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Ice caps existed throughout the Lateglacial Interstadial in northern Scotland

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Abstract

We constrain, in detail, fluctuations of two former ice caps in NW Scotland with multibeam seabed surveys, geomorphological mapping and cosmogenic ^{10}Be isotope analyses. We map a continuous sequence of 40 recessional moraines stretching from ~10 km offshore to the Wester Ross mountains. Surface-exposure ages from boulders on moraine ridges in Assynt and the Summer Isles region show that substantial, dynamic, ice caps existed in NW Scotland between 13–14 ka BP. We interpret this as strong evidence that large active glaciers probably survived throughout the Lateglacial Interstadial, and that during the Older Dryas period (c.14 ka BP) ice caps in NW Scotland were thicker and considerably more extensive than in the subsequent Younger Dryas Stadial. By inference, we suggest that Lateglacial ice-cap oscillations in Scotland reflect the complex interplay between changing temperature and precipitation regimes during this climatically unstable period (~15–11 ka BP).

150 words

Key words: *Older Dryas, moraines, cosmogenic dating, multibeam bathymetry*

Introduction

Many workers have examined the nature of the climate in Britain during the last glacial-interglacial transition (c. 15–11 ka BP), yet crucial uncertainties still remain. Traditionally, glacial deposits and landforms from the mountains and glens of western Scotland have been ascribed to the Younger Dryas (YD) chronozone (12.9–11.7 ka BP; Greenland Stadial 1 (GS-1) (Lowe et al., 2008)), locally known in Britain as the Loch Lomond Stadial (e.g. Sissons, 1977, 1979; Ballantyne, 1989, 2007; Bennett and Boulton, 1993; Benn and Lukas, 2006; Golledge, 2007). Examples of earlier, unequivocal, glacial advances or oscillations in Scotland are rare in the literature – the most notable being the Wester Ross Readvance, along the NW seaboard of mainland Scotland c. 16 ka BP (Robinson and Ballantyne, 1979; Everest *et al*., 2006). During the intervening Lateglacial Interstadial (GI-1) (14.7–12.9 ka BP) many authors have argued, based on scattered pollen sites and basal radiocarbon dates, that Britain was extensively, if not completely, ice free (e.g. Sissons, 1967; Bowen *et al*., 1986; Lowe *et al*., 1994). Whether or not glaciers in Scotland disappeared completely before re-growing in the YD is a long-debated point. Although many workers have argued convincingly for the existence of small glaciers in favourable locations during the Lateglacial Interstadial (e.g. Sugden, 1980; Sutherland, 1984; Ballantyne and Sutherland, 1987; Clapperton, 1997), the idea of ‘ice-survival’ remains untested.

Recently, cosmogenic-exposure ages on glacially transported boulders and ice-worn bedrock have yielded dates that sit uneasily with models of complete Scottish deglaciation by the onset of GI-1. Everest and Kubik (2006), Stone and Ballantyne (2006) and Golledge *et al*. (2007) have all reported uncorrected ^{10}Be exposure ages that fall within the period ~13–15 ka BP. The question remains, therefore: Did significant ice volumes persist into the Lateglacial Interstadial? And did any glaciers in Scotland remain active throughout this period and into the Younger Dryas?

In this short article we present new geomorphological and cosmogenic-isotope evidence from NW Scotland demonstrating that two substantial ice caps did indeed exist and remained active during the Lateglacial Interstadial.

Study Site and Methods

The seaboard of the NW Scottish Highlands is a classic fjord landscape with a deeply indented, glacially sculpted, coastline. The geology of the area is dominated by Neoproterozoic Torridonian sandstone, psammite and Archaean gneiss. For the purpose of this study the Summer Isles region includes all the land and seafloor between the headlands of Gairloch in the south and Rubha Còigeach in the north; centred on Loch Broom and Little Loch Broom (Figure 1). The Assynt Mountains delimit the northeast boundary of the area, and the Beinn Dearg massif delimits the southeast. The landscape is dissected by numerous well-developed troughs that continue offshore as bathymetric deeps (Figure 1). During the last ice-sheet glaciation the Summer Isles region was crossed by a major tributary of The Minch palaeo-ice stream (Bradwell *et al*., 2007). The glacial geology and an overview of the bedrock geology of the area has been described in more detail by Stoker *et al*. (2006) and Bradwell *et al*. (2008).

