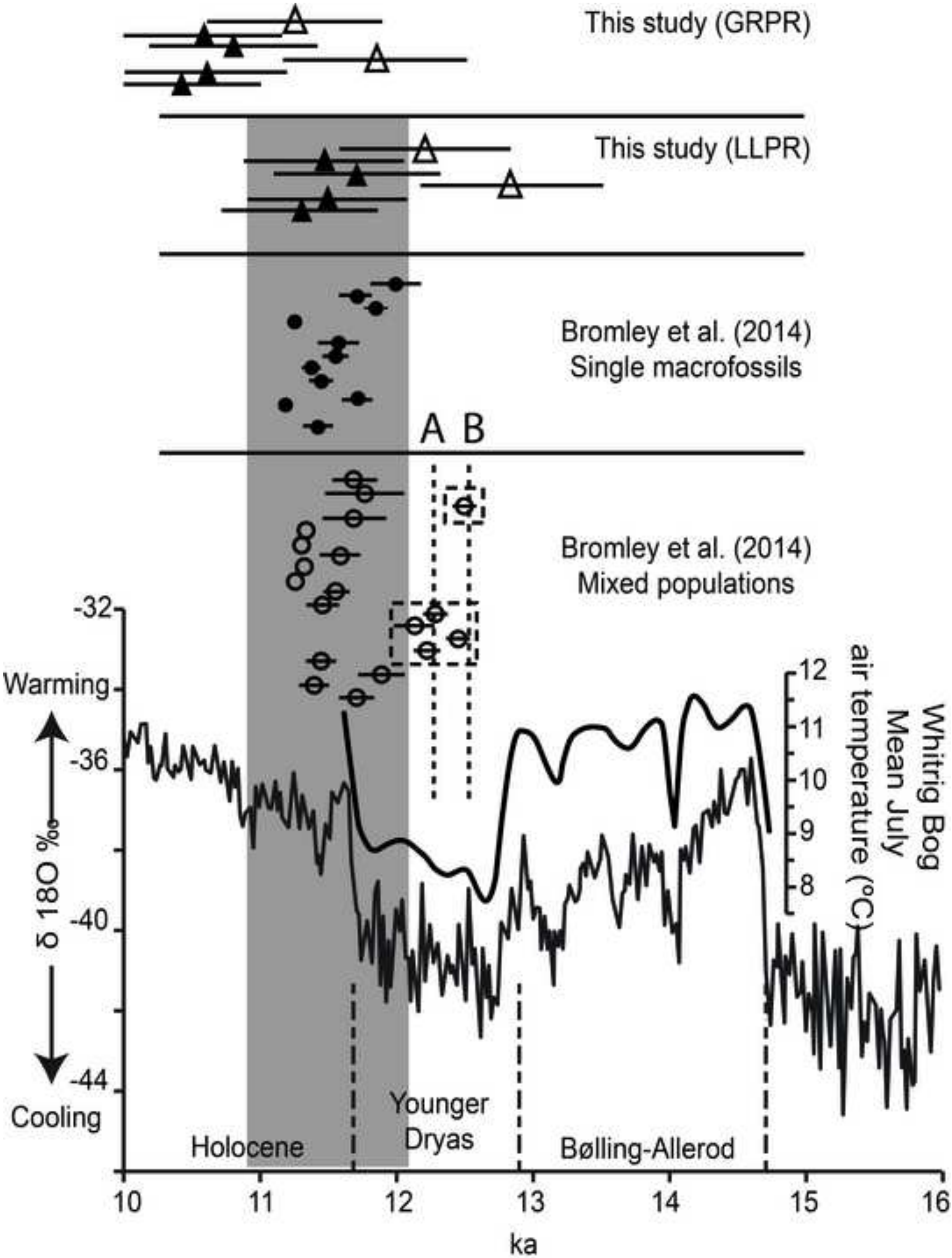


*Figure 4
Click here to download high resolution image



***Highlights (for review)**

Small and Fabel Ms. Ref. No.: JQSR-D-16-00010
Title: Was Scotland deglaciated during the Younger Dryas?

Highlights

- New ^{10}Be exposure ages constrain Younger Dryas deglaciation of Scotland.
- Four ages cluster at 11.5 ± 0.6 ka.
- Suggests deglaciation occurred in the late Younger Dryas – early Holocene.
- Not consistent with suggestion of Early – mid Younger Dryas deglaciation.