New age constraints for the maximum extent of the last British-Irish Ice Sheet (NW sector)

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ABSTRACT: This paper presents the first terrestrial age constraints from the outer continental shelf for the maximum extent of the NW sector of the last British-Irish Ice Sheet. Cosmogenic ^{10}Be ages from eight glacially transported boulders on the island of North Rona, show that the Late Devensian (Late Weichselian) British-Irish Ice Sheet overrode the island at its maximal stage and retreated c.25 ka BP. These new dates, supported by other geological evidence, indicate that the north-western part of the ice sheet was most extensive between 27 - 25 ka BP, reaching the outer continental shelf during the global eustatic sea level minimum at Last Glacial Maximum.

Introduction

At its maximum extent the British-Irish Ice Sheet (BIIS) extended westward from the main ice divide across mainland Britain onto the UK Continental Shelf, reaching the shelf edge in places (Figure 1a) (Stoker *et al.*, 1993, Sejrup *et al.*, 2005). Eastward it converged with the Fennoscandian Ice Sheet (FIS) from Scandinavia in the North Sea Basin at, or soon after, the Last Glacial Maximum (LGM) (Carr *et al.*, 2006, Bradwell *et al.*, 2008). The timing of the maximum glacial extent in the British Isles and on the continental shelf remains uncertain and evidence suggests it was probably geographically and spatially variable (Thomas and Chiverrell, 2010; Clark *et al.*, 2012). The NW sector of the BIIS has been the subject of heightened interest recently due to the identification of numerous, complex, Pleistocene moraine sequences offshore (Bradwell *et al.*, 2008) and the former presence of the Minch palaeo-ice stream (Figure 1a) – likely to have dominated the configuration, ice-divide location, and ice-sheet thickness of this sector of the BIIS (Stoker and Bradwell, 2005; Bradwell *et al.*, 2007).

The island of North Rona lies 70 km northwest of Cape Wrath, NW Scotland, and along with Sula Sgeir, St Kilda and the Flannan Isles is one of only a few terrestrial sites capable of providing cosmogenic surface exposure age data for the offshore NW sector of the BIIS. Mapping using seismic techniques (Stoker and Holmes, 1991; Davison, 2005) and echosounder data (Bradwell *et al.*, 2008) identified numerous large moraines on the seabed around northern Scotland (Figure 1b), which record sequential ice sheet retreat from continental shelf-edge positions at LGM. These moraines form part of the Hjaltland Eilean Siar Glacigenic Group (Stoker *et al.*, 2011), and although presently undated, the younger moraines are locally overlain by marine sediments dated to c. 18 ka BP (Selby 1989; Peacock *et al.*, 1992). North Rona is within the transition from the outermost 'LGM' moraine assemblage to the 'Post-LGM' moraines, thought to reflect a later ice sheet configuration (Bradwell *et al.*, 2008). It has been proposed, based on a major increase in sedimentation on the Barra Fan, that the BIIS reached its maximum size around ~26 ka BP (Knutz *et al.*, 2001; Peck *et al.*, 2007). At this time the BIIS extended well onto the continental shelf, and is believed to have reached the shelf break along much of its Irish and UK margins (Stoker *et al.*, 1993; Peck *et al.*, 2007; Bradwell *et al.*, 2008; Scourse *et al.*, 2009; Clark *et al.*, 2012; O Cofaigh *et al.*, 2012). AMS radiocarbon dates from overridden organic deposits at Tolsta Head, NE Lewis (Whittington and Hall, 2002) and marine fauna from borehole 78/4 off Stornoway (Graham *et al.*, 1990) do at least provide bracketing ages for glaciation, and hence ice streaming, in The Minch between <30 ka >15 ka BP.

In this short article new cosmogenic isotope evidence is presented which tightly constrains the maximum extent of the last BIIS in its NW sector. Using this new data this paper examines how this dating evidence helps to constrain the timing of the Last Glacial Maximum in the northern British Isles.

