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Late Quaternary glaciation in the Hebrides sector of the continental shelf: cosmogenic nuclide dating of glacial events on the St Kilda archipelago

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The St Kilda archipelago lies ~65 km west of the Outer Hebrides and ~60 km east of the Atlantic shelf break, and represents a key site for testing the assertion that during the Last Local Glacial Maximum (LLGM; *c.* 27 ka) the British–Irish Ice Sheet (BIIS) extended to near the shelf edge in all sectors. Two consistent cosmogenic ^{36}Cl exposure ages averaging (≥) 81.6±7.8 ka for perched boulders at 290 m altitude demonstrate that the last ice sheet failed to overrun high ground on the largest island, Hirta. ^{36}Cl and ^{10}Be exposure ages for glacially emplaced boulders on low ground indicate deposition by small, locally nourished glaciers that last occupied a north-facing valley (Gleann Mòr) at *c.* 30.9±3.2 ka, prior to extension of the last ice sheet to the outer shelf, and a south-facing valley (Village Bay) at *c.* 19.2±2.3 ka, several millennia after the LLGM. Our dating evidence is consistent with previous interpretations of lithostratigraphical, seismostratigraphical and geomorphological evidence and confirms that the last ice sheet failed to encroach on St Kilda. A simple ice-flow model demonstrates that even if thin, low-gradient ice lobes encircled the archipelago during the LLGM, the ice margin can only have reached the outermost moraine banks, ~40 km west of St Kilda, under extremely low (<2 kPa) driving stresses, implying either surge-like transient streaming behaviour at the ice-sheet margin or that the moraine banks relate to an earlier, more extensive ice sheet. The final glaciation of the Village Bay area at *c.* 19.2±2.3 ka was out of phase with the behaviour of the BIIS, which was undergoing net retreat during this period.

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The past decade has witnessed radical reassessment of the dimensions and chronology of the last (Late Devensian) British–Irish Ice Sheet (BIIS), which during the Last Local Glacial Maximum (LLGM) is now generally accepted to have overtopped all mountain summits in Scotland and Ireland (Fabel *et al.* 2012; Ballantyne & Stone 2015) and to have been confluent with the Fennoscandian Ice Sheet in the North Sea Basin (e.g. Carr *et al.* 2006; Graham *et al.* 2007, 2010; Sejrup *et al.* 2009, 2015, 2016). To the west of the British Isles, bathymetric and seismostratigraphical data have revealed the presence of moraine banks that extend along much of the Atlantic shelf edge from SW Ireland to Shetland. Several authors have concluded that these moraines were deposited at grounded ice margins during the LLGM (Bradwell *et al.* 2008; Dunlop *et al.* 2010; Clark *et al.* 2012; Ó Cofaigh *et al.* 2012; Peters *et al.* 2015), prompting speculation that westwards expansion of grounded ice was halted by increased water depth. Attribution of all shelf-edge moraine banks on the Hebrides Shelf NW of Scotland to deposition by the last ice sheet, however, rests entirely on interpretation of seabed imagery. However, seismostratigraphical research by Stoker & Holmes (1991) has demonstrated that the shelf-edge moraines on the northern Hebrides Shelf pre-date those on the West Shetland Shelf, being separated by an angular stratigraphical discordance. Although the time gap represented by this discordance is unknown, they postulated that the two sets of moraines were deposited during two separate episodes of widespread ice-sheet glaciation. More recently, Bradwell & Stoker (2015a) have suggested that the shelf-edge moraines of LLGM age on the West Shetland Shelf are correlated with mid-shelf moraines west of the Outer Hebrides, supporting a long-held view that the last ice sheet failed to reach the edge of the Hebridean shelf (Stoker *et al.* 1993, 1994; Stoker 1995, 2013; Sejrup *et al.* 2005), and implying that moraines on the outer Hebridean shelf were deposited by a pre-Late Devensian ice sheet.

Extension of the last ice sheet to the Atlantic shelf break is nevertheless supported by numerical ice-sheet modelling experiments driven by proxy climate data derived from the Greenland ice-core stable isotope record (Boulton & Hagdorn 2006; Hubbard *et al.* 2009) and by studies of ice-rafted detritus (IRD) in cores obtained from large shelf-edge trough-mouth fans and the sea floor adjacent to and beyond the shelf edge (Kroon *et al.* 2000; Knutz *et al.* 2001; Wilson & Austin 2002; Wilson *et al.* 2002; Peck *et al.* 2007; Scourse *et al.* 2009). These trough-mouth fans represent the depocentres of large, quasi-stable ice streams and take the form of massive wedges of stacked glacigenic debrisflow diamicts interbedded with hemipelagic sediments. The former have been inferred to represent subglacial sediment supply when the ice margin terminated at or near the shelf

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break, the latter to represent marine deposition when the ice margin lay closer to the present coastline. Adjacent to the shelf west of Scotland are two prominent shelf-edge fans (Fig. 1): the Sula Sgeir Fan, which received sediment from the Minch Ice Stream (Stoker & Bradwell 2005; Bradwell *et al.* 2007; Bradwell & Stoker 2015b, 2016; Owen & Long 2016), and the Barra-Donegal Fan, which acted as a depocentre for sediment from converging ice streams sourced from western Scotland (the Hebrides Ice Stream) and Ireland (Dunlop *et al.* 2010; Howe *et al.* 2012; Ó Cofaigh *et al.* 2012; Dove *et al.* 2015; Ballantyne & Ó Cofaigh 2017). During the LLGM the Outer Hebrides constituted an independent centre of ice dispersal that was confluent with mainland ice in the Minches and deflected westward-moving ice from the Scottish mainland both northwards towards the Minch Ice Stream and southwards towards the Hebrides Ice Stream (Flinn 1978; Von Weymarn 1979; Peacock 1984, 1991; Ballantyne & McCarroll 1995; Ballantyne & Hallam 2001; Stone & Ballantyne 2006). This pattern of ice movement implies that during the LLGM the shelf west of the Outer Hebrides was occupied by ice flowing from the Outer Hebrides rather than ice from the Scottish mainland (Selby 1989; Fig. 1).

The timing of ice-sheet extension to near the shelf edge is indirectly dated with reference to the dated flux of IRD in cores recovered from the NE Atlantic deep-sea continental slope and from patterns of sedimentation on the Barra-Donegal Fan (Scourse *et al.* 2009). The latter are recorded in giant piston core MD95-2006, a 30-m-long sediment core recovered from the distal section of the fan (Wilson & Austin 2002; Wilson *et al.* 2002; Peters *et al.* 2008). This core records replacement of hemipelagic sedimentation by IRD linked to turbiditic sedimentation due to ice-sheet expansion after *c.* 29 ka, and Scourse *et al.* (2009) attributed turbidity currents on the distal fan to arrival of the ice-sheet margin at the shelf edge at *c.* 27 ka. There is evidence, moreover, for phased expansion of the ice sheet across the shelf such that the ice margin west of Ireland reached the shelf edge a few millennia later (Scourse *et al.* 2009; Peters *et al.* 2015; Ballantyne & Ó Cofaigh 2017). Even within the Hebridean sector of the shelf it is likely that the arrival of the ice margin on the outer shelf was diachronous, with ice streams arriving at or near the shelf edge before zones of slower ice flow.

Confirmation that the last ice sheet reached the outer shelf NW of Scotland has been provided by cosmogenic ^{10}Be ages obtained for large glacially deposited boulders on the island of North Rona, ~70 km NW from the Scottish mainland and ~45 km from the shelf edge (Everest *et al.* 2013; Fig. 1). These yielded reported ages that average *c.* 25 ka, apparently consistent with the timing of the retreat of the ice-sheet margin from its shelf-edge maximum. Another key site for testing the proposition that the last ice sheet reached the shelf break