We used multibeam Geoswath imagery, boomer seismic profiles, colour stereoscopic aerial photographs and NEXTMap digital surface models, combined with detailed geological field surveys to map the onshore and offshore glacial geomorphology of the Summer Isles region of NW Scotland. As part of a wider geochronological investigation, we sampled 10 glacially transported boulders on 3 moraine systems for surface-exposure dating using ^{10}Be in quartz (Figures 1, 2). Site 1 is a large steep-sided moraine running for 800 m along the side of Sail Mhor, the northwest spur of An Teallach (Figure 1). This lateral moraine formed at the margin of a large ice mass that once filled Little Loch Broom to a height of at least 200 m asl. Three Torridonian sandstone boulders and one Eriboll sandstone (quartzite) boulder were sampled for cosmogenic analysis from the crest of the moraine (Figure 2a). Site 2 is a small yet pronounced moraine ridge surrounded by a wide expanse of boulder-strewn ground adjacent to the western flank of Ben More Coigach, near Achiltibuie (Figure 1). This latero-frontal moraine complex occurs at a similar height (200 m asl) to the Sail Mhor moraine. Three Torridonian sandstone boulders were sampled from the crest of the moraine ridge (Figure 2b). Site 3 is a small moraine ridge, part of a larger assemblage of morainic mounds and ridges in the Loanan Valley in Assynt (Figure 1). These moraines are recessional features deposited by a former ice cap sourced on the Assynt mountains to the east (Bradwell, 2006). Three large Eriboll sandstone (quartzite) boulders were sampled for cosmogenic analysis from a single ridge crest (Figure 2c). Samples were processed at the University of Glasgow's Centre for Geosciences cosmogenic isotope laboratory using methods adapted from Kohl and Nishiizumi (1992), Ditchburn and Whitehead (1994) and Child *et al*. (2000). Beryllium ratios were determined at the Scottish Universities Environmental Research Centre (SUERC) AMS facility.

Figure 1 here [Whole page landscape; colour]

Results

New multibeam bathymetry has revealed a continuous sequence of 40 seafloor moraines spanning ~40 km from The Minch to inner Loch Broom. These large well-preserved moraines are up to 10 km in length, 10-20 m high and most display spacings of ~100-1000 m (Figures 1, 2d, 2f) (Stoker *et al*., 2006). Many of the ridges have intricate plan morphologies and asymmetric cross profiles typical of recessional push moraines (cf. Boulton, 1986). Some of these seafloor ridges cut straight across topography as De Geer moraines, formed at a grounded marine-terminating ice margin (Figure 2e). Several of these seafloor moraines can be traced onshore, for example at the mouths of Loch Ewe and Little Loch Broom and on the western flank of Ben More Coigach (Figure 1).

Minimum ^{10}Be exposure ages for 8 of the glacially transported boulders on three of these moraine systems overlap at 1 sigma and range from 12.9–14.1 ka BP (Table 1; Figure 3). All 8 of these dates fall within the Lateglacial Interstadial (GI-1), as defined by the Greenland Ice Core Chronology 2005 (Lowe et al., 2008). The mean of the overlapping exposure ages from each of the Sail Mhor, Achiltibuie and Loanan Valley moraines are: 13.5, 13.6 and 13.5 ka respectively. Two exposure ages from the Sail Mhor moraine are anomalously young outliers (10.0 and 6.8 ka BP). We attribute these outlying samples to boulder instability (overturning) or possibly Holocene rockfall. The eight overlapping, tightly clustered, minimum exposure ages strongly suggest glacial deposition c. 14 ka BP, during GI-1.

Table 1 here

Figure 2 here [half page; colour]

Reconstruction of glacial events

Previously published cosmogenic-exposure ages in the Summer Isles region of NW Scotland have helped to bracket the rate and timing of Lateglacial deglaciation. Three glacially transported boulders on a well-defined ice-sheet moraine crossing the Gairloch peninsula (Figure 1) yielded exposure ages suggesting deposition c. 16 ka BP (Everest *et al*., 2006). Three bedrock samples from the plucked surfaces within the large east-facing corrie on An Teallach yielded ^{10}Be isotope accumulations consistent with exposure at the end of the YD (~11.5 ±0.5 ka) (Stone et al., 1998). Our ten new ^{10}Be exposure ages from three moraine systems provide refined temporal constraints on intervening glacier oscillations in this part of NW Scotland.

