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3 **Ice caps existed throughout the Lateglacial Interstadial in**  
4 **northern Scotland**

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20  
21 **Abstract**

22  
23 We constrain, in detail, fluctuations of two former ice caps in NW Scotland with  
24 multibeam seabed surveys, geomorphological mapping and cosmogenic <sup>10</sup>Be isotope  
25 analyses. We map a continuous sequence of 40 recessional moraines stretching from  
26 ~10 km offshore to the Wester Ross mountains. Surface-exposure ages from boulders  
27 on moraine ridges in Assynt and the Summer Isles region show that substantial,  
28 dynamic, ice caps existed in NW Scotland between 13–14 ka BP. We interpret this as  
29 strong evidence that large active glaciers probably survived throughout the Lateglacial  
30 Interstadial, and that during the Older Dryas period (c.14 ka BP) ice caps in NW  
31 Scotland were thicker and considerably more extensive than in the subsequent  
32 Younger Dryas Stadial. By inference, we suggest that Lateglacial ice-cap oscillations  
33 in Scotland reflect the complex interplay between changing temperature and  
34 precipitation regimes during this climatically unstable period (~15–11 ka BP).

35  
36 *150 words*

37  
38  
39 **Key words:** *Older Dryas, moraines, cosmogenic dating, multibeam bathymetry*

1 **Introduction**

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

20

21 Recently, cosmogenic-exposure ages on glacially transported boulders and ice-worn  
22 bedrock have yielded dates that sit uneasily with models of complete Scottish  
23 deglaciation by the onset of GI-1. Everest and Kubik (2006), Stone and Ballantyne  
24 (2006) and Golledge *et al.* (2007) have all reported uncorrected <sup>10</sup>Be exposure ages  
25 that fall within the period ~13–15 ka BP. The question remains, therefore: Did  
26 significant ice volumes persist into the Lateglacial Interstadial? And did any glaciers  
27 in Scotland remain active throughout this period and into the Younger Dryas?

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

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## 1 **Study Site and Methods**

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

15  
16 We used multibeam Geoswath imagery, boomer seismic profiles, colour stereoscopic  
17 aerial photographs and NEXTMap digital surface models, combined with detailed  
18 geological field surveys to map the onshore and offshore glacial geomorphology of  
19 the Summer Isles region of NW Scotland. As part of a wider geochronological  
20 investigation, we sampled 10 glacially transported boulders on 3 moraine systems for  
21 surface-exposure dating using  $^{10}\text{Be}$  in quartz (Figures 1, 2). Site 1 is a large steep-  
22 sided moraine running for 800 m along the side of Sail Mhor, the northwest spur of  
23 An Teallach (Figure 1). This lateral moraine formed at the margin of a large ice mass  
24 that once filled Little Loch Broom to a height of at least 200 m asl. Three Torridonian  
25 sandstone boulders and one Eriboll sandstone (quartzite) boulder were sampled for  
26 cosmogenic analysis from the crest of the moraine (Figure 2a). Site 2 is a small yet  
27 pronounced moraine ridge surrounded by a wide expanse of boulder-strewn ground  
28 adjacent to the western flank of Ben More Coigach, near Achiltibuie (Figure 1). This  
29 latero-frontal moraine complex occurs at a similar height (200 m asl) to the Sail Mhor  
30 moraine. Three Torridonian sandstone boulders were sampled from the crest of the  
31 moraine ridge (Figure 2b). Site 3 is a small moraine ridge, part of a larger assemblage  
32 of morainic mounds and ridges in the Loanan Valley in Assynt (Figure 1). These  
33 moraines are recessional features deposited by a former ice cap sourced on the Assynt  
34 mountains to the east (Bradwell, 2006). Three large Eriboll sandstone (quartzite)

1 boulders were sampled for cosmogenic analysis from a single ridge crest (Figure 2c).  
2 Samples were processed at the University of Glasgow's Centre for Geosciences  
3 cosmogenic isotope laboratory using methods adapted from Kohl and Nishiizumi  
4 (1992), Ditchburn and Whitehead (1994) and Child *et al.* (2000). Beryllium ratios  
5 were determined at the Scottish Universities Environmental Research Centre  
6 (SUERC) AMS facility.