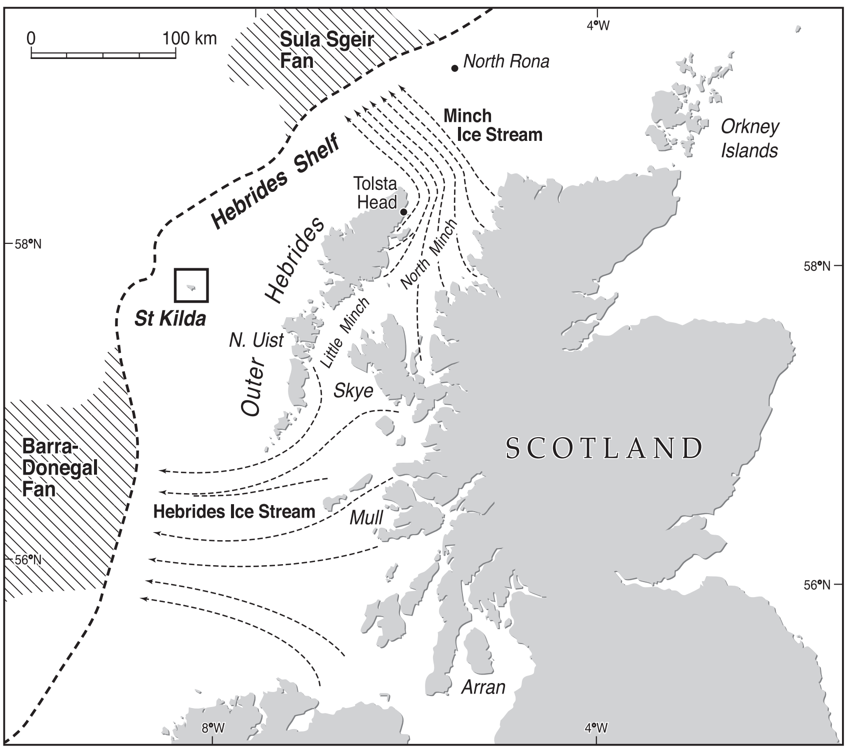

Fig. 1. Location of the St Kilda Archipelago and other sites mentioned in the text, showing the limit of the last ice sheet as depicted by Bradwell *et al.* (2008), trough-mouth fans and approximate flowlines of the Minch and Hebrides palaeo-ice streams, based on Bradwell *et al.* (2007, 2008) and Dove *et al.* (2015).

is the St Kilda archipelago, which lies 65 km WNW of North Uist in the Outer Hebrides and ~60 km east of the shelf edge. The location of St Kilda is interesting as it lies between tracks of the Minch and Hebrides Ice Streams in the area of the Hebrides Shelf that was fed by ice from the Outer Hebrides (Fig. 1). Studies of the Quaternary geomorphology and lithostratigraphy of St Kilda, moreover, have suggested that the archipelago may not have been over-run by the last ice sheet, but supported only small, locally nourished glaciers during the LLGM (Sutherland *et al.* 1984; Hiemstra *et al.* 2015). The aim of the research reported here is to employ cosmogenic ^{10}Be and ^{36}Cl dating of boulders on St Kilda to determine whether or not the last ice sheet over-ran the archipelago and the timing of local glaciation, and to explore the wider implications of the results.

The St Kilda archipelago

Geology and topography

The St Kilda archipelago (latitude 57°49′N, longitude 08°35′W; Fig. 1) comprises four small islands and outlying sea stacks that represent the terrestrial remnants of a roughly circular Palaeogene igneous complex, ~14 km in diameter. Much of the igneous complex forms a shallow platform 40–80 m below sea level that rises, locally steeply, above a deeper platform developed across the adjacent Lewisian Gneiss at ~120–130 m below sea level (Harding *et al.* 1984; Sutherland 1984). As the highest point of the archipelago is at 426 m OD, the igneous complex represents a prominent area of upland, rising up to 550 m above the adjacent sea floor. Of the four islands (Hirta, Soay, Dùn and Boreray), only the largest, Hirta (~6 km^2), is readily accessible. Hirta comprises two small valleys, Gleann Mòr in the northwest and Village Bay in the southeast, separated by a 239 m high col (Fig. 2). The remainder of the island consists of rolling hills that culminate in Mullach Bi (358 m OD), Mullach Mòr (361 m OD), Conachair (426 m OD) and Oisebhal (290 m OD), all of which are flanked on their seaward sides by steep cliffs. The island is underlain by a range of intrusive rocks, principally gabbros, dolerites, gabbro-dolerite breccias, granites, granite-dolerite hybrids and granophyres (Harding *et al.* 1984; Fig. 3).

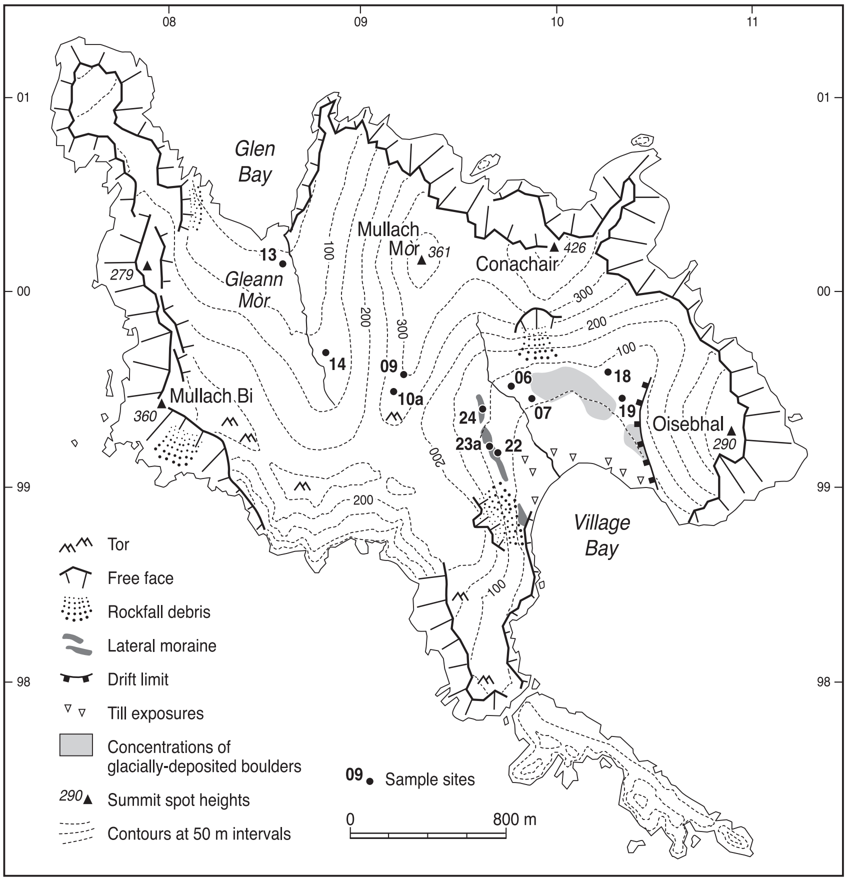

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Fig. 2. The island of Hirta, showing glacial features, tors and areas of rockfall debris, based partly on Sutherland *et al.* (1984). The location of samples selected for cosmogenic isotope surface exposure dating is also shown; bold numbers refer to sample numbers, which are prefixed by 'StK-' in Table 1.

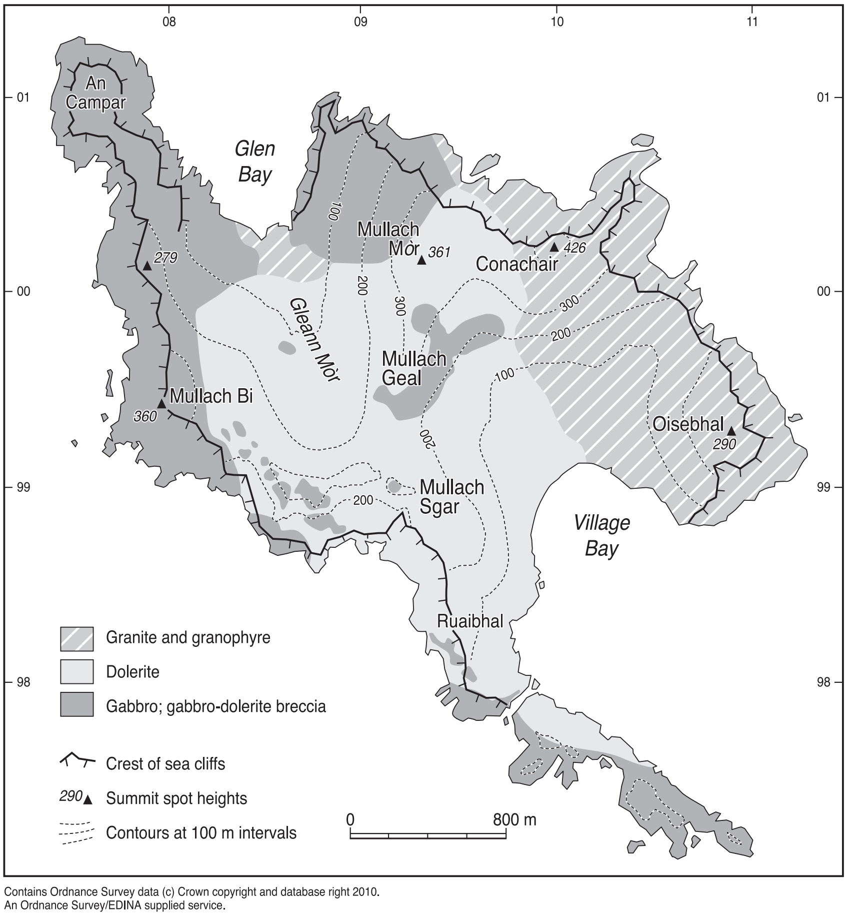

Fig. 3. Generalized solid geology of Hirta, adapted from Harding *et al.* (1984).