Study site

North Rona (Figure 2) is an isolated island 2 km across at its widest point, and rising to 108 m elevation at its far south-eastern tip. Overall the island displays a glacially smoothed surface, with distinct bedrock streamlining from ESE to WNW. This streamlining also is reflected in the large-scale seabed morphology surrounding the island (unpublished BGS data). North Rona is composed of a dark coloured, medium-grained, banded amphibolite, which has been intruded by a lighter coloured, coarse-grained, quartz-rich pegmatitic granite. These rocks outcrop at the top of the main east-west ridge of the island. The southern higher portion of the island is capped by a thin discontinuous smear (typically <1 m thick) of diamicton containing erratics of mixed lithology, primarily of gravel to cobble grade.

Large pegmatitic granite boulders are relatively common, occupying the higher ground of the main E-W ridge, and the westernmost slopes of the island. Some of these boulders may be locally sourced, either from the cliffs of North Rona, or the surrounding seabed. However, based on mineralogical similarities it is considered more likely that they derive from distinctive pegmatitic granites within the Laxfordian Suite of the Lewisian Gneiss (between Laxford Bridge and Kinlochbervie) or the neighbouring seabed.

Methods

Eight coarse-grained, quartz-rich pegmatitic granite samples were collected in the summer of 2009. Samples were taken from stable erratics which either sit directly on exposed bedrock or are firmly embedded in the thin till surface (Figure 2). Though the island supported a small 12th Century monastery, the sampled boulders are well away from sites formerly occupied by buildings or cultivation, and in the field were deemed too large to be moved by former inhabitants. The boulders measure on average c. 1.5 x 1.5 m and sampled upper surfaces stand at between 0.8 and 1.5 m above the surrounding ground surface. Boulders display some evidence of surface weathering, with quartz crystal agglomerations protruding between 2 and 5 mm above more felspathic components of the granite. There is no evidence for colonisation of the island by trees, or of significant pre-existing accumulations of soil. All selected samples were located above 50 m elevation, to avoid possible remobilisation by storm waves. All samples were taken from the top surface of granitic boulders using a hammer and chisel and sample data are presented in Table 1. Sample locations were recorded using hand-held GPS and altitudes confirmed using the NextMap Digital Elevation Model. For each sample topographic shielding was measured in the field using standard methods (Balco *et al.*, 2008). Sample thickness was measured and samples were crushed and sieved to 125-250 and 250-500 μm fractions at BGS Keyworth using a disk mill. Separation and purification of quartz and Beryllium extraction was carried out at the NERC Cosmogenic Isotope Analysis Facility Laboratory at the Scottish Universities Environmental Research Centre (SUERC). Methods followed are modified from Child *et al.* (2000). Beryllium isotope ratios of 8 samples and a procedural blank were measured at the SUERC Accelerator Mass Spectrometry (Williams) Laboratory.

The ages were calculated using the CRONUS-Earth exposure age calculator v2.2 (http://hess.ess.washington.edu/math; Balco *et al.*, 2008). Ages are presented using the 'Lm' scaling scheme of Balco *et al.* (2008), with no correction for postglacial erosion or snow coverage. However, ages are also presented with an erosion rate (ε) of 1 mm ka^{-1} to account for loss of surface material over the time period since deposition. As long-term erosion rates of glaciated crystalline rocks rarely exceed 1 mm ka^{-1} (André, 2002), this value is seen as a plausible maximum, especially given the relative small height difference between quartz agglomerations and the surrounding rock. The effects of various scaling schemes are discussed by Ballantyne (2010) and will not be revisited here.

Results

Ages derived from the 8 samples are shown in Table 1. With no erosion correction applied, ages range from 20.0 ± 1.9 to 28.8 ± 2.7 ka BP, and yield an arithmetic mean age of 24.8 ± 2.7 ka BP, and an error weighted mean age of 24.3 ± 0.8 ka BP. This should be seen as a *minimum age* for the deposition and, hence, exposure of the boulders. With a 1 mm ka^{-1} erosion-rate correction applied, ages range from 20.3 ± 2.0 to 29.5 ± 2.9 ka BP, with an arithmetic mean age of 25.3 ± 2.9 ka BP and an error weighted mean age of 24.7 ± 0.9.