7

8 **Figure 1 here [Whole page landscape; colour]**

9

10 **Results**

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

21

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

32

33 **Table 1 here**

34

1 **Figure 2 here [half page; colour]**

2

### 3 **Reconstruction of glacial events**

4 Previously published cosmogenic-exposure ages in the Summer Isles region of NW  
5 Scotland have helped to bracket the rate and timing of Lateglacial deglaciation. Three  
6 glacially transported boulders on a well-defined ice-sheet moraine crossing the  
7 Gairloch peninsula (Figure 1) yielded exposure ages suggesting deposition c. 16 ka  
8 BP (Everest *et al.*, 2006). Three bedrock samples from the plucked surfaces within the  
9 large east-facing corrie on An Teallach yielded  $^{10}\text{Be}$  isotope accumulations consistent  
10 with exposure at the end of the YD ( $\sim 11.5 \pm 0.5$  ka) (Stone *et al.*, 1998). Our ten new  
11  $^{10}\text{Be}$  exposure ages from three moraine systems provide refined temporal constraints  
12 on intervening glacier oscillations in this part of NW Scotland.

13

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

25

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

1 deglaciation in NW Scotland occurred rapidly at the onset of the Holocene c. 11.7 ka  
2 BP.

3

4 **Figure 3 here [half page b/w]**

5

6 **Discussion**

7 Complete deglaciation of NW Scotland during the Lateglacial Interstadial seems  
8 implausible for the following reasons. Well-preserved moraines on the seafloor off  
9 Rubha Coigeach and Rubha Reidh (Figure 1), at present-day water depths of up to  
10 100 m, suggest punctuated retreat of a thick coherent ice margin shortly after the  
11 Wester Ross Readvance. We find no geomorphological evidence for rapid areal  
12 collapse or stagnation of the ice front at the onset of the Lateglacial Interstadial (GI-  
13 1e; c. 15 ka BP). The pattern and morphology of the moraine sequence strongly  
14 suggests oscillatory retreat of a large ice mass over a substantial period of time.  
15 Complete deglaciation of NW Scotland during the brief thermal maximum (GI-1e)  
16 followed by a major readvance to the Summer Isles in the Older Dryas (GI-1d) would  
17 have required extremely rapid horizontal ice-sheet retreat of ~40 km in as little as one  
18 or two centuries followed by ice-cap regrowth and a readvance of c. 30 km in the  
19 following 200-300 yrs (i.e. by ~14 ka BP). This version of events would require quite  
20 remarkable glacier turnover rates, beyond those currently experienced by even the  
21 most dynamic glaciers on Earth (e.g. Paterson, 1994; Dyurgerov, 2002). Furthermore,  
22 fossil chironomids from Borrobol, Sutherland, indicate that the thermal maximum  
23 between 14.5–15 ka BP was probably very short-lived or subdued in northern  
24 Scotland (Mayle *et al.*, 1999). The presence of large glaciers in warm maritime  
25 climates today, notably in southern Iceland, Patagonia and New Zealand, clearly  
26 illustrate that significant ice masses can survive relatively unharmed during periods of  
27 unfavourable warmth, especially if winter precipitation is high or if they possess long  
28 response times (e.g. Oerlemans, 1989; Pfeffer *et al.*, 1998). In fact, we suggest that  
29 increased glacier melt in warmer air temperatures may have been offset by increased  
30 precipitation and changes in seasonality in NW Scotland during the Lateglacial  
31 Interstadial. This phenomenon can result in glacial equilibrium being maintained or  
32 even glacier advance – as seen recently in several high-turnover glacier regions (e.g.  
33 Nesje *et al.*, 1995; Johannesson and Sigurdsson, 2001; Chinn *et al.*, 2005), and is  
34 especially pronounced in tidewater glaciers (Bentley *et al.*, 2007). We surmise that

1 glaciers in NW Scotland may have survived between 15–13 ka BP owing to this  
2 complex interplay of climatic factors coupled with relatively long glacier-response  
3 times. Consequently, we find it highly improbable that ice caps in NW Scotland  
4 disappeared during the brief ~600-yr GI-1e period (14.7–14.1 ka BP) only for  
5 considerable ice masses to grow anew immediately after (GI-1d; 14.1–13.9 ka BP). A  
6 much simpler explanation, strongly supported by our new data, is that active glaciers  
7 persisted throughout the entire Lateglacial Interstadial (GI-1) and into the Younger  
8 Dryas (GS-1) in NW Scotland.