Quaternary glacial history

Early studies of the Quaternary landforms and deposits of Hirta produced conflicting interpretations. Cockburn (1935) reported the presence of exotic mineral grains in a soil sample and the presence of a few rounded gneiss boulders below 30 m OD in the Village Bay area; he inferred that these boulders may represent erratics transported westward by a former ice sheet, but could not exclude the possibility that these represent discarded ship's ballast. By contrast, Wager (1953) reported several moraines in the Village Bay area and maintained that Hirta had supported only local glaciers. Research by Harding *et al.* (1984), however, provided additional support for former ice-sheet glaciation of St Kilda in the form of exotic, strongly abraded mineral grains, apparently derived from Lewisian basement rocks, in several samples of alluvial sediments. Two samples dredged from nearshore sea-floor sediments at water depths of 30 and 50 m also produced exotic rock fragments, including gneisses and arkosic sandstone.

Detailed survey of the landforms and lithostratigraphy of Hirta led Sutherland *et al.* (1984) to conclude that there was evidence for three glacial episodes on the island: (i) over-running of part or all of the island by a pre-Devensian ice sheet, as represented by the erratic mineral grains detected by Cockburn (1935) and Harding *et al.* (1984); (ii) an Early- or pre-Devensian advance of locally nourished glacier ice in the Village Bay area, represented by a thick lithostratigraphical unit that they termed the 'Ruaival Drift' and interpreted as a till; and (iii) a more restricted Late Devensian (LLGM) advance of locally nourished glacier ice in the Village Bay area, represented by a subglacial till, a lateral moraine along the western side of the Village Bay area (Fig. 2), and an indistinct drift limit along the eastern side of the same valley. They noted that in Gleann Mòr the evidence for former glaciation is limited to apparent transport of ultrabasic boulders up reverse slopes, and suggested that these may provide evidence for a small former glacier in the valley. Finally, they interpreted two debris ridges below cliffs in the Village Bay area as protalus ramparts and attributed these to the Loch Lomond (Younger Dryas) Stade of *c.* 12.9–11.7 ka, the final period of stadial conditions in Scotland. Their dating evidence was limited to a single radiocarbon age determination of 24710 +1470/−1240 ^{14}C a BP (32.7–26.3 cal. ^{14}C ka) obtained from a bulk sample of organic-rich sand (slopewash deposit) buried under bouldery periglacial slope deposits outside the limit of the most recent local glaciation in the Village Bay area, but noted that this date provides only a minimum age estimate for emplacement of the overlying slope deposit as there is evidence for incomplete removal of modern contaminating material.

Following re-examination of the landforms and lithostratigraphy of Hirta, Hiemstra *et al.* (2015) proposed that there is evidence for only two glacial events on the island, corresponding to the earliest and most recent glaciations proposed by Sutherland *et al.* (1984; events (i) and (iii) above), and tentatively attributed the most recent (local) glaciation to the Last Glacial Maximum. The main difference between the conclusions of their study and those of Sutherland *et al.* (1984) is reinterpretation of the 'Ruaival Drift' deposit as 'an association of gelifluctates and other periglacial and/or paraglacial slope deposits rather than a subglacial till' (Hiemstra *et al.* 2015: p. 189), on the basis of the lithology and angularity of constituent clasts, scarcity of matrix material and absence of structures indicative of subglacial deformation or glaciotectonic thrusting. We examined this deposit in the field and agree with this reinterpretation. Hiemstra *et al.* (2015) also presented a 2D ice-flow model based on an assumed equilibrium line altitude of 190 m OD. This model suggested that ice cover initially accumulated on high ground before eventually occupying the western part of the Village Bay area and filling Gleann Mòr. They also reinterpreted the supposed 'protalus rampart' identified by Sutherland *et al.* (1984) SE of Mullach Sgar as a continuation of the Village Bay lateral moraine. The prominent putative 'protalus rampart' below the cliffs of Conachair (Ballantyne 2002) is here reinterpreted as an arcuate rockslide runout deposit, similar to others in the British Isles (Ballantyne & Stone 2009; Ballantyne *et al.* 2013, 2014). This rockslide may have occurred at any time following deglaciation of the Village Bay area, and has no palaeoclimatic significance.

The key conclusions reached by both Sutherland *et al.* (1984) and Hiemstra *et al.* (2015) are that although an ice sheet sourced from the east reached and partly over-ran St Kilda at some time during the Pleistocene, during the LLGM St Kilda supported only locally nourished glacier ice of very limited extent and was not over-run by the last ice sheet. This interpretation conflicts with the view that the last ice sheet terminated to the west of the archipelago at or near the Atlantic shelf edge (Bradwell *et al.* 2008; Chiverrell & Thomas 2010; Gibbard & Clark 2011; Clark *et al.* 2012), a scenario that implies at least partial overrunning of the archipelago by the ice sheet.

Material and methods

Sampling

Samples for cosmogenic nuclide dating were chiselled from the tops of large boulders at four locations: (i) at 285–295 m OD on the ridge (Mullach Geal) separating the Village Bay area from Gleann Mòr; (ii) within Gleann Mòr; (iii) on the Village Bay lateral moraine; and (iv) within the area occupied by a local glacier in the Village Bay area (Fig. 2). Although numerous boulders litter the high ground, most are derived from weathering of the underlying bedrock in the form of periglacial blockfields (Sutherland *et al.* 1984), and high-level boulders resting on bedrock are confined to a small area on Mullach Geal (Fig. 4A). Similarly, large boulders are rare in Gleann Mòr, apart from those deposited by rockfall along the flanks of the valley, and here we restricted our sampling to large glacially deposited boulders near the valley axis (Fig. 4B). Granite, granophyre, dolerite and gabbro boulders are much more abundant in the Village Bay area, and here we sampled large embedded boulders outside the area of former settlement (to avoid sampling boulders displaced by human activity; Fig. 4C) and on the lateral moraine (Fig. 4D). From our 23 samples we selected 11 for analysis based on location and boulder characteristics (Table 1). Boulder location and altitude were established using handheld GPS and checking against a 1:25 000 Ordnance Survey contoured map, and topographical shielding was assessed in the field using a compass and clinometer.

Laboratory analysis

For ^{10}Be analysis mineral separation, quartz isolation and purification were carried out at the School of Geographical and Earth Sciences, University of Glasgow (GU). Aluminium concentration in the quartz separates is a proxy for quartz purity and was measured by flame atomic absorption spectroscopy. Extraction of beryllium and preparation of targets for accelerator mass spectrometry (AMS) analysis were performed at the GU/SUERC Cosmogenic Isotope Laboratory housed at the Scottish Universities Environmental Research Centre (SUERC) in East Kilbride, following methods modified from Kohl & Nishiizumi (1992) and Child *et al.* (2000). Samples were processed with one full-chemistry (procedural) blank. Beryllium isotope ratios in the samples and procedural blank were measured with the SUERC 5MV accelerator mass spectrometer (Xu *et al.* 2010). Procedural blank correction represents <8% of the total ^{10}Be atoms in the samples. Details of sample and ^{9}Be spike masses, AMS measurement, and exposure age calculation are presented in Table 2.

For whole rock ^{36}Cl analysis samples were processed at the NERC Cosmogenic Isotope Analysis Facility (CIAF) at SUERC. Samples were crushed and sieved to <500 μm, leached in hot HNO_3 (trace metal analysis grade) and then washed thoroughly with ultrapure water to remove meteoric ^{36}Cl contamination from grain surfaces. Each sample was then split into two fractions: about 2 g for elemental analysis by ICP-OES and ICP-MS, and about 20 g for analysis of ^{36}Cl with AMS.

Fig. 4. Sampled boulders. A. Sample StK-10A: dolerite boulder resting on bedrock at 285 m altitude on Mullach Geal. B. Sample StK-13: dolerite boulder at 62 m altitude in Gleann Mòr. C. Sample StK-07: granite boulder at 58 m altitude in the Village Bay area. D. Sample StK-22: dolerite boulder at 95 m altitude on the Village Bay lateral moraine. [Colour figure can be viewed at www.boreas.dk]

Chlorine was extracted and purified from the 125–250 μm fraction of leached samples to produce AgCl for AMS analysis according to a modified version of procedures developed by Stone *et al.* (1996). Samples were processed together with a full chemistry blank. $^{36}Cl/^{35}Cl$ and $^{36}Cl/^{37}Cl$ ratios were measured with the SUERC 5 MV accelerator mass spectrometer (Wilcken *et al.* 2013). Procedural blank correction represents <4% of the total ^{36}Cl atoms in the samples. Details of sample and Cl spike masses, AMS measurement, and exposure age calculation are presented in Table 3.

Results

The surface exposure ages presented in Tables 2, 3 are based on assumption of zero erosion of the sampled surfaces since exposure; the effects of factoring in erosion rates are considered below. Arithmetic mean exposure ages for pairs or groups of samples differ from uncertainty-weighted mean exposure ages by ≤0.2 ka, so only the latter are cited here. Similarly, ^{10}Be ages calculated using the Loch Lomond production rate (LLPR) are almost identical to those calculated using CRONUScalc

Table 1. Sample locations and properties.