The coherent, incremental pattern of moraines in the Summer Isles region is strongly suggestive of dynamic oscillatory ice-front retreat after the Wester Ross Readvance and before the YD. ^{10}Be exposure ages on the Sail Mhor and Achiltibuie moraines constrain the time of retreat of a large glacier that terminated amongst the Summer Isles c. 14 ka BP (i.e. GI-1d). This coherent palaeo-ice margin deposited a moraine that runs almost unbroken for 10 km on the seafloor from Gruinard Bay to Tanera Mor, and is part of a continuous moraine sequence charting the recession of an ice-margin that once stretched from Rubha Reidh to Rubha Coigeach (Figures 1, 2d). The moraine morphology and simple stratigraphy within this sequence suggests that the ice margin underwent punctuated stepwise retreat from the open waters of The Minch to the fjords of Loch Broom and Little Loch Broom. (Figures 1, 2f)

The continued eastward retreat of the Summer Isles ice lobe during GI-1 probably resulted in glaciers separating across topographic divides. Further recession and thinning led to a more topographically confined ice mass with outlet glaciers occupying the main valleys: e.g. the Loch Broom trough, Glen Achall, and the Dundonnell Valley (Figure 1). By the YD ice volumes had significantly decreased – possibly in response to precipitation starvation or increased seasonality – with glaciers existing only in the large north- and east-facing corries on An Teallach, and as separate mountain icefields on the high ground around Ben More Assynt and Beinn Dearg (Sissons, 1977; Bradwell, 2006; Finlayson and Bradwell, 2007). Final deglaciation in NW Scotland occurred rapidly at the onset of the Holocene c. 11.7 ka BP.

Figure 3 here [half page b/w]

Discussion

Complete deglaciation of NW Scotland during the Lateglacial Interstadial seems implausible for the following reasons. Well-preserved moraines on the seafloor off Rubha Coigeach and Rubha Reidh (Figure 1), at present-day water depths of up to 100 m, suggest punctuated retreat of a thick coherent ice margin shortly after the Wester Ross Readvance. We find no geomorphological evidence for rapid areal collapse or stagnation of the ice front at the onset of the Lateglacial Interstadial (GI-1e; c. 15 ka BP). The pattern and morphology of the moraine sequence strongly suggests oscillatory retreat of a large ice mass over a substantial period of time. Complete deglaciation of NW Scotland during the brief thermal maximum (GI-1e) followed by a major readvance to the Summer Isles in the Older Dryas (GI-1d) would have required extremely rapid horizontal ice-sheet retreat of ~40 km in as little as one or two centuries followed by ice-cap regrowth and a readvance of c. 30 km in the following 200-300 yrs (i.e. by ~14 ka BP). This version of events would require quite remarkable glacier turnover rates, beyond those currently experienced by even the most dynamic glaciers on Earth (e.g. Paterson, 1994; Dyurgerov, 2002). Furthermore, fossil chironomids from Borrobol, Sutherland, indicate that the thermal maximum between 14.5–15 ka BP was probably very short-lived or subdued in northern Scotland (Mayle *et al.*, 1999). The presence of large glaciers in warm maritime climates today, notably in southern Iceland, Patagonia and New Zealand, clearly illustrate that significant ice masses can survive relatively unharmed during periods of unfavourable warmth, especially if winter precipitation is high or if they possess long response times (e.g. Oerlemans, 1989; Pfeffer *et al.*, 1998). In fact, we suggest that increased glacier melt in warmer air temperatures may have been offset by increased precipitation and changes in seasonality in NW Scotland during the Lateglacial Interstadial. This phenomenon can result in glacial equilibrium being maintained or even glacier advance – as seen recently in several high-turnover glacier regions (e.g. Nesje *et al.*, 1995; Johannesson and Sigurdsson, 2001; Chinn *et al.*, 2005), and is especially pronounced in tidewater glaciers (Bentley *et al.*, 2007). We surmise that glaciers in NW Scotland may have survived between 15–13 ka BP owing to this complex interplay of climatic factors coupled with relatively long glacier-response times. Consequently, we find it highly improbable that ice caps in NW Scotland disappeared during the brief ~600-yr GI-1e period (14.7–14.1 ka BP) only for considerable ice masses to grow anew immediately after (GI-1d; 14.1–13.9 ka BP). A much simpler explanation, strongly supported by our new data, is that active glaciers persisted throughout the entire Lateglacial Interstadial (GI-1) and into the Younger Dryas (GS-1) in NW Scotland.

