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Short communication

Was Scotland deglaciated during the Younger Dryas?

David Small [a, *], Derek Fabel [b]

[a] Department of Geography and Geosciences, University of Glasgow, Glasgow, G12 8QQ Scotland, United Kingdom
[b] SUERC AMS Laboratory, Scottish Universities Environmental Research Centre, East Kilbride, G75 0QF Scotland, United Kingdom

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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 (Fig. 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) (Fig. 1). Sample information is summarised in Table 1. Quartz was separated

* Corresponding author.
E-mail address: David.Small@glasgow.ac.uk (D. Small).

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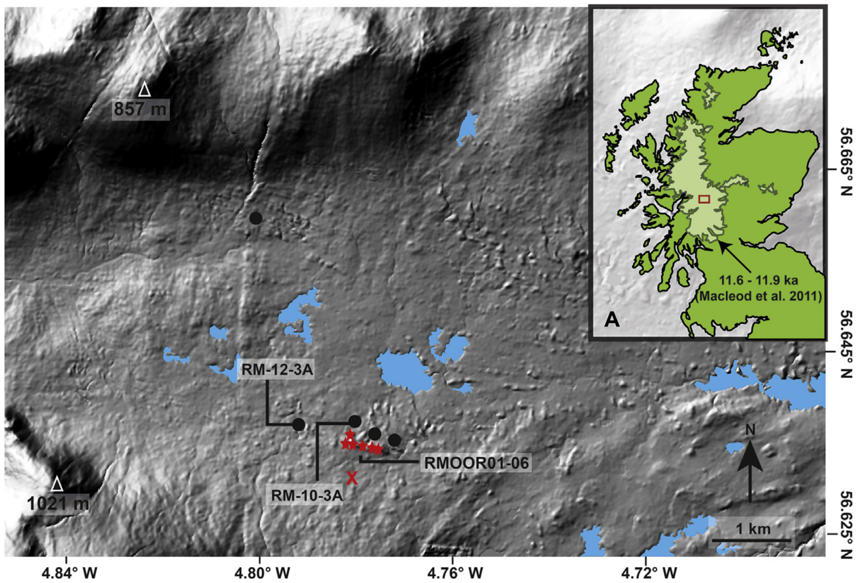

Fig. 1. Location map of Rannoch Moor showing the location of the sampled boulders (red stars) and the core sites of Bromley et al. (2014). The cores yielding the youngest radiocarbon ages are labelled. The inset map shows the location of Rannoch Moor within the limits of the Loch Lomond Readvance (Golledge, 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 Fig. 2 was taken. NEXTmap hillshade DEM by Intermap Technologies. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

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 ($\times 10^{-15}$)
RMOOR01	56.635	−4.778	327	1.6	0.9989	2.5 × 1.9 × 1.0	49.19	247.9	193.07	3.32
RMOOR02	56.635	−4.781	326	1.2	0.9998	2.5 × 2.0 × 1.4	43.48	247.7	174.65	2.90
RMOOR03	56.634	−4.781	329	1.2	0.9998	2.7 × 2.1 × 1.4	32.63	246.6	147.87	2.78
RMOOR04	56.634	−4.779	329	1.2	0.9998	3.0 × 2.8 × 1.2	38.55	247.8	158.47	3.12
RMOOR05	56.634	−4.777	326	3.0	0.9997	2.6 × 1.4 × 1.0	50.21	251.3	195.02	3.43
RMOOR06	56.634	−4.775	323	1.5	0.9997	3.6 × 3.4 × 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.

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 5 MW 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 Fig. 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 (Fig. 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