Sample	OS Grid Reference	Latitude (°N)	Longitude (°W)	Altitude (m OD)	Thickness (mm)	Density (g cm^{-3})	Shielding correction	Boulder lithology	Nuclide
High-level perched boulders on Mullach Geal									
StK-09	NF092996	57.8135	8.5852	295	70	2.8	0.9923	Dolerite	^{36}Cl
StK-10A	NF092994	57.8131	8.5856	285	20	2.8	0.9923	Dolerite	^{36}Cl
Gleann Mór									
StK-13	NA085001	57.8187	8.5976	62	50	2.8	0.9900	Gabbro	^{36}Cl
StK-14	NF089996	57.8141	8.5914	124	50	2.8	0.9808	Gabbro	^{36}Cl
Village Bay area									
StK-06	NF098995	57.8153	8.5695	87	15	2.6	0.9747	Granite	^{10}Be
StK-07	NF099994	57.8148	8.5708	58	40	2.6	0.9790	Granite	^{10}Be
StK-18	NF103996	57.8151	8.5676	91	25	2.6	0.9852	Granite	^{10}Be
StK-19	NF104994	57.8139	8.5654	76	23	2.6	0.9867	Granite	^{10}Be
Village Bay lateral moraine									
StK-22	NF097991	57.8101	8.5762	95	48	2.8	0.9780	Dolerite	^{36}Cl
StK-23A	NF097991	57.8104	8.5766	90	10	2.8	0.9793	Gabbro	^{36}Cl
StK-24	NF096991	57.8126	8.5779	115	45	2.8	0.9842	Dolerite	^{36}Cl

Table 2. Laboratory data and calculation of ^{10}Be exposure ages.

Sample ID[1]	Quartz (g)[2]	Be spike (μg)[3]	^{10}Be/^{9}Be ($\times10^{-15}$)[4,5]	^{10}Be (10^5 at g^{-1} SiO_2)[6]	Surface exposure ages (ka)	
					CRONUS v2.3 with LLPR[7]	CRONUScalc[8]
Village Bay area						
StK-06	18.777	260.5±1.8	98.77±3.04	8.513±0.336	19.23±(0.76) 1.14	19.20±(0.76) 1.70
StK-07	21.316	255.4±1.8	90.95±2.70	6.727±0.267	15.90±(0.63) 0.94	15.90±(0.63) 1.40
StK-18	15.482	258.4±1.8	83.42±2.70	8.529±0.371	19.14±(0.84) 1.18	19.10±(0.84) 1.70
StK-19	16.218	259.1±1.8	206.5±5.05	21.29±0.594	48.77±(1.36) 2.55	48.80±(1.38) 4.10

[1]AMS targets were prepared at GU/SUERC and measured at the SUERC AMS Laboratory.
[2]A density of 2.6 g cm^{-3} is used for all samples.
[3]Be carrier concentration: 1642±12 μg g^{-1}.
[4]The ^{10}Be/^{9}Be isotope ratios are normalized to the NIST SRM Be standard assuming a ^{10}Be/^{9}Be nominal value of 2.79×10^{-11}. Uncertainties are reported at 1σ confidence.
[5]A procedural ^{10}Be/^{9}Be blank of 6.947±1.389 $\times10^{-15}$ is used to correct for background.
[6]Propagated uncertainties include error in the blank and counting statistics.
[7]The ^{10}Be surface exposure ages were calculated using the Lm scaling model in the CRONUS-Earth online calculator (http://hess.ess.washington.edu/math/) version 2.3, wrapper script 2.3, Main calculator 2.1, Constants 2.3, Muons 1.1 (Balco *et al.* 2008) with the Loch Lomond sea level high latitude production rate (LLPR): 4.00±0.17 atom g^{-1} a^{-1} (Fabel *et al.* 2012).
[8]The ^{10}Be surface exposure ages were calculated with the CRONUScalc online calculator (Marrero *et al.* 2016, version 1.0, wrapper script 0.2) using the Lm scaling method and default calibration data set. For both exposure age calculations we assume no atmospheric pressure anomalies, no significant erosion during exposure (ε = 0 mm ka^{-1}), no prior exposure and no temporal shielding (e.g. snow, sediment, soil, vegetation). Analytical uncertainties are given in parentheses; systematic uncertainties (after parentheses) include uncertainty of the ^{10}Be production rate and the ^{10}Be decay constant.

(Table 2). For consistency with ^{36}Cl ages, only the ages calculated using CRONUScalc were used in calculation of weighted mean ages. Uncertainties (±1σ) cited below are systematic (external) uncertainties.

All but two of our samples (StK-07 and StK-19) produced consistent ages for particular locations (Tables 2, 3; Fig. 5). The two samples from high-level perched boulders on Mullach Geal (StK-09 and St K-10A) yielded a weighted mean ^{36}Cl exposure age of 81.6±7.8 ka, and the two from boulders in Gleann Mòr yielded a weighted mean ^{36}Cl exposure age of 30.9±3.2 ka. Reduced χ^2 values for each pair are 0.002 and 0.743, respectively, both values being consistent with ages drawn from a single population. The three ^{36}Cl exposure ages obtained from boulders on the Village Bay lateral moraine (19.4±2.9, 18.8±3.8 and 19.8±2.2 ka) yield a weighted mean age of 19.2±2.3 ka, very similar to the ^{10}Be exposure ages (19.2±1.1 and 19.1±1.2 ka) of

Table 3. Laboratory data and calculated ^{36}Cl exposure ages.

Sample ID[1]	Sample (g)[2]	Cl spike (g)[3]	Cl (μg g^{-1})[4]	^{36}Cl in blank (10^5 at)[5]	^{36}Cl (10^5 at g^{-1})[6]	Surface exposure age (ka)[7]
High-level perched boulders on Mullach Geal						
StK-09	15.14	0.328	19.92±0.11	0.586±0.069	4.919±0.150	81.7±(2.8) 8.2
StK-10A	16.06	0.337	10.26±0.05	0.602±0.103	4.991±0.135	81.5±(2.5) 7.8
Gleann Mòr						
StK-13	16.23	0.337	35.98±0.27	1.109±0.906	1.566±0.053	32.0±(1.7) 3.8
StK-14	13.87	0.337	10.17±0.06	1.109±0.906	1754±0.048	30.1±(1.4) 2.9
Village Bay lateral moraine						
StK-22	14.06	0.339	82.52±1.01	0.602±0.103	1.364±0.058	19.4±(1.0) 2.9
StK-23	11.79	0.338	215.37±5.35	0.602±0.103	2.435±0.107	18.8±(1.1) 3.8
StK-24	15.21	0.330	45.36±0.97	0.679±0.120	1.352±0.078	19.8±(1.2) 2.2

[1]AMS targets were prepared by NERC CIAF and measured at the SUERC AMS Laboratory.
[2]A density of 2.8 g cm^{-3} is used for all samples.
[3]Cl carrier concentration: 4.079±0.018 mg g^{-1}.
[4]Total Cl concentrations in the samples were determined by AMS isotope dilution using a carrier solution with a ^{35}Cl/^{37}Cl ratio of 20.49±0.07 atoms/atom.
[5, 6]The ^{36}Cl concentrations are normalized to Z93-0005 (PRIME Lab, Purdue) assuming a ^{36}Cl/Cl nominal value of 1.2×10^{-12}. Uncertainties are reported at 1σ confidence and include error in the blank and counting statistics.
[7]The ^{36}Cl surface exposure ages were calculated using the CRONUScalc online calculator (Marrero *et al.* 2016, version 2.0, main calculator 1.0, wrapper script 0.2) using the Lm scaling method and default calibration data set. Calculations assume no atmospheric pressure anomalies, no significant erosion during exposure (ε = 0 mm ka^{-1}), no prior exposure and no temporal shielding (e.g. snow, sediment, soil, vegetation). Analytical uncertainties are given in parentheses; systematic uncertainties (after parentheses) include uncertainty of the ^{36}Cl production rate and the ^{36}Cl decay constant.