In the light of our new chronological and geomorphological evidence, we believe that the two well-known Lateglacial age constraints at Cam Loch (Pennington *et al*., 1977) and Loch Droma (Kirk and Godwin, 1963) are probably unreliable. More specifically, we would agree with the initial assertions of Kirk and Godwin (1963) who suggested, based on their own pollen profile, that the Loch Droma conventional ^{14}C date (12,550 ±240 ^{14}C a BP) was erroneously old. Furthermore, we would revise the accepted error estimate of c. 1000 years upwards (cf. Ballantyne and Sutherland, 1987). The core retrieved from Cam Loch (Figure 1) has radiocarbon reversals and discrepancies that cast serious doubt on the published age of the basal unit (12,956 ±240 ^{14}C a BP). These systematic errors can probably be attributed to the presence of calcareous rocks and reworked fossil carbon in the catchment of both lochs (cf. Sutherland, 1980)

Our new cosmogenic-exposure ages confirm the existence of substantial ice caps in NW Scotland during the first half of GI-1. We equate this significant moraine-building phase with the Older Dryas event seen widely elsewhere around the North Atlantic – most notably in western Norway, Iceland and offshore Greenland (e.g. Ingolfsson and Norddahl 1994; Bennike *et al*., 2002; Lohne *et al*., 2007 and references therein). Evidence is mounting to suggest that many glaciers and ice caps worldwide experienced significant glacier fluctuations at around this time (~14 ka BP) – most notably in the Pacific Northwest, Patagonia, New Zealand and the Peruvian Andes (e.g. Clark and Gillespie, 1997; McCulloch *et al*., 2005; Barrows *et al*., 2007; Kelly *et al*., 2007). We suggest that glaciers in northern Scotland were no different. In fact, we propose that dynamically oscillating glaciers may have been characteristic of the Lateglacial Interstadial in NW Europe – possibly as a consequence of rapidly changing temperature and precipitation regimes at the end of the last glaciation.

Conclusions

1. We identify a suite of 40 well-preserved moraines, in the Summer Isles region of NW Scotland, that chart the punctuated retreat of a coherent ice margin from ~10 km offshore to the mountains of Wester Ross. Similar moraines relating to a neighbouring palaeo-ice cap are also identified in Assynt.
2. Cosmogenic ^{10}Be isotope analyses of boulders from two moraines in the Summer Isles region and one moraine in Assynt yield 8 overlapping zero-erosion exposure ages of between 12.9 and 14.1 ka BP (i.e. all within Greenland Interstadial 1).
3. These ice-cap oscillations are the first in the UK to be unequivocally ascribed to the Lateglacial Interstadial (GI-1). Our combined evidence shows that glaciers in northern Scotland were considerably larger in the Older Dryas period than during the subsequent Younger Dryas Stadial. By inference, we suggest that some ice masses in Scotland, as elsewhere in NW Europe, probably survived throughout the entire Lateglacial Interstadial into the Younger Dryas.

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Figure captions

Figure 1: Merged multibeam and hill-shaded NEXTMap surface models showing the topography and bathymetry of the Summer Isles region, NW Scotland. White solid lines are moraines mapped onshore and offshore; dashed white lines are inferred ice-front positions. WRR – Wester Ross Readvance; LLS – Loch Lomond Stadial (YD) limits. Previously dated Late Devensian sites are also shown. Inset map shows location of study area and other sites referred to in the text. Bathymetric data collected by BGS in July 2005 (see Stoker *et al*., 2006 for technical details). Colour bar shows bathymetric depths. NEXTMap data collected by Intermap Technologies, 2005.