Probability density distributions of the 8 samples show the consistency, statistical similarity and closely overlapping form of the derived ages (Figure 3). The correspondence between the interquartile range (2.4 ka) of all 8 samples and the mean of the individual uncertainties (2.4 ka) precludes discrimination of the group into subsets on statistical grounds. Hence, we deem the 8 samples from North Rona to be part of a single population with normally distributed values (and errors), recording a single phase of glacial deposition by a retreating ice sheet.

Looking more closely at the individual samples, NR03 yields the youngest zero-erosion age 20.0 ± 1.9, and is the furthest (-4.8 ka) from the arithmetic mean value (24.8 ka). This boulder sits directly on bedrock just below the western summit of the island. It has clearly not moved since deposition, neither is it likely to have been buried, however it does exhibit a concave upper surface. It is possible that some of the upper surface may have been lost through enhanced freeze-thaw action by ponding of surface water, resulting in a loss of isotopes through spalling of surface material. The other two samples that lie numerically furthest from the mean NR07 and NR08 are found on the western flank of the island, embedded in c. 30 cm of thin till, directly overlying bedrock. Both exhibit slightly older zero-erosion ages than the mean, 27.9 ± 2.6 and 28.7 ± 2.7 ka, respectively. It is possible that these samples display some inherited ^{10}Be from prior (pre-glacial) exposure. Their close geographical proximity to NR09, which has an age very close to the mean, would strengthen this interpretation and argue against any specific issues with the sample locality.

Discussion

Our results from North Rona show that the BIIS reached its maximum position offshore northwest Scotland several thousand years before the traditionally cited LGM at 18-22 ka (e.g. Bowen *et al.*, 2002), and that the sampled boulders were deposited by ice sheet retreat across the island around 25 ka BP. This finding is consistent with ice sheet reconstructions by Sejrup *et al.*, (1994, 2005), Bradwell *et al.* (2008) and Clark *et al.* (2012) who all argue for an LGM position in this sector near the continental shelf edge at c. 27 ka.

However the timing of the ice sheet maximum around the British Isles can now be constrained further by other key geological proxy data. Onset of glaciations is recorded most clearly by the abrupt appearance of ice-rafted debris (IRD) in deep sea sediments. Working on sediments from the North East Atlantic strongly influenced by the growth and decay of the BIIS, Peck *et al.* (2007) found discrete IRD events with British mineral signatures (Figure 3). They identified a significant increase in British-sourced IRD after Greenland Interstadial 3 (28 ka BP), increasingly rapidly from 26.5 ka BP and culminating around 24-25 ka BP, reflecting the existence of extensive marine ice-sheet margins. Prior to this time IRD fluxes were significantly lower suggesting that the BIIS was much smaller between 35-27 ka BP (Peck *et al.*, 2007). Furthermore, and notably, the findings of Peltier and Fairbanks (2006) demonstrated that the LGM is characterised by a global sea-level minimum at c. 26 ka BP. These data are entirely consistent with our cosmogenic-age constraints from North Rona, placing the BIIS glacial maximum in this sector shortly before 25 ka BP and after Greenland Interstadial 3 (~28 ka BP).

It has been proposed that large North Atlantic wide iceberg-release events, such as Heinrich Event-2, at c. 25 ka BP, coupled with eustatic sea level rise may have led to a re-organization of the conjoined BIIS-FIS ice sheet along its Atlantic margin (Bradwell et al., 2008; Clark et al., 2012; O'Cofaigh et al., 2012). We expect that the BIIS was highly dynamic during retreat, as shown by the complex pattern of seabed moraines (Bradwell *et al.*, 2008) and numerical modelling simulations (Hubbard *et al.*, 2009); hence we stress that our data can only provide constraints for the retreat of the NW sector of the ice sheet. The possibility that a single coherent ice sheet margin existed at LGM (25-27 ka BP) at, or close to, the continental shelf edge from north of Shetland to offshore western Ireland (cf. Bradwell *et al.*, 2008; Scourse *et al.*, 2009; Clark *et al.*, 2012) needs to be investigated further before any definitive statements can be made.