9  
10 In the light of our new chronological and geomorphological evidence, we believe that  
11 the two well-known Lateglacial age constraints at Cam Loch (Pennington *et al.*, 1977)  
12 and Loch Droma (Kirk and Godwin, 1963) are probably unreliable. More specifically,  
13 we would agree with the initial assertions of Kirk and Godwin (1963) who suggested,  
14 based on their own pollen profile, that the Loch Droma conventional  $^{14}\text{C}$  date ( $12,550$   
15  $\pm 240$   $^{14}\text{C}$  a BP) was erroneously old. Furthermore, we would revise the accepted error  
16 estimate of c. 1000 years upwards (cf. Ballantyne and Sutherland, 1987). The core  
17 retrieved from Cam Loch (Figure 1) has radiocarbon reversals and discrepancies that  
18 cast serious doubt on the published age of the basal unit ( $12,956 \pm 240$   $^{14}\text{C}$  a BP).  
19 These systematic errors can probably be attributed to the presence of calcareous rocks  
20 and reworked fossil carbon in the catchment of both lochs (cf. Sutherland, 1980)

21  
22 Our new cosmogenic-exposure ages confirm the existence of substantial ice caps in  
23 NW Scotland during the first half of GI-1. We equate this significant moraine-  
24 building phase with the Older Dryas event seen widely elsewhere around the North  
25 Atlantic – most notably in western Norway, Iceland and offshore Greenland (e.g.  
26 Ingolfsson and Norddahl 1994; Bennike *et al.*, 2002; Lohne *et al.*, 2007 and  
27 references therein). Evidence is mounting to suggest that many glaciers and ice caps  
28 worldwide experienced significant glacier fluctuations at around this time (~14 ka BP)  
29 – most notably in the Pacific Northwest, Patagonia, New Zealand and the Peruvian  
30 Andes (e.g. Clark and Gillespie, 1997; McCulloch *et al.*, 2005; Barrows *et al.*, 2007;  
31 Kelly *et al.*, 2007). We suggest that glaciers in northern Scotland were no different. In  
32 fact, we propose that dynamically oscillating glaciers may have been characteristic of  
33 the Lateglacial Interstadial in NW Europe – possibly as a consequence of rapidly  
34 changing temperature and precipitation regimes at the end of the last glaciation.

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**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 <sup>10</sup>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.

**Acknowledgements**

The authors would like to thank the crew of *R/V Calanus* for their help during the cruise of July 2005. Nick Golledge and Andrew Finlayson are thanked for their helpful comments on an earlier version of this manuscript. John Lowe and David Sugden provided constructive reviews which improved this paper. Martin Smith, Bob Gatliff and Stuart Freeman are thanked for their continued support of this project. Published with the permission of the Executive Director, BGS (NERC).

## 1 **References**

2  
3 Ballantyne CK. 1989. The Loch Lomond Advance on the Isle of Skye, Scotland:  
4 glacier reconstruction and palaeoclimatic implications. *Journal of Quaternary Science*  
5 **4**: 95-108.

6  
7 Ballantyne CK. 2007. The Loch Lomond Readvance on north Arran, Scotland: glacier  
8 reconstruction and palaeoclimatic implications. *Journal of Quaternary Science* **22**:  
9 343-359.

10  
11 Ballantyne CK, Sutherland DG. 1987. *Wester Ross Field Guide*. Quaternary Research  
12 Association, Cambridge.

13  
14 Barrows TT, Lehman SJ, Fifield LK, De Deckker P. 2007. Absence of cooling in New  
15 Zealand and the adjacent ocean during the Younger Dryas chronozone. *Science* **318**  
16 (5847): 86-89.