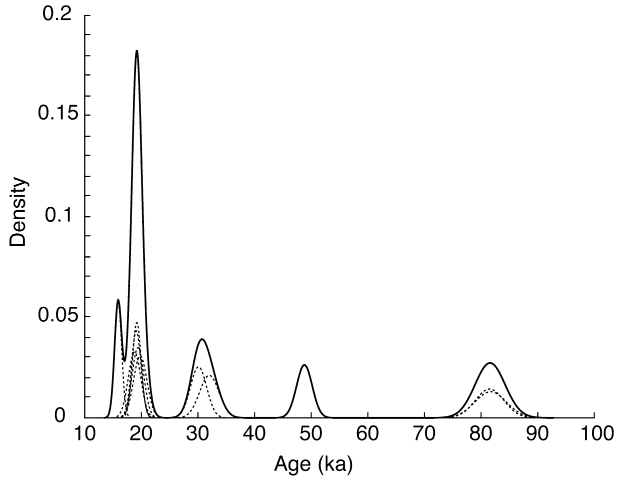

Fig. 5. Summed normal kernel density estimates (solid line) of the observed exposure ages and their analytical uncertainties (dashed lines).

samples StK-06 and StK-18 obtained from boulders inside the limit of the most recent glaciation in the Village Bay area as defined by this lateral moraine. Collectively, these five samples produced a reduced χ^2 value of 0.105, consistent with sampling from a single age population, and weighted mean age of 19.2±2.3 ka. The two other samples from the Village Bay area, StK-07 (15.9±1.4 ka) and StK-19 (48.8±4.1 ka), both differ from this weighted mean age at p <0.001 (Fig. 5). We attribute these discrepancies to probable transient shielding of StK-07 by sediment cover (Putkonen & Swanson 2003; Heyman *et al.* 2011), and to exposure of StK-19 prior to the final glaciation of the Village Bay area. Both are excluded from further consideration.

To assess the influence of erosion rate on our results, we calculated the weighted mean ages for the three groups of samples (Mullach Geal high-level boulders, Gleann Mòr boulders and Village Bay samples) for erosion rates (ε) of 1, 2 and 3 mm ka^{-1}. As can be seen from Table 4, assumption of different erosion rates has very little effect on the weighted mean age of the five Village Bay samples, in part because increases in the apparent age of the two samples analysed using ^{10}Be is counterbalanced by decreases in the apparent ages of the three samples analysed using ^{36}Cl, so the weighted mean age remains similar under all erosion rate scenarios. Under the assumption that $0 \leq \varepsilon \leq 3$ mm ka^{-1}, the weighted mean ages obtained for the two Gleann Mòr samples also vary little, from 30.5±3.2 to 31.0±3.4 ka. The much older weighted mean ages for the two high-level boulders on Mullach Geal, however, exhibit a marked rise in apparent age with increasing erosion rate. The results presented in Table 4 therefore demonstrate that a weighted mean age based on assumption of zero erosion rates for the five Village Bay samples (19.2± 2.3 ka) and the two Gleann Mòr samples (30.9±3.2 ka) can be considered representative for $\varepsilon \leq 3$ mm ka^{-1}, irrespective of whether the arithmetic or uncertainty-weighted mean is used. Less confidence can be placed on the assumption of a zero-erosion weighted mean age of 81.6±7.8 ka for the two Mullach Geal samples, as within the range $0 \leq \varepsilon \leq 3$ mm ka^{-1} the true weighted mean exposure age may be up to 15% greater.

Discussion

The discussion below focuses first on the implications of our exposure ages for the lateral extent of the last ice sheet on the Hebridean Shelf, then on the interpretation of these ages in terms of the timing of glacial events on St Kilda.

Implications for the extent of the last ice sheet

The case for extension of the last ice sheet to the edge of the Hebrides Shelf rests mainly on the presence of ice-marginal moraines on the outermost shelf and the evidence for glacigenic sedimentation on trough-mouth fans. Moraine banks on the northern Hebrides Shelf were first detected mainly from seismostratigraphical evidence (Stoker & Holmes 1991) and initially attributed to a pre-Late Devensian glaciation, with the limit of the last ice sheet being depicted as a broad arc west of the Outer Hebrides but terminating a short distance east of St Kilda (Selby 1989; Stoker *et al.* 1993). Subsequent research based on high-resolution echo-sounder data has verified the existence of broad shelf-edge ridges on much of the Hebrides Shelf and identified similar features on the edge of the Shetland Shelf to the north

Table 4. Effect of erosion rates on mean ages. UWM = uncertainty-weighted mean; AM = arithmetic mean.

Sampling site (sample size)		Erosion rate (ε)			
		Zero	1 mm ka^{-1}	2 mm ka^{-1}	3 mm ka^{-1}
Mullach Geal (n = 2)	UWM	81.6±7.8	83.5±8.4	89.8±9.5	93.5±11.6
	AM	81.6±8.0	83.5±8.6	89.8±9.9	93.5±12.0
Gleann Mòr (n = 2)	UWM	30.9±3.2	30.5±3.2	30.8±3.3	31.0±3.4
	AM	31.1±3.4	30.6±3.4	30.8±3.5	31.0±3.6
Village Bay (n = 5)	UWM	19.2±2.3	19.1±2.2	19.0±2.2	18.9±2.2
	AM	19.3±2.5	19.1±2.4	19.0±2.4	19.0±2.4

(Bradwell *et al.* 2008; Clark *et al.* 2012; Bradwell & Stoker 2015a), and along the edge of the Malin Shelf and the Irish Shelf to the south (Dunlop *et al.* 2010; Ó Cofaigh *et al.* 2012). Radiocarbon ages obtained on shells and benthic foraminifera on the Irish Shelf appear to confirm that the last ice sheet reached the shelf edge in that sector (Peters *et al.* 2015; Ballantyne & Ó Cofaigh 2017). For the Hebrides Shelf, a radiocarbon age of 22 480±300 ^{14}C a BP (27.2–25.9 cal. ^{14}C ka) reported by Peacock *et al.* (1992) for a marine bivalve recovered from glaciomarine sediments west of moraine banks to the south of St Kilda is consistent with the last ice sheet extending to the outer shelf (although not necessarily to the shelf edge), as are the cosmogenic ^{10}Be exposure ages obtained from North Rona (Everest *et al.* 2013). The evidence for a pronounced increase in IRD deposited on the Barra-Donegal Fan at *c.* 29–27 ka (Kroon *et al.* 2000; Knutz *et al.* 2001; Wilson *et al.* 2002; Peck *et al.* 2007; Scourse *et al.* 2009) indicates that the contributing ice stream reached the shelf edge by *c.* 27 ka, but does not necessarily imply that all shelf-edge moraine banks on the Hebridean Shelf are of Late Devensian age. In this context it is notable that the seismostratigraphical and borehole evidence reported by Stoker & Holmes (1991) and Stoker *et al.* (1994) indicates that the shelf-edge moraine banks on the northern Hebrides Shelf were deposited by a pre-Late Devensian Ice Sheet of probable Mid to Late Pleistocene (<0.45 Ma) age. This interpretation has been developed by Bradwell & Stoker (2015a), who employed a combination of seismostratigraphical evidence with high-resolution bathymetric data to argue that the LLGM shelf-edge moraines on the West Shetland shelf correlate with mid-shelf moraines north of the Outer Hebrides, implying that the shelf-edge moraines on the North Hebrides shelf were deposited during a previous ice-sheet glaciation.

The geomorphological and lithological evidence presented by Sutherland *et al.* (1984) and refined by Hiemstra *et al.* (2015) suggests that the last ice sheet failed to over-run St Kilda. This interpretation is supported by some of our exposure ages. The exposure ages of (≥)81.7±8.2 ka and (≥)81.5±7.8 ka obtained for perched boulders at ~290 m on Mullach Geal imply that the higher parts of St Kilda were not over-run by the last ice sheet. This interpretation is supported by two observations. First, the higher parts of the more easterly summits (Conachair and Oisebhal) are underlain by granite and granophyre (Fig. 3) and littered with numerous frost-detached boulders that form summit blockfields. Had westward-moving ice over-run the high ground, it would be expected that granite and granophyre erratics would occur on Mullach Mòr, immediately to the west, but none has been observed. Second, high ground along the SE of the island is crowned by dolerite tors surrounded by slabs detached by frost wedging (Sutherland *et al.* 1984). Examination of these tors provided no evidence of modification by glacier ice or displacement of detached slabs (cf. André 2004; Hall & Phillips 2006) and indeed some tors support precariously balanced capstone slabs that appear very unlikely to have survived over-running by an ice sheet.

In the Village Bay area there is evidence for only local ice cover, as represented by the distribution of till and the Village Bay lateral moraine (Fig. 2). Both Sutherland *et al.* (1984) and Hiemstra *et al.* (2015) argued that this local glaciation represented the Last Glacial Maximum on St Kilda. Five samples obtained from the lateral moraine or within the area occupied by the former Village Bay glacier, however, have produced consistent post-LLGM ages within the range 19.8±2.2 to 18.8±3.8 ka (Tables 2, 3) and a weighted mean age of 19.2±2.3 ka that is independent of assumed erosion rate (Table 4). Given that there is evidence for the ice margin reaching the shelf edge at the Barra-Donegal Fan at *c.* 27 ka (Scourse *et al.* 2009), glaciomarine sedimentation south of St Kilda at 27.2–25.9 cal. ^{14}C ka (Peacock *et al.* 1992) and that the ice margin retreated past North Rona at *c.* 25 ka (Everest *et al.* 2013), the timing of local glaciation in the Village Bay area was manifestly not coincident with advance of the ice-sheet margin to the shelf edge, but occurred several millennia later. The evidence for local glaciation of the Village Bay area therefore does not conflict with the proposition that the last ice sheet crossed lower ground on St Kilda and advanced towards the shelf edge, as it is feasible that advance and retreat of the ice sheet was followed by later development of locally nourished glacier ice at *c.* 19.2 ka or slightly earlier.