Figure 2: (a) Torridonian sandstone boulders sampled on the Sail Mhor moraine, Little Loch Broom. (b) Torridonian sandstone boulders sampled on the Achiltibuie Moraine. (c) Erribol sandstone (quartzite) boulder sampled on a moraine in the Loanan Valley (see Table 1). (d) Multibeam bathymetry of the seafloor in the vicinity of Tanera More, Eilean Dubh and Horse Island showing numerous well-developed recessional moraines with intricate morphologies. 'ACH limit' is equivalent to the Achiltibuie moraine onshore. Colour bar shows bathymetric depths for Figures 2d & 2e. (e) Oblique perspective view of seafloor at the mouth of Little Loch Broom looking northeast, taken from X on Figure 1. De Geer moraine at depths of 40–100 m highlighted with white arrows. S – submarine slumps and failure scars. (f) Seismic profile across seafloor moraines offshore Tanera Mor (along line f on Figure 2d). Note the simple stratigraphy and asymmetric moraine morphology. SBM – Seabed multiple; BT – Bed tracking pulse. For technical details of seismic data collection see Stoker *et al*. (2006).

Figure 3: Zero-erosion ^{10}Be exposure ages from three moraines in NW Scotland plotted against NGRIP ice-core data from 8–16 ka BP. Ice-core stages and age model from INTIMATE group (Lowe *et al*., 2008). Grey shading indicates most probable moraine-building phase, centred around the Older Dryas (GI-1d).

Table 1. Cosmogenic nuclide data.

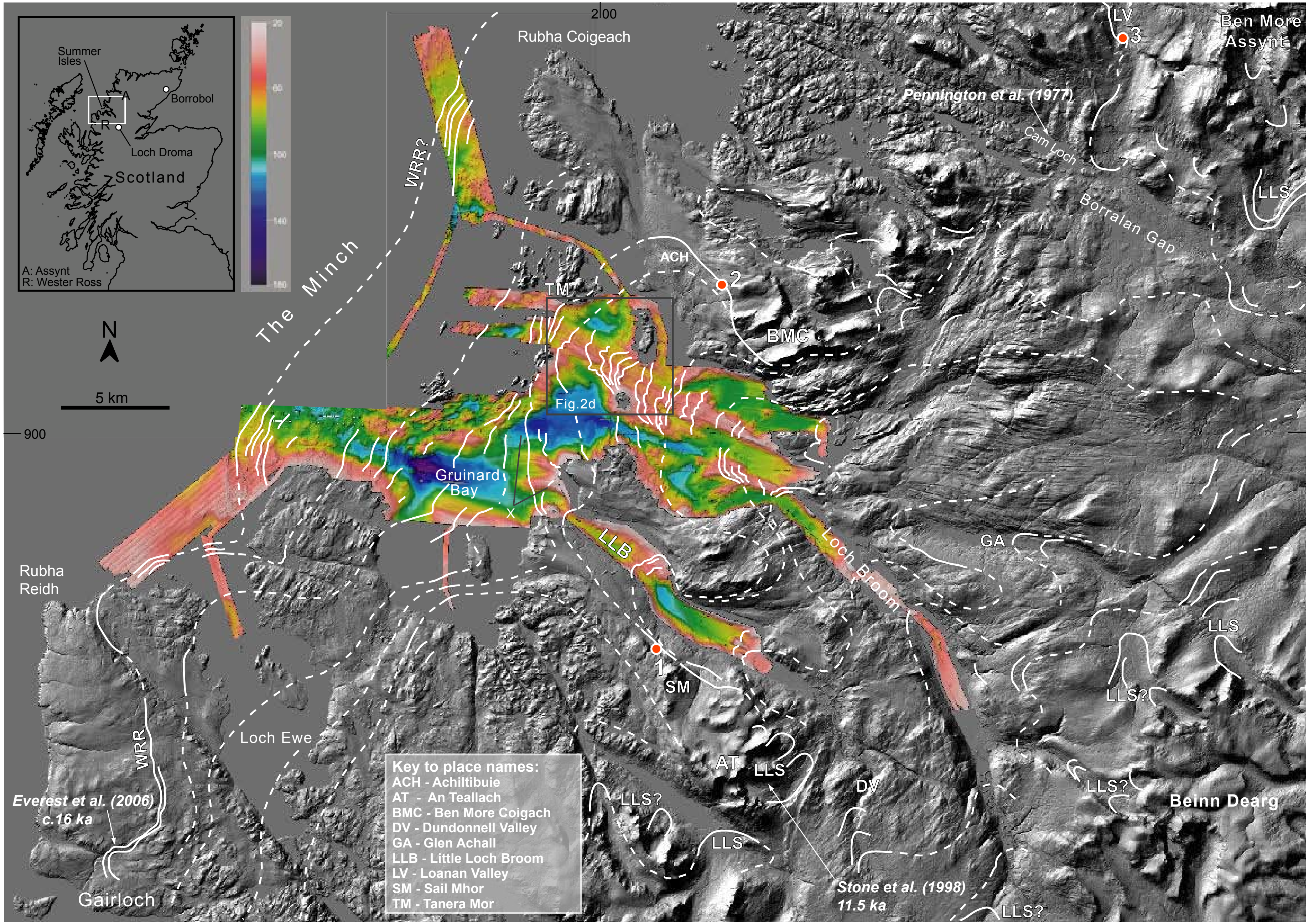
Lab ID	Lat. (N)	Long. (E)	Elevation (m)	Thickness (cm) (scaling factor)*	[10Be] (x 10^4 g^{-1})[#]	Adjusted Exposure Age (ka) [§]
ACH1	58.0127	-5.2914	255	5 (0.959)	8.79±0.50	13.8±1.4 (0.8)
ACH2	58.0127	-5.2915	250	5 (0.959)	8.74±0.49	13.7±1.4 (0.8)
ACH3	58.0133	-5.2925	240	5 (0.959)	8.40±0.54	13.3±1.4 (0.8)
LLB1	57.8562	-5.3236	250	5 (0.959)	8.51±0.69	13.4±1.6 (1.1)
LLB2	57.8570	-5.3261	235	5 (0.959)	6.48±0.37	10.3±1.1 (0.6)
LLB3	57.8576	-5.3279	220	5 (0.959)	4.19±0.36	6.8±0.8 (0.6)
LLB4	57.8604	-5.3338	200	5 (0.959)	8.20±0.64	13.5±1.6 (1.0)
LV0601	58.1239	-4.9812	105	3 (0.975)	7.94±0.40	14.1±1.4 (0.7)
LV0602	58.1239	-4.9812	105	3 (0.975)	7.27±0.40	12.9±1.3 (0.7)
LV0603	58.1239	-4.9812	105	4 (0.967)	7.56±0.36	13.6±1.3 (0.6)