17  
18 Benn DI, Lukas S. 2006. Younger Dryas glacial landsystems in North West Scotland:  
19 an assessment of modern analogues and palaeoclimatic implications. *Quaternary*  
20 *Science Reviews* **25**: 2390-2408.

21  
22 Bennett MR, Boulton GS. 1993. Deglaciation of the Younger Dryas or Loch Lomond  
23 Stadial ice-field in the northern Highlands, Scotland. *Journal of Quaternary Science*  
24 **8**: 133-145.

25  
26 Bennike O, Bjork S, Lambeck K. 2002. Estimates of south Greenland lateglacial ice  
27 limits from a new relative sea-level curve. *Earth and Planetary Science Letters* **197**:  
28 171-186.

29  
30 Bentley MJ, Evans DJA, Fogwill CJ, Hansom JD, Sugden DE, Kubik PW. 2007.  
31 Glacial geomorphology and chronology of deglaciation, South Georgia, sub-  
32 Antarctic. *Quaternary Science Reviews* **26**: 644-677.

33  
34 Bowen DQ, Rose J, McCabe AM, Sutherland DG. 1986. Correlation of Quaternary  
35 glaciations in England, Ireland, Scotland and Wales. *Quaternary Science Reviews* **4**:  
36 299-340.

37  
38 Boulton GS. 1986. Push moraines and glacier-contact fans in marine and terrestrial  
39 environments. *Sedimentology* **33**: 677-698.

40  
41 Bradwell T. 2006. The Loch Lomond Stadial Glaciation in Assynt: a reappraisal.  
42 *Scottish Geographical Journal* **122**: 274-292.

43  
44 Bradwell T, Stoker MS, Larter RD. 2007. Geomorphological signature and flow  
45 dynamics of The Minch palaeo-ice stream, NW Scotland. *Journal of Quaternary*  
46 *Science* **22**: 609-617.

47  
48 Bradwell T, Stoker MS, Krabbendam M. 2008. Megagrooves and streamlined  
49 bedrock: the role of ice streams in landscape evolution. *Geomorphology*  
50 doi:10.1016/j.geomorph.2007.02.040

- 1  
2 Child D, Elliott G, Mifsud C, Smith AM, Fink D, 2000. Sample processing for earth  
3 science studies at ANTARES. *Nuclear Instruments & Methods in Physics Research*  
4 *Section B- Beam Interactions with Materials and Atoms* **172**: 856-860.  
5  
6 Chinn T, Winkler S, Salinger MJ, Haakensen N, 2005. Recent glacier advances in  
7 Norway and New Zealand: a comparison of their glaciological and meteorological  
8 causes. *Geografiska Annaler* **87A**: 141–157.  
9  
10 Clark DH, Gillespie AR, 1997. Timing and significance of late-glacial and Holocene  
11 cirque glaciation in the Sierra Nevada, USA. *Quaternary International* **38/39**: 21-38.  
12  
13 Clapperton CM. 1997. Greenland ice cores and North Atlantic sediments: implications  
14 for the last glaciation in Scotland. In *Reflections on the Ice Age in Scotland: An*  
15 *Update on Quaternary Studies*, Gordon JE (ed.). Scottish Association of Geography  
16 Teachers and Scottish Natural Heritage Glasgow: 45–58.  
17  
18 Ditchburn RG, Whitehead NE. 1994. The separation of  $^{10}\text{Be}$  from silicates. *3rd*  
19 *Workshop of the South Pacific Environmental Radioactivity Association*, 4-7.  
20  
21 Dyurgerov M. 2002. *Glacier Mass Balance and Regime: Data of Measurements and*  
22 *Analysis*. INSTAAR Occasional Paper No. 55. Meier M, Armstrong R (ed.). Institute  
23 of Arctic and Alpine Research, University of Colorado, Boulder, Colorado.  
24  
25 Everest JD, Kubik PW. 2006. The deglaciation of eastern Scotland: cosmogenic  $^{10}\text{Be}$   
26 evidence for a Lateglacial stillstand. *Journal of Quaternary Science* **21**: 95-104  
27  
28 Everest JD, Bradwell T, Fogwill CJ, Kubik, PW. 2006. Cosmogenic  $^{10}\text{Be}$  age  
29 constraints for the Wester Ross Readvance Moraine: insights into British Ice Sheet  
30 behaviour. *Geografisker Annaler* **88A**: 9-18.  
31  
32 Finlayson AG, Bradwell T. 2007. Evidence for Loch Lomond Stadial ice cap  
33 glaciation of the Beinn Dearg massif, northern Scotland. *Quaternary Newsletter* **113**:  
34 10-17.  
35  
36 Golledge NR. 2007. An ice-cap landsystem for palaeoglaciological reconstructions:  
37 characterizing the Younger Dryas in western Scotland. *Quaternary Science Reviews*  
38 **26**: 213-229  
39  
40 Golledge NR, Fabel D, Everest JD, Freeman S, Binnie S. 2007. First cosmogenic  $^{10}\text{Be}$   
41 age constraint on the timing of Younger Dryas glaciation and ice cap thickness,  
42 western Scottish Highlands. *Journal of Quaternary Science* **22**: 785-791.  
43  
44 Kelly M, Lowell T, Schaefer J, 2007. A comparison of late Pleistocene and Holocene  
45 glacier fluctuations in high and low latitudes based on  $^{10}\text{Be}$  dates and  $^{14}\text{C}$  dates of  
46 moraines in Greenland and Peru. *Quaternary International* **167/168**: Abstract 0876.  
47  
48 Kirk W, Godwin H. 1963. A lateglacial site at Loch Droma, Ross and Cromarty,  
49 *Transactions Royal Society Edinburgh* **65**: 225-248.  
50