Conversely, the ^{36}Cl exposure ages obtained for samples StK-13 and StK-14 from two widely separated large boulders in Gleann Mòr (32.0±3.8 and 30.1±2.9 ka) suggest that glacier ice occupied this valley long before the ice-sheet margin reached St Kilda. Given the large uncertainties associated with these ages the possibility that ice flowing from the Outer Hebrides was responsible for depositing these boulders cannot be excluded, but seems extremely unlikely for several reasons. First, to enter Gleann Mòr, a westward-flowing ice sheet would have to cross the col at 239 m OD that separates Gleann Mòr from Village Bay. However, the exposure ages (>80 ka) of the boulders sampled at ~290 m OD on Mullach Geal, <300 m from the col, limit the possible thickness of ice crossing the col into Gleann Mòr to <50 m. That the last ice sheet should have been just thick enough to cross the col and extend into Gleann Mòr but not remove the Mullach Geal perched boulders is implausible. Second, there is no evidence for a westward-moving ice sheet crossing the Village Bay area prior to the local Village Bay glaciation. Instead, as Hiemstra *et al.* (2015) have demonstrated, the slopes on the west side of Village Bay outside the limit of local glaciation are covered by a periglacial slope deposit up to 13 m thick that overlies fractured and weathered bedrock (Fig. 6). This deposit is composed entirely of

Fig. 6. Periglacial slope deposits up to 13 m thick resting on weathered bedrock on the western shore of Village Bay. [Colour figure can be viewed at www.boreas.dk]

locally derived (dolerite) material in the form of a clast- or matrix-supported diamicton with coarse gravel (cobble to boulder) subunits. Clasts are generally angular, and in appearance this deposit closely resembles some of the thick 'head' or gelifluctate deposits found in coastal cliffs outside the limit of Late Devensian glaciation in SW England and south Wales (Harris 1987; Ballantyne & Harris 1994). As Hiemstra *et al.* (2015) pointed out, the remarkable thickness of this deposit implies a very prolonged period of rock weathering and mass movement under severe periglacial conditions, uninterrupted by glaciation. Finally, the radiocarbon age of 24 710 +1470/−1240 ^{14}C a BP (32.7–26.3 cal. ^{14}C ka) obtained by Sutherland *et al.* (1984) for an organic-rich sand layer buried under a bouldery periglacial slope deposit on the western slope of Village Bay represents a *minimum* age for the sand in view of possible contamination, and there is no evidence that this sand or the overlying slope deposit have been modified by glacier ice.

In sum, the exposure ages reported here support the conclusions reached by Sutherland *et al.* (1984) and Hiemstra *et al.* (2015) that the last ice sheet failed to overrun St Kilda. Hiemstra *et al.* (2015) pointed out that the bathymetric evidence suggests that submarine moraines defining broad lobes of ice exist on the sea floor both north and south of St Kilda (Fig. 7), and suggested that the archipelago represented an obstacle in the path of the advancing ice sheet, diverting ice flow both northwards and southwards at the LLGM and possibly leaving the islands of the archipelago standing proud of the ice sheet as a nunatak. Given the absence of any evidence for the encroachment of the last ice sheet on the present land surface of St Kilda (and particularly the evidence provided by thick periglacial slope deposits extending to near sea level in the Village Bay area), they acknowledged that this scenario requires that former ice lobes encircling St Kilda cannot have been thicker than the depth of the surrounding submarine platform, ~120–130 m below present sea level (Harding *et al.* 1984; Sutherland 1984).

This interpretation appears plausible, but even if correct appears to imply that a narrow unglacierized zone extended from the lee of the archipelago northwestwards to the shelf edge. Moreover, for a thin (~120 m thick) ice sheet encircling St Kilda to have deposited the moraine banks on the outer shelf ~40 km to the west and ~20 km east of the shelf edge (Fig. 7), it must have moved under very low basal shear stress. The profile of a laterally unconstrained ice sheet moving over a rigid horizontal bed may be approximated by a parabola described by:

$$h = \sqrt{2\tau_b L/\rho g} \tag{1}$$

where h is ice thickness, τ_b is basal shear stress (≈ driving stress, if lateral drag is assumed to be negligible), L is distance to the ice margin, ρ is ice density (900 kg m^{-3}) and g is gravitational acceleration (9.8 m s^{-2}). Rearranging this equation, τ_b is approximated by:

$$\tau_b = (\rho g h^2)/2L. \tag{2}$$

Setting h at 120 m and L at 40 km yields $\tau_b \approx 1.6$ kPa, and setting L at 60 km (the approximate distance to the shelf edge) yields $\tau_b \approx 1.1$ kPa. Both values of driving stress are nearly two orders of magnitude lower than the 50–100 kPa typical of grounded ice sheets outside zones of ice streaming, although movement at lower shear stresses is possible over a deforming bed (Paterson 1994; Benn & Evans 2010). Conversely, if we assume $\tau_b = 50$ kPa, assumption of a parabolic ice profile implies that ice 120 m thick would have terminated just ~1.3 km west of St Kilda, and assumption of $\tau_b = 10$ kPa places

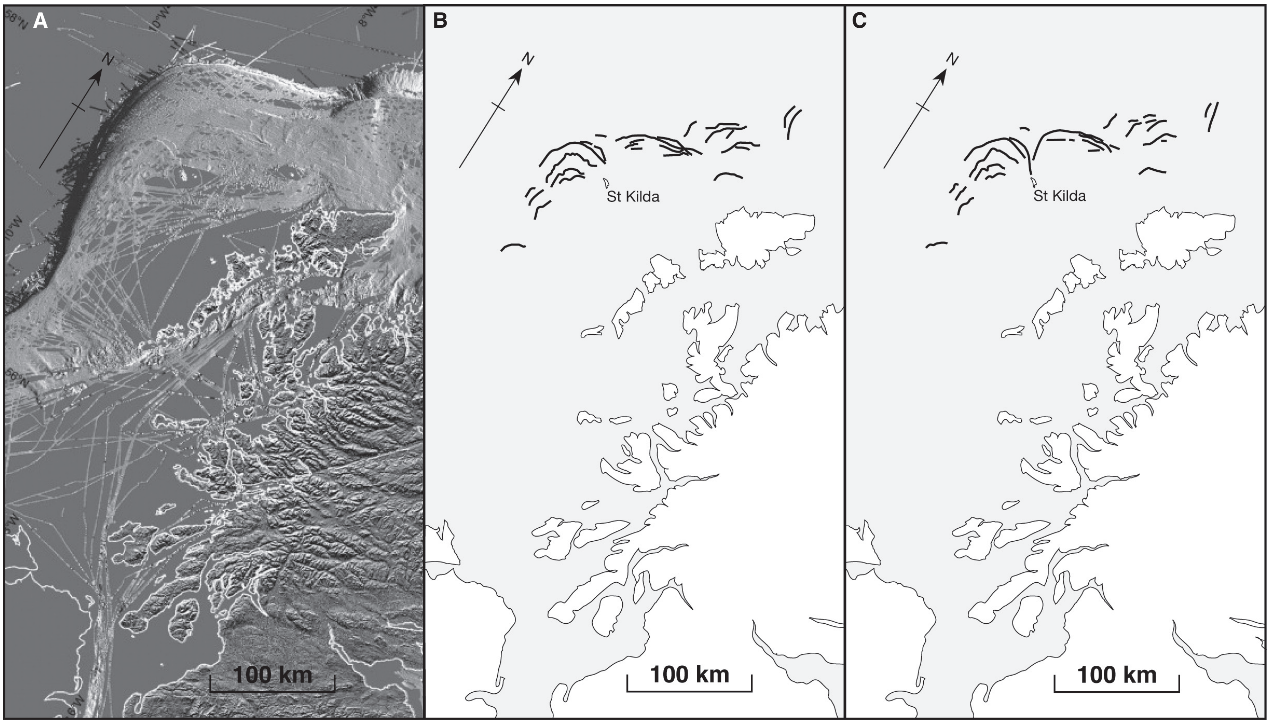

Fig. 7. A. Bathymetric image of the Hebrides Shelf based on Olex AS (offshore) data and NextMap (onshore) data, reproduced from Bradwell *et al.* (2008) with permission from Elsevier. B. Map of outer shelf moraines interpreted from (A) by Bradwell *et al.* (2008). C. Reinterpretation of the moraines in the vicinity of St Kilda by Hiemstra *et al.* (2015), which suggests that broad lobes of ice formerly existed both north and south of the archipelago. B and C are reproduced with permission of John Wiley and Sons Ltd.

the ice margin just 6.3 km west of St Kilda. The implications of these calculations are discussed below.