Conclusions

The cosmogenic ^{10}Be exposure ages presented here represent the first absolute terrestrial age constraints for glaciation of the outer UK continental shelf. The 8 glacially transported boulders from North Rona show a high degree of internal consistency, accuracy, and overall agreement. Consequently, they are deemed to be a single population with a mean (uncorrected) exposure age of 24.8 ka BP.

From these new age constraints we draw the following main conclusions:

1. The last British-Irish Ice Sheet overrode North Rona and the surrounding continental shelf at its maximum extent during the Late Devensian (Late Weichselian) Stadial, depositing boulders as it retreated at c. 25 ka BP.

2. Several important strands of evidence indicate that the British-Irish Ice Sheet maximum can now be constrained more precisely to between ~27 ka and ~25 ka BP – coincident with the major increase in British-sourced ice-rafted debris and the global sea level minimum associated with the Last Glacial Maximum at c. 26 ka BP.

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Sample	Northing	Easting	Altitude	Thickness	Thickness scaling	Production rate atoms/g/yr Muons (a)	Spallation (b)	Shielding scaling (c)	^{10}Be conc. (d,e,f,g,h,i)	Age(g, j) (zero erosion)	Age(g, j) (1mm/ka)
	° N	° W	m	cm					10^4 at/g SiO_2	kyr	kyr
NR02	59° 7' 23"	5° 49' 22"	80	1.5	0.9874	0.188	5.01	0.999974	124.8 ± 4.3	24.1 ± 2.3	24.6 ± 2.4
NR03	59° 7' 25"	5° 49' 30"	96	6	0.951	0.188	4.91	0.999999	101.3 ± 3.9	20.0 ± 1.9	20.3 ± 2.0
NR04	59° 7' 27"	5° 49' 42"	79	3	0.9751	0.187	4.95	0.999999	120.0 ± 5.9	23.5 ± 2.4	24.0 ± 2.5
NR05	59° 7' 27"	5° 49' 47"	81	3	0.9751	0.188	4.96	0.999999	121.5 ± 4.6	23.8 ± 2.3	24.2 ± 2.4
NR06	59° 7' 26"	5° 49' 52"	75	2	0.9833	0.187	4.97	0.999999	130.4 ± 4.9	25.5 ± 2.4	26.0 ± 2.5
NR07	59° 7' 21"	5° 49' 52"	60	1	0.9916	0.186	4.93	0.999880	141.8 ± 4.9	27.9 ± 2.6	28.6 ± 2.8
NR08	59° 7' 21"	5° 49' 51"	61	1.5	0.9874	0.186	4.91	0.999880	145.6 ± 5.4	28.8 ± 2.7	29.5 ± 2.9
NR09	59° 7' 20"	5° 49' 53"	56	2	0.9833	0.186	4.87	0.999880	124.9 ± 3.8	24.9 ± 2.3	25.4 ± 2.4

a: Constant (time-invariant) local production rate based on (Heisinger et al., 2002a,b).

b: Constant (time-invariant) local production rate based on Lal (1991) and Stone (2000). A sea-level, high-latitude value of 4.39 ± 0.37 atoms g^{-1} a^{-1} was used, as employed by the CRONUS online calculator.

c: Calculated using the CRONUS online calculator (v.2.2).

d: A density of 2.7 g cm^{-3} was used based on the pegmatitic granitic composition of the samples.

e: Isotope ratios normalised to NIST SRM4325 with a ^{10}Be/Be ratio of 2.79 × 10^{-11} and using a ^{10}Be half-life of 1.39 × 10^{6} years.

f: Sample ^{10}Be/Be ratios ranged between 1.6573 x 10^{-13} and 2.3799 x 10^{-13}.

g: Uncertainties are reported at the 1σ confidence level.

h: The processed chemistry blank ratios ranged between 4.2966 x 10^{-15} and 9.9882 x 10^{-15} and were subtracted from the measured ratios. The uncertainty of this correction is included in the stated standard uncertainties.

i: Propagated uncertainties include error in the chemistry blank, carrier mass (1%) and AMS counting statistics.

j: (^{10}Be) ages calculated using the CRONUS online calculator (Balco et al., 2008) version 2.2 (http://hess.ess.washington.edu/). Ages quoted in table are from the Lm scaling scheme.