- 1 Kohl CP, Nishiizumi K. 1992. Chemical isolation of quartz for measurement of in-situ-produced cosmogenic nuclides. *Geochimica et Cosmochimica Acta* **56**: 3583–  
2 3587.  
3  
4
- 5 Ingolfsson, O, Norddahl, H. 1994. A review of the environmental history of Iceland,  
6 13000-9000 yr BP. *Journal of Quaternary Science* **9**: 147-150.  
7
- 8 Jóhannesson T, Sigurðsson O. 1998 Interpretation of glacier variations in Iceland  
9 1930-1995. *Jökull* **45**: 27-33.  
10
- 11 Lowe JJ, Ammann B, Birks, HH, Bjorck S, Coope GR, Cwynar L, de Beaulieu, JL  
12 Mott RJ, Peteet DM, Walker MJC. 1994. Climatic changes in areas adjacent to the  
13 North Atlantic during the last glacial-interglacial transition (14-9 ka BP): a  
14 contribution to IGCP-253. *Journal of Quaternary Science* **9**: 185-198.  
15
- 16 Lowe JJ, Rasmussen SO, Bjorck S, Hoek WZ, Steffensen JP, Walker MJC, Yu Z,  
17 INTIMATE group. 2008. Synchronisation of palaeoenvironmental events in the North  
18 Atlantic region during the Last Termination: a revised protocol recommended by the  
19 INTIMATE group. *Quaternary Science Reviews*, doi:10.1016/j.quascirev.2007.09.016  
20
- 21 Lohne OS, Bondevik S, Mangerud J, Svendsen JI. 2007. Sea-level fluctuations imply  
22 that the Younger Dryas ice-sheet expansion in western Norway commenced during  
23 the Allerød. *Quaternary Science Reviews* **26**: 2128-2151.  
24
- 25 McCulloch RD, Fogwill CJ, Sugden DE, Bentley MJ, Kubik PW. 2005. Chronology  
26 of the last glaciation in central Strait of Magellan and Bahía Inútil, southernmost  
27 South America. *Geografiska Annaler* **87A**: 289–312.  
28
- 29 Mayle FE, Bell M, Birks HH, Brooks J, Coope GR, Lowe JJ, Sheldrick C, Shijie L,  
30 Turney CSM, Walker MJC. 1999. Climate variations in Britain, during the last  
31 Glacial-Holocene transition (15-11.5 cal ka BP): comparison with the GRIP ice-core  
32 record. *Journal of the Geological Society, London* **156**: 411-423.  
33
- 34 Middleton R, Brown L, Dezfouly-Arjomandy B, Klein J, 1993. On <sup>10</sup>Be standards and  
35 the half-life of <sup>10</sup>Be. *Nuclear Instruments & Methods in Physics Research B* **82**: 399-  
36 403.  
37
- 38 Nesje A, Johannessen T, Birks HJB. 1995. Briksdalsbreen, western Norway: climatic  
39 effects on the terminal response of a temperate glacier between AD 1901 and 1994.  
40 *The Holocene* **5**: 343-347.  
41
- 42 Oerlemans J. 1989. On the response of valley glaciers to climatic change. In: *Glacier*  
43 *Fluctuations and Climatic Change*. Oerlemans, J. (ed.) Kluwer Academic Publishers,  
44 Dordrecht: 353-372.  
45
- 46 Paterson WSB, 1994. *The Physics of Glaciers*. 3<sup>rd</sup> Edition. Pergamon, Oxford.  
47
- 48 Pennington W. 1977. Lake sediments and the Lateglacial environment in Northern  
49 Scotland. In *Studies in the Scottish Lateglacial Environment*. Gray JM, Lowe JJ,  
50 (eds.) Oxford, Pergamon: 119-143.