The timing of glaciation on St Kilda

At face value, the two consistent ^{36}Cl exposure ages obtained for boulders resting on bedrock at ~290 m altitude on Mullach Geal (Table 3) would appear to imply contemporaneous deposition of these boulders by a thick ice sheet that over-ran much of St Kilda then retreated at 81.6±7.8 ka or earlier (Table 4). This interpretation is highly unlikely. As noted above, there is no evidence for (i) westward transport of granophyre and granite erratics sourced from the extensive outcrop in the east of Hirta (Fig. 3), (ii) glacial modification of dolerite tors, or (iii) till deposits apart from those emplaced during the most recent local glaciation of the Village Bay area (Hiemstra *et al.* 2015). Moreover, the Greenland ice-core stable isotope record shows that the period *c.* 84.7–79.7 ka was represented by a prolonged interstadial (GI-21e; Wolff *et al.* 2010; Rasmussen *et al.* 2014; Fig. 8), suggesting that advance of a thick ice sheet over St Kilda or growth of local ice on St Kilda was unlikely at this time. We conclude that both sampled boulders on Mullach Geal were probably released from the underlying dolerite bedrock by *in situ* frost wedging (Fig. 4A) rather than deposited by glacier ice. This interpretation implies that neither a former ice sheet nor a local icecap occupied Mullach Geal over at least the past *c.* 80 ka.

In contrast, the two boulders sampled on the floor of Gleann Mòr (samples StK-13 and StK-14) can only have been deposited by glacier ice. Both are isolated gabbro boulders resting on level ground, the former over 220 m from the foot of the nearest slope and the latter over 60 m from the slope foot, so rockfall deposition can be excluded. Moreover, the boulder from which sample StK-13 was obtained (Fig. 4B) is an erratic, resting on terrain underlain by granite (Fig. 3). There is, however, no persuasive geomorphological or lithostratigraphical evidence for former glaciation in Gleann Mòr. Both Harding *et al.* (1984) and Sutherland *et al.* (1984) mapped the sediment cover on the surrounding slopes as periglacial slope deposits (‘head’) and the latter also mapped shallow exposures of periglacial slope deposits at the mouth of the glen. There are, however, no exposures on the floor of the valley, and it is possible that the slope deposits on the valley sides and the valley mouth represent, at least in part, soliflucted till deposits.

The weighted mean exposure age of the two Gleann Mòr samples (30.9±3.2 ka) implies prior ice expansion then retreat of a small, locally nourished glacier. These ages are consistent with the timing of the initial expansion of Outer Hebrides ice as determined by radiocarbon ages spanning 29.1–26.2 ^{14}C ka (34.0–29.7 cal. ^{14}C ka) obtained for organic sediments buried by till at Tolsta

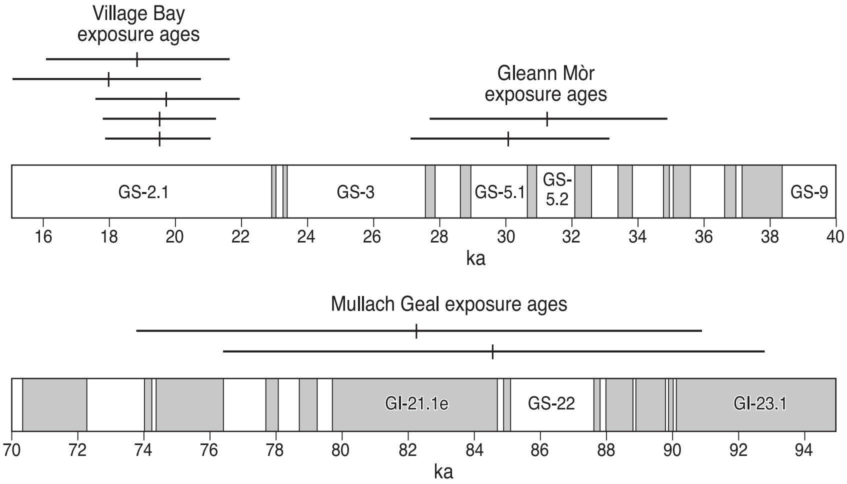

Fig. 8. Exposure ages of St Kilda samples plotted against the succession of stadial–interstadial events identified by Rasmussen *et al.* (2014) for the periods 15–40 and 70–95 ka in the Greenland stable isotope ice-core record. Interstadials are shaded. Horizontal lines for each exposure age represent $\pm 1\sigma$ uncertainties.

Head in NE Lewis (Whittington & Hall 2002). Both events are, within dating uncertainty, coincident with a prolonged stadial, Greenland Stadial 5 (GS-5), in the Greenland ice-core record (*c.* 32.0–28.9 ka; Fig. 8), when $\delta^{18}O$ values were as low as at any time in the past 100 000 years (Rasmussen *et al.* 2014), and which incorporated Heinrich Stadial 3 of *c.* 32.7–31.3 ka (Sanchez Goñi & Harrison 2010). It seems possible that limited glacier expansion in Gleann Mòr was approximately synchronous with that of the Outer Hebrides icecap in response to GS-5 cooling, but whereas the latter survived subsequent warming during Greenland Interstadial 4 (GI-4) and continued to expand under conditions of renewed cooling during GS-4, the much smaller Gleann Mòr glacier shrank and disappeared. As there is no evidence of later glaciation in the valley, it appears to have remained ice-free and subject to severe periglacial conditions throughout the LLGM.

An alternative possibility is that glaciation of Gleann Mòr occurred at the same time as that of the Village Bay area (19.2±2.3 ka), as suggested by the ice-flow model depicted by Hiemstra *et al.* (2015), and that both exposure ages obtained for boulders in Gleann Mòr are compromised by nuclide inheritance from a previous period of exposure. This appears unlikely given the consistency of the two ages. It is also notable that the ice-flow model does not take into account the effects of redistribution of snow by wind, and probably for this reason generated a small icecap on high ground feeding valley glaciers in both Gleann Mòr and the western part of Village Bay. As noted above, however, the two exposure ages obtained for perched boulders on Mullach Geal (Fig. 4A) indicate that high ground on Hirta has been ice-free for at least the past 80 ka; had an icecap existed, it seems unlikely that such perched boulders could have remained in place.

Both Sutherland *et al.* (1984) and Hiemstra *et al.* (2015) inferred that the abundant evidence for a former small valley glacier in the Village Bay area represented glaciation during the Last Glacial Maximum. However, the five consistent exposure ages of 19.8±2.2 to 18.8±3.8 ka (weighted mean 19.2±2.3 ka) obtained for boulders on the Village Bay lateral moraine and terrain inside this moraine (Tables 2–4) demonstrate that the final glacial event on St Kilda occurred several millennia after the LLGM, at a time when marine-terminating sectors of the last BIIS were in retreat (Clark *et al.* 2012; Chiverrell *et al.* 2013). In terms of the Greenland ice-core record, the final glaciation and deglaciation of St Kilda occurred under stadial conditions during GS-2.1a to GS-2.1b (22.9–17.5 ka; Rasmussen *et al.* 2014; Fig. 8). In view of the large uncertainties of our exposure ages it is not possible to attribute the expansion and retreat of the Village Bay glacier to climatic forcing within GS-2.1, particularly as the limited extent of the former glacier (<1 km^2) implies that it could have developed and vanished within a few centuries. Moreover, the timing of Village Bay glaciation pre-dates established re-advances of the last ice sheet on land, such as the Clogher Head Readvance (*c.* 18.4 ka) and Killard Point Readvance (*c.* 17.3–16.6 ka) in northern Ireland (McCabe *et al.* 2007; Ballantyne & Ó Cofaigh 2017); the Wester Ross Readvance (*c.* 15.2 ka) in NW Scotland (Ballantyne & Stone 2012) or re-advances dated by Small *et al.* (2016) in southern Skye (*c.* 17.6 ka) and on the Isle of Soay (*c.* 15.2 ka).

The difference in the weighted mean exposure ages obtained for boulders in Gleann Mòr (30.9±3.2 ka) and Village Bay (19.2±2.3) poses a conundrum, as there is no geomorphological, lithostratigraphical or dating evidence for glaciation of the Village Bay area prior to the *c.* 19.2 ka event (Hiemstra *et al.* 2015). There are three possible explanations. First, there may have been limited local glaciation of the Village Bay area at the time that ice occupied Gleann Mòr, but the later Village Bay glaciation was more extensive and removed all evidence of the earlier event. Second, as suggested above, the exposure ages obtained for boulders in Gleann Mòr may be compromised by prior exposure, such that both valleys were occupied by glacier ice at *c.* 19.2 ka, although the consistency in the Gleann Mòr exposure ages suggests that this is unlikely. Finally, it is possible that climatic circumstances and particularly different patterns of snow accumulation favoured glacier formation in Gleann Mòr during the earlier event but ice accumulation in Village Bay during the later event. On present evidence there is no way of resolving these alternative scenarios.