Figure captions

Figure 1:

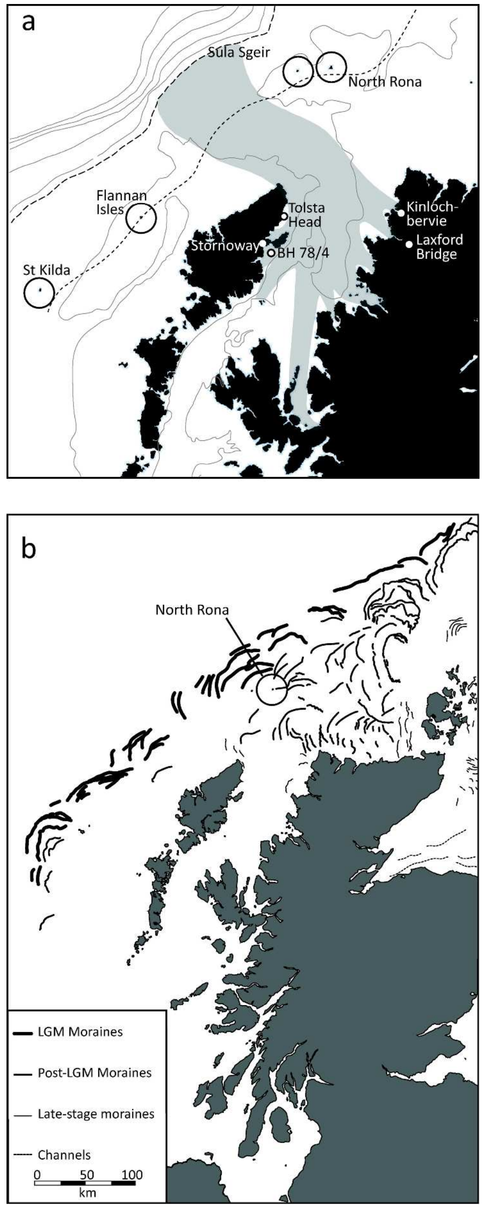
a) Location Map of NW Scotland and continental shelf showing position of North Rona, Sula Sgeir and St Kilda in relation to the Minch Ice Stream (Bradwell *et al.*, 2007), and most likely mainland source for sampled erratics (Kinlochbervie/Laxford Bridge granite suite). LGM limits: long-dash line (inner) from Bradwell *et al.* (2007); short-dash line (outer) from Bradwell *et al.* (2008) and Clark *et al.* (2012).
b) Map of continental shelf moraine sequences (from Bradwell *et al.*, 2008)

Figure 2:

NEXTMap hill-shaded DEM of North Rona showing locations of sampled boulders with zero erosion ages. (a–c): Field photos of three typical samples (NR02, NR05, NR08).

Figure 3:

a) Probability density distributions for all 8 ^{10}Be exposure ages from glacially transported boulders on North Rona. Distributions calculated using the Lm scaling with $\varepsilon = 0$ (uncorrected for erosion) and full (external) uncertainties. Colours relate to specific boulders sampled.
b) Probability density function of mean for all 8 exposure ages. NR-mean = no erosion correction; NR-mean is erosion corrected (ε =1 mm.ka-1). Individual exposure ages are also shown (coloured lines).
c) Mean age for glacially transported boulders on North Rona (Uncorrected = 24.8 ka BP; erosion corrected = 25.3 ka BP) plotted against NGRIP ice core data spanning the last 35 ka (Rasmussen *et al.*, 2006). Horizontal bars are 1 sigma (full) uncertainties. Greenland ice core stages from Lowe *et al.* (2008). Red bar shows timing of Global sea level minimum = GSLM (from Peltier and Fairbanks, 2006). Light blue boxes show major British-sourced IRD events; width shows duration, height shows relative volume of IRD flux (from Peck *et al.*, 2007). We show that the last BIIS covered North Rona during the LGM (grey bar), now constrained between 25-27 ka BP, depositing boulders as it retreated.