1  
2 Pfeffer WT, Sassolas C, Bahr DB, Meier MF, 1998. Response time of glaciers as a  
3 function of size and mass balance. 2. Numerical experiments. *Journal of Geophysical*  
4 *Research* **103**: 9783–9789.  
5  
6 Robinson M, Ballantyne CK. 1979. Evidence for a glacial advance predating the Loch  
7 Lomond Advance in Wester Ross. *Scottish Journal of Geology* **15**: 271-277.  
8  
9 Sissons JB. 1967. *The Evolution of Scotland's Scenery*. Oliver & Boyd, Edinburgh.  
10  
11 Sissons, JB, 1977. The Loch Lomond Readvance in the northern mainland of  
12 Scotland. In: *Studies in the Scottish Lateglacial Environment*. Gray JM, Lowe JJ  
13 (eds.) Oxford, Pergamon: 45-59.  
14  
15 Sissons JB. 1979. The Loch Lomond Stadial in the British Isles. *Nature* **280**: 199-203.  
16  
17 Stoker MS, Bradwell T, Wilson C, Harper C, Smith D, Brett C, 2006. Pristine fjord  
18 landsystem revealed on the seabed in the Summer Isles region, NW Scotland, *Scottish*  
19 *Journal of Geology* **42**: 89-99.  
20  
21 Stone JO, Ballantyne CK. 2006. Dimensions and deglacial chronology of the Outer  
22 Hebrides Ice Cap, northwest Scotland: implications of cosmic-ray exposure dating,  
23 *Journal of Quaternary Science* **21**: 75-84.  
24  
25 Stone JO, Ballantyne CK, Fifield LK. 1998. Exposure dating and validation of  
26 periglacial weathering limits, northwest Scotland. *Geology* **26**: 587-590.  
27  
28 Sugden DE. 1980. The Loch Lomond Advance in the Cairngorms (a reply to  
29 J.B.Sissons) *Scottish Geographical Magazine* **96**: 18-19.  
30  
31 Sutherland DG. 1980. Problems of dating deposits from newly deglaciated terrain. In  
32 *Studies in the Lateglacial of North-west Europe*, Lowe JJ, Gray JM, Robinson JE  
33 (eds.) Oxford, Pergamon: 31-43.  
34  
35 Sutherland DG. 1984. The Quaternary deposits and landforms of Scotland and the  
36 neighbouring shelves: a review. *Quaternary Science Reviews* **3**: 157-254.  
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2 **Figure captions**

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4 Figure 1: Merged multibeam and hill-shaded NEXTMap surface models  
5 showing the topography and bathymetry of the Summer Isles region, NW Scotland.  
6 White solid lines are moraines mapped onshore and offshore; dashed white lines are  
7 inferred ice-front positions. WRR – Wester Ross Readvance; LLS – Loch Lomond  
8 Stadial (YD) limits. Previously dated Late Devensian sites are also shown. Inset map  
9 shows location of study area and other sites referred to in the text. Bathymetric data  
10 collected by BGS in July 2005 (see Stoker *et al.*, 2006 for technical details). Colour  
11 bar shows bathymetric depths. NEXTMap data collected by Intermap Technologies,  
12 2005.