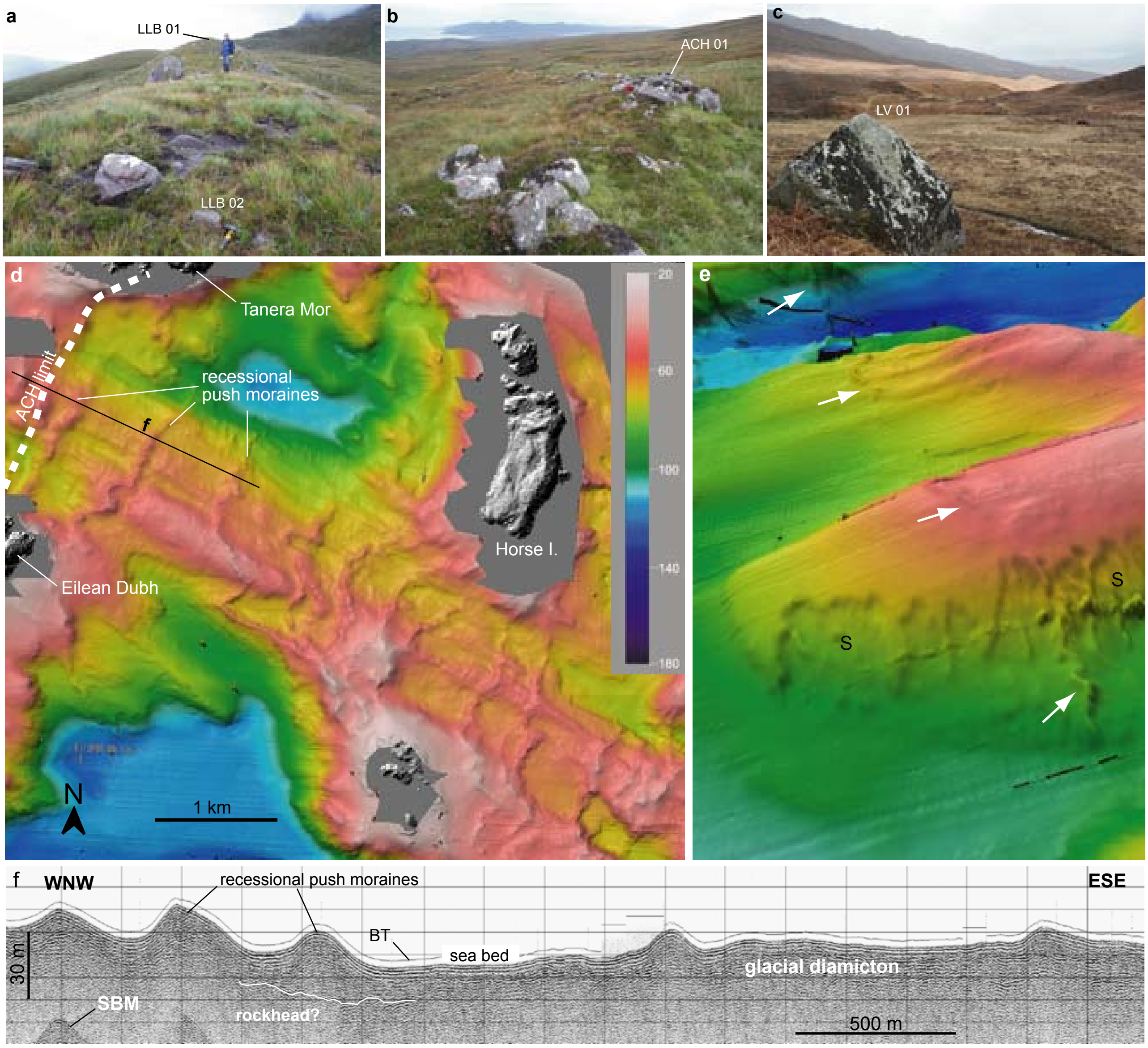
Topographic and geometric shielding factor was <0.5% for all samples