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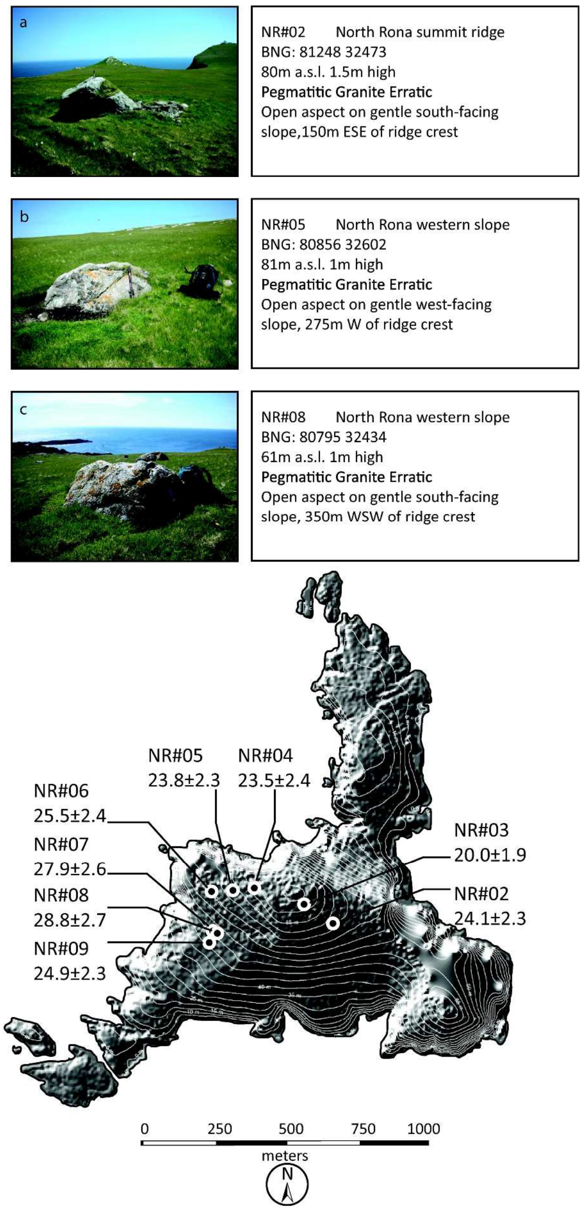
265x674mm (300 x 300 DPI)



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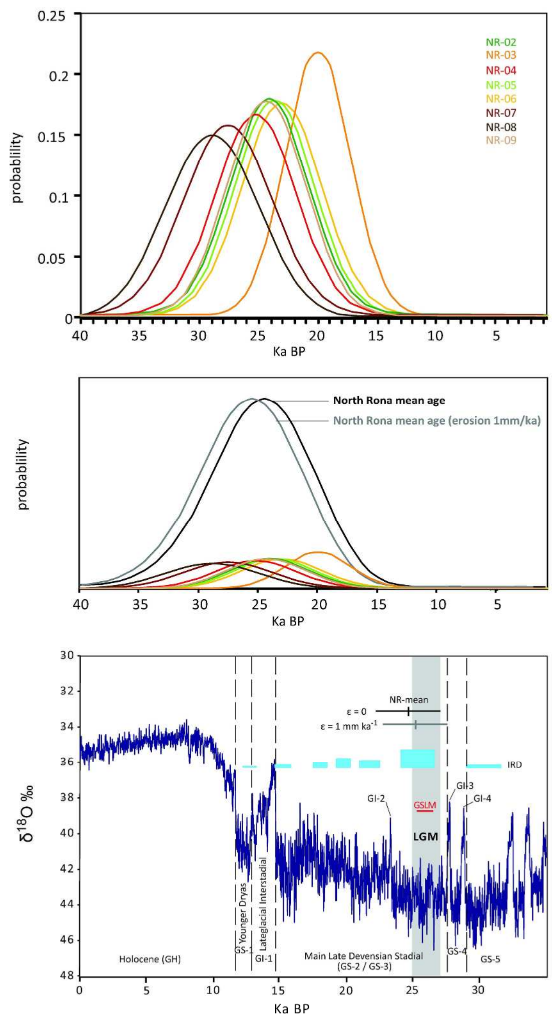

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