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14 Figure 2: (a) Torridonian sandstone boulders sampled on the Sail Mhor moraine,  
15 Little Loch Broom. (b) Torridonian sandstone boulders sampled on the Achiltibuie  
16 Moraine. (c) Erribol sandstone (quartzite) boulder sampled on a moraine in the  
17 Loanan Valley (see Table 1). (d) Multibeam bathymetry of the seafloor in the vicinity  
18 of Tanera More, Eilean Dubh and Horse Island showing numerous well-developed  
19 recessional moraines with intricate morphologies. ‘ACH limit’ is equivalent to the  
20 Achiltibuie moraine onshore. Colour bar shows bathymetric depths for Figures 2d &  
21 2e. (e) Oblique perspective view of seafloor at the mouth of Little Loch Broom  
22 looking northeast, taken from X on Figure 1. De Geer moraine at depths of 40–100 m  
23 highlighted with white arrows. S – submarine slumps and failure scars. (f) Seismic  
24 profile across seafloor moraines offshore Tanera Mor (along line f on Figure 2d).  
25 Note the simple stratigraphy and asymmetric moraine morphology. SBM – Seabed  
26 multiple; BT – Bed tracking pulse. For technical details of seismic data collection see  
27 Stoker *et al.* (2006).

28  
29 Figure 3: Zero-erosion  $^{10}\text{Be}$  exposure ages from three moraines in NW Scotland  
30 plotted against NGRIP ice-core data from 8–16 ka BP. Ice-core stages and age model  
31 from INTIMATE group (Lowe *et al.*, 2008). Grey shading indicates most probable  
32 moraine-building phase, centred around the Older Dryas (GI-1d).  
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Table 1. Cosmogenic nuclide data.

Lab ID	Lat. (N)	Long. (E)	Elevation (m)	Thickness (cm) (scaling factor)*	[ <sup>10</sup> Be] (x 10 <sup>4</sup> g <sup>-1</sup> )#	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)