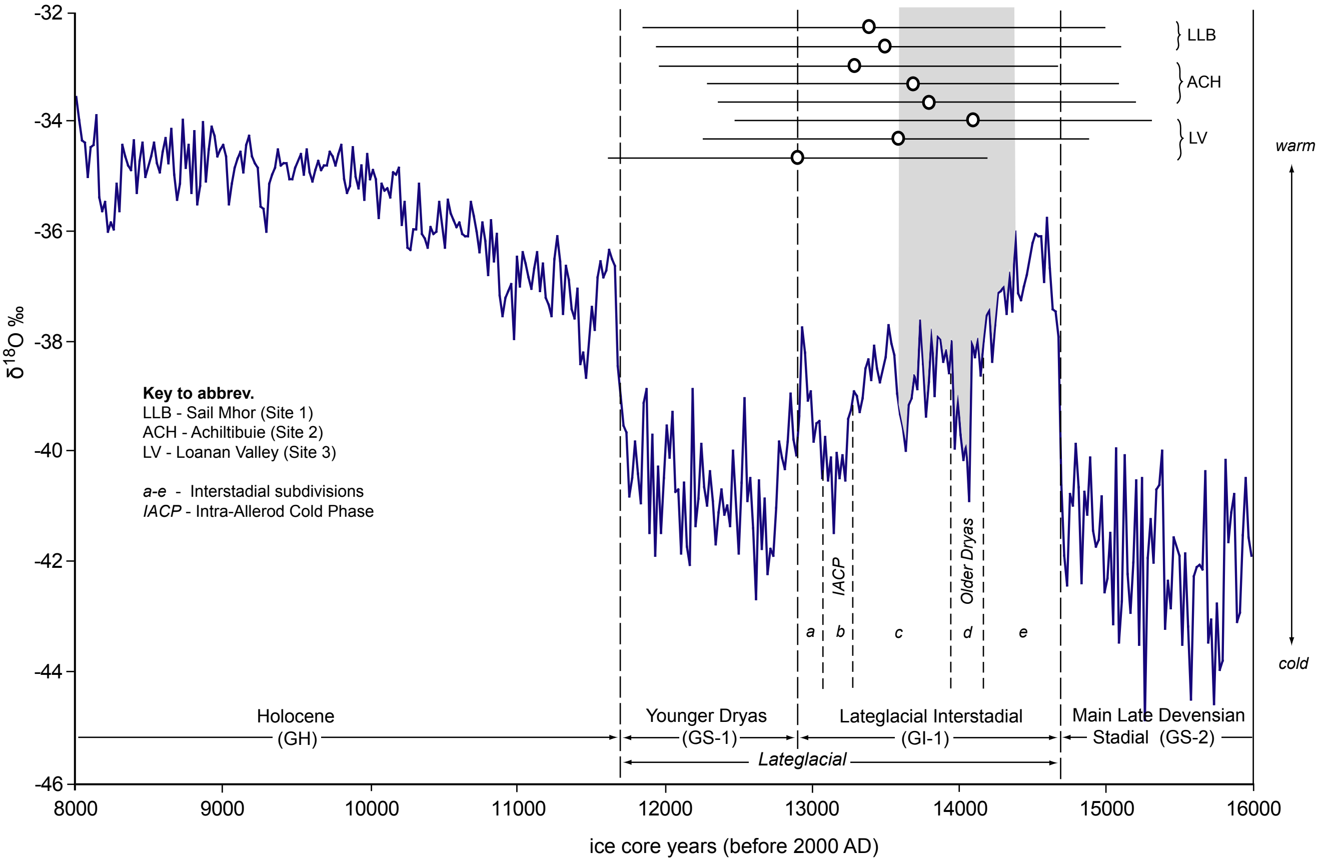
* Calculated using 160 g cm^{-2} for the effective attenuation length for high energy spallation and a rock density of 2.7 g cm^{-3}.