Wider implications

As outlined earlier, the notion that the last BIIS extended along its entire length to the Atlantic Shelf edge has been widely promoted (Bradwell *et al.* 2008; Hubbard *et al.* 2009; Chiverrell & Thomas 2010; Gibbard & Clark 2011). Clark *et al.* (2012: p. 141), for example, concluded that there is '. . .unequivocal evidence for glaciation to the continental shelf edge all the way from SW Ireland to the Shetland Isles'. Others, however, have continued to argue that this interpretation (which is largely based on the interpretation of shelf-edge moraine banks from bathymetric imagery) contravenes the stratigraphical evidence in the area of the northern Hebrides Shelf (Stoker & Holmes 1991; Stoker *et al.* 1993, 1994; Stoker 2013). This latter view implies that the last ice sheet failed to extend to the shelf edge in at least part of the inter-ice-stream sector between the Minch and Hebrides Ice Streams, but extended no farther than mid-shelf; Bradwell & Stoker (2015a: p. 317) even suggest that the LLGM ice margin was '. . .situated close to the present-day coastline in NW Lewis. . .' although this interpretation is also based on interpretation of moraine configuration on bathymetric imagery.

Although the presence of exotic mineral grains in glacial, periglacial and alluvial sediments detected by Cockburn (1935) and Harding *et al.* (1984) provides evidence that a former ice sheet encroached on St Kilda, the geomorphological and lithostratigraphical evidence presented by Sutherland *et al.* (1984) and Hiemstra *et al.* (2015) together with the exposure ages reported here demonstrate that the *last* ice sheet failed to do so. Hiemstra *et al.* (2015) attempted to reconcile this finding with the LLGM Atlantic shelf-edge model by suggesting encirclement of St Kilda by thin ice lobes (Fig. 7). As noted above, however, this solution implies extension of ice to the outermost moraine banks under extremely low (~1.6 kPa) driving stresses.

Low (<2 kPa) values of basal shear stress have been inferred for the distal parts of West Antarctic ice streams moving over deforming beds (Kamb 2001; Joughin *et al.* 2002), but these flow into deep water, which maintains the high hydrological base level necessary to sustain elevated basal water pressures that permit fast ice flow under low driving stresses. This situation appears unlikely for ice flowing across the St Kilda platform and adjacent shelf (−120 to −130 m OD) during the LLGM, when global eustatic sea level was ~125±10 m below present (Clark *et al.* 2009; Lambeck *et al.* 2014), implying grounded ice termination in shallow water or even on dry land. However, Clark (1992) calculated from moraine altitudes and ice palaeoflow vectors that some of the vast land-based ice lobes that drained the southern margin of the Laurentide Ice Sheet comprised thin, low-gradient ice moving under driving stresses <2 kPa, which he explained in terms of rapid rates of ice advance through basal sliding and/or bed deformation. Although there appears to be no present-day analogue for such behaviour, it suggests the possibility that thin, low-gradient ice lobes flanking St Kilda may have reached the outermost moraine banks as transient ice streams or surges. The possible role of subglacial sediment deformation is difficult to assess. According to echo-soundings reported by Harding *et al.* (1984: p. 35) 'much of the sea floor near the islands is free of unconsolidated sediment'. This does not, however, exclude the possibility of sediment cover on the seabed flanking the St Kilda platform.

An alternative possibility is that the features interpreted as moraine banks west of St Kilda (Fig. 7) predate the LLGM (MIS 2) and were deposited by an earlier, more extensive ice sheet, such as that responsible for deposition of erratic material on St Kilda. It is notable that shelf-edge moraine banks on the northern Hebrides Shelf were initially attributed to a pre-MIS 2 glaciation on the basis of amino-acid diagenesis (Stoker & Holmes 1991; Stoker *et al.* 1993; Stoker & Bradwell 2005). This conclusion was queried by Bradwell *et al.* (2008) on the grounds of the unreliability of the dating technique, even though the stratigraphical evidence presented by Stoker and his co-researchers (Stoker & Holmes 1991; Stoker *et al.* 1994) provided evidence to the contrary. The recent reappraisal of moraine systems on the northern and central parts of the Hebrides Shelf by Bradwell & Stoker (2015a) appears to conform with the stratigraphical evidence and suggests that ice moving westward from the Outer Hebrides extended no farther than mid-shelf. The failure of the last ice sheet to encroach on St Kilda is entirely consistent with this view.

Irrespective of which of the above interpretations is valid, there is no evidence that the margin of the last ice sheet reached the shelf edge in this sector, as the outermost moraine banks are located ~20 km east of the shelf break (Fig. 7). This suggests that although the ice margin reached the shelf break in at least some areas of former ice streaming, generating turbiditic flows on trough-mouth fans (e.g. Baltzer *et al.* 1998; Kroon *et al.* 2000; Wilson & Austin 2002; Scourse *et al.* 2009), the limits of the last ice sheet in some inter-ice-stream sectors may have been more conservative than those depicted in recent shelf-edge models. It also implies that westward extension of the margin of the last ice sheet was not invariably halted by a rapid increase in water depth at the shelf break, but that on some sectors of the outer shelf the ice margin remained grounded in shallow tidewater or dry land (cf. Stoker *et al.* 1993).

It is also notable that the timing of the two episodes of inferred local glaciation on St Kilda, at 30.9±3.2 ka (Gleann Mòr) and 19.2±2.3 ka (Village Bay) are out of phase with the timing of the LLGM. It seems likely that the climatic impetus for limited local glaciation and deglaciation of St Kilda was too short-lived to have affected an ice sheet that was responding to longer-term climatic trends. The absence of evidence for glaciation on St Kilda during the Younger Dryas Stade of *c.* 12.9–11.7 ka is also of interest. At this time small glaciers formed on the mountains of the Outer Hebrides, with reconstructed equilibrium line altitudes of 150–289 m OD (Ballantyne 2006, 2007). It seems likely that glaciers failed to develop on St Kilda during the Younger Dryas because of the lack of high-level accumulation areas, with snow being blown into valleys that were too low to allow progressive seasonal snow accumulation and the formation of glacier ice.

Conclusions

- The St Kilda archipelago, ~65 km W of the Outer Hebrides and ~60 km from the Atlantic shelf break, is a key site for testing the assertion that the last BIIS extended to the Atlantic shelf break in all sectors. Previous studies based on geomorphology and lithostratigraphy (Sutherland *et al.* 1984; Hiemstra *et al.* 2015) have suggested that at the LLGM St Kilda supported only locally nourished glacier ice, but lacked dating control.
- Samples from undisturbed boulders at three locations on Hirta produced three consistent sets of exposure ages. Two perched boulders on the Mullach Geal ridge at ~290 m yielded an average ^{36}Cl exposure age of (≥) 81.6±7.8 ka. Two isolated boulders on the floor of a north-facing valley (Gleann Mòr) produced an average ^{36}Cl exposure age of 30.9±3.2 ka. Five samples from a lateral moraine and terrain inside the lateral moraine in the south-facing Village Bay valley produced consistent ^{36}Cl and ^{10}Be ages averaging 19.2±2.3 ka.
- The Mullach Geal exposure ages confirm other evidence (undisturbed tors and absence of erratic carry) that the last ice sheet did not cross high ground on St Kilda. The Gleann Mòr exposure ages not only pre-date the estimated timing of the ice margin reaching the shelf edge (*c.* 27 ka), but also cannot be explained in terms of deposition by the last ice sheet, and we infer that they represent deposition of the boulders during retreat of a small locally nourished glacier that formed in this valley during GS-5. The Village Bay exposure ages represent glaciation during GS-2.1, and post-date the assumed timing of the ice-sheet maximum by several millennia.
- The evidence provided by the Mullach Geal and Gleann Mòr exposure ages confirms that the last ice sheet did not encroach on St Kilda. As the surrounding sea floor lies at 120–130 m depth, ice encircling St Kilda cannot have exceeded ~120 m in thickness. A simple parabolic model indicates that for ice of this thickness to have reached the outermost moraine banks ~40 km to the west, ice movement must have occurred under extremely low (<2 kPa) driving stress. This implies either that extremely thin, low-gradient ice lobes exhibiting surge-like behaviour crossed the outer shelf to deposit these moraines during the LLGM, or that some moraine banks at and near the shelf edge are of pre-MIS 2 age, as argued by Bradwell & Stoker (2015a). There is no evidence that the margin of the last ice sheet reached the shelf edge in this sector, suggesting that expansion of the last ice sheet in this sector was not terminated by increasing water depth.
- The very small glaciers inferred to have been responsible for depositing boulders in Gleann Mòr (at *c.* 30.9 ka) and in the Village Bay area (at *c.* 19.2 ka) were out of phase with the last ice sheet: the former Gleann Mòr glacier apparently retreated during a period of overall ice-sheet advance, but the ages of boulders on the Village Bay lateral moraine imply advance of local ice at a time when the marine-terminating limits of the last ice sheet were retreating. The absence of evidence for Younger Dryas glaciation is attributed to the low elevation of valley floors, which lie well below the reconstructed equilibrium line altitudes of Younger Dryas glaciers in the Outer Hebrides.

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