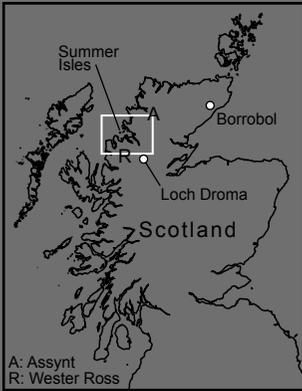
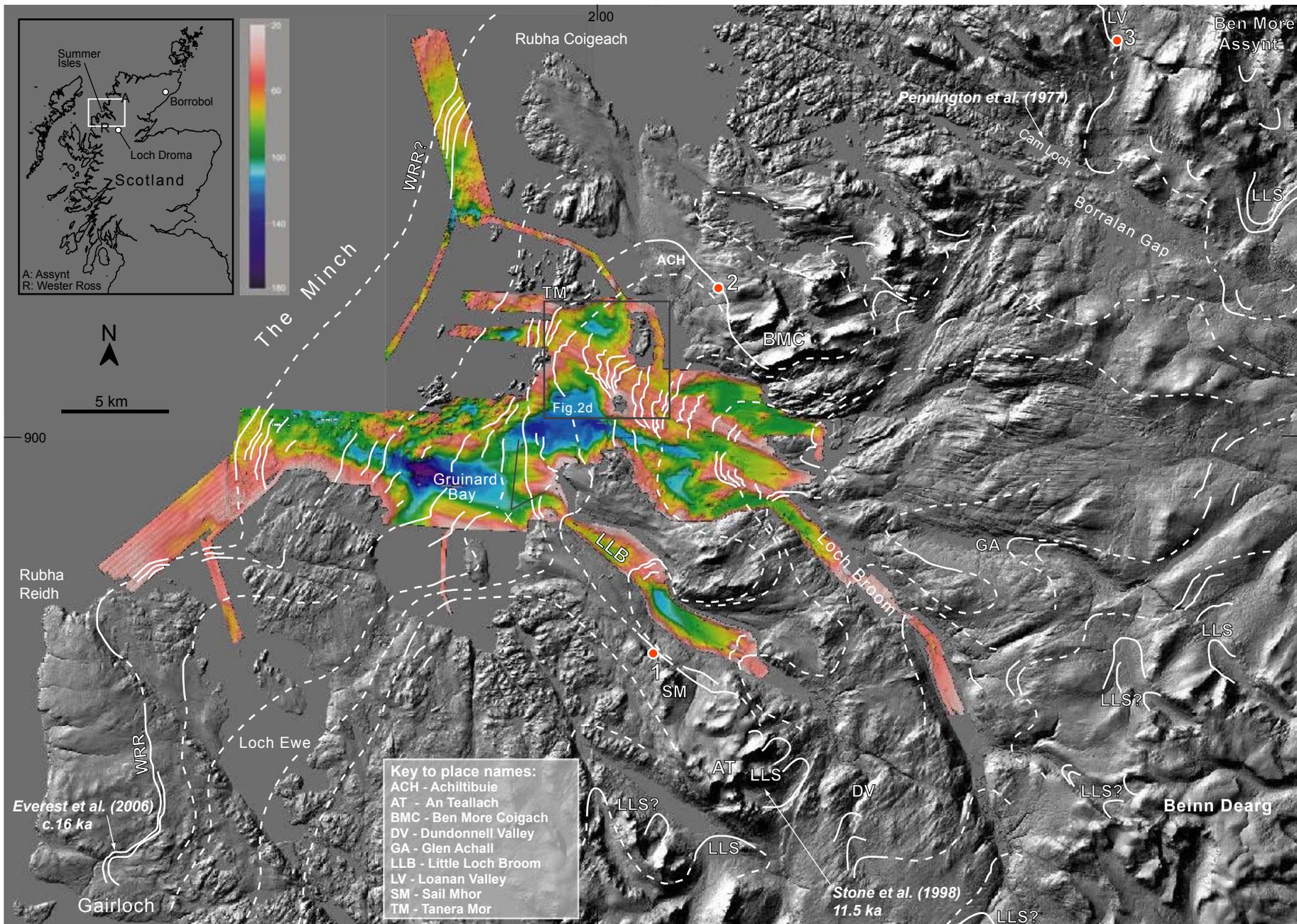
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Topographic and geometric shielding factor was <0.5% for all samples

\* Calculated using 160 g cm<sup>-2</sup> for the effective attenuation length for high energy spallation and a rock density of 2.7 g cm<sup>-3</sup>.

# Data relative to NIST SRM 4325 taking <sup>10</sup>Be/<sup>9</sup>Be = 3.06 x 10<sup>-11</sup> (Middleton *et al.*, 1993). Procedural <sup>10</sup>Be blanks < 4.7 x 10<sup>4</sup> atoms (<sup>10</sup>Be/<sup>9</sup>Be < 4 x 10<sup>-15</sup>).

§ Calculated using CRONUS-Earth <sup>10</sup>Be-<sup>26</sup>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.



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**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

Everest et al. (2006)  
 c. 16 ka

Stone et al. (1998)  
 11.5 ka

Fig. 2d

2100  
 Rubha Coigeach

Ben More  
 Assynt

Pennington et al. (1977)

Rubha  
 Reidh

Loch Ewe

Gruinard  
 Bay

1  
 SM

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 ACH

3  
 LV

BMC

GA

LLS?

AT

LLS

DV

LLS?

Beinn Dearg

LLS

LLS?

LLS

Borrailan Gap

Cam Loch

LLB

Loch Broom

WRR?

The Minch