[#] Data relative to NIST SRM 4325 taking $^{10}Be/^{9}Be = 3.06 \times 10^{-11}$ (Middleton *et al.*, 1993). Procedural ^{10}Be blanks < 4.7 x 10^4 atoms ($^{10}Be/^{9}Be < 4 \times 10^{-15}$).

[§] Calculated using CRONUS-Earth ^{10}Be-^{26}Al exposure age calculator (Version 2) assuming zero erosion and adjusted for variations in palaeomagnetic field strength - the ‘Lm’ scaling scheme in the CRONUS-Earth exposure age calculator. The calculator and associated documentation including production rate parameters can be found at http://hess.ess.washington.edu/math. Uncertainties include production rate uncertainty and AMS measurement uncertainty. Uncertainties in brackets include analytical uncertainties only.


Summer Isles
A
R
Borrobol
Loch Droma
Scotland
A: Assynt
R: Wester Ross
20
60
100
140
180
N
5 km
900
200
Rubha Coigeach
The Minch
WRR?
TM
Fig.2d
ACH
2
BMC
LV
3
Ben More Assynt
Pennington et al. (1977)
Cam Loch
Borralan Gap
LLS
Gruinard Bay
X
LLB
Loch Broom
GA
LLS
LLS?
1
SM
Rubha Reidh
Loch Ewe
WRR
Everest et al. (2006) c.16 ka
Gairloch
AT
LLS
DV
LLS?
LLS
LLS?
Beinn Dearg
Stone et al. (1998) 11.5 ka
LLS?
Key to place names:
ACH - Achiltibuie
AT - An Teallach
BMC - Ben More Coigach
DV - Dundonnell Valley
GA - Glen Achall
LLB - Little Loch Broom
LV - Loanan Valley
SM - Sail Mhor
TM - Tanera Mor


a
LLB 01
LLB 02
b
ACH 01
c
LV 01
d
Tanera Mor
ACH limit
recessional push moraines
f
Horse I.
Eilean Dubh
N
1 km
20
60
100
140
180
e
S
S
f
WNW
ESE
recessional push moraines
BT
sea bed
30 m
SBM
rockhead?
glacial diamicton
500 m


δ18O ‰
-32
-34
-36
-38
-40
-42
-44
-46
8000
9000
10000
11000
12000
13000
14000
15000
16000
ice core years (before 2000 AD)
LLB
ACH
LV
warm
cold
Key to abbrev.
LLB - Sail Mhor (Site 1)
ACH - Achiltibuie (Site 2)
LV - Loanan Valley (Site 3)
a-e - Interstadial subdivisions
IACP - Intra-Allerod Cold Phase
IACP
Older Dryas
a
b
c
d
e
Holocene
(GH)
Younger Dryas
(GS-1)
Lateglacial Interstadial
(GI-1)
Main Late Devensian
Stadial (GS-2)
Lateglacial