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Paired ^{26}Al and ^{10}Be exposure ages from Lundy: new evidence for the extent and timing of Devensian glaciation in the southern British Isles

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ABSTRACT

Lundy lies in a strategic geographical position for understanding the glacial history of the British Isles. The island bears evidence of glaciation, largely in the form of ice-moulded bedrock and glacially-transported boulders – an unusual occurrence this far south in the British Isles. Irish Sea ice penetrated the western Bristol Channel overriding Lundy from the northwest during the last phase of glaciation in this area. The results of paired terrestrial cosmogenic nuclide analyses ($^{26}\text{Al}/^{10}\text{Be}$) constrain the timing of this extensive glaciation and provide, for the first time, an age for the exposure of Lundy granite following deglaciation. The results from nine paired samples yield $^{26}\text{Al}/^{10}\text{Be}$ exposure ages of 31.4–48.8 ka (^{10}Be) and 31.7–60.0 ka (^{26}Al). This challenges the view that any glaciation this far south must belong to Middle Pleistocene glaciations, such as the Anglian Stage (c. 480–420 ka) and a Devensian age for the last glaciation is consistent with findings from the Isles of Scilly further south. However, the findings suggest early-mid Devensian (marine isotope stage (MIS) 4–3) glaciation of Lundy. It also implies that the island was exposed or covered for a short time by non-erosive cold-based ice at the global Last Glacial Maximum (LGM) during MIS 2 (26–21 ka). The potential exposure of the island throughout MIS 2 contrasts with the evidence from the Isles of Scilly and the Celtic Sea, which were glaciated at the LGM.

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1. Introduction

Lundy lies in an important strategic position for understanding the glacial history of the British Isles (Fig. 1). Along with the Isles of Scilly (Scourse, 1991; Hiemstra et al., 2006) Lundy is unique in recording offshore terrestrial evidence of glaciation at the southernmost limits of the Pleistocene glaciation of the British Isles. Mitchell (1968) interpreted smoothed bedrock features in the north of the island as glacial in origin and deep dry valleys in the northeast of the island as glacial meltwater channels. Mitchell also identified a large area of surface gravels composed of numerous erratic clasts on the watershed of the northern part of the island. Mitchell (1968) suggested that Lundy was glaciated by ice from the northwest during both the Anglian cold stage and 'Wolstonian

Interval'. Bowen (1994) suggested an even older age – Marine Isotope Stage (MIS) 16 – for the Lundy gravels, although no geochronological evidence was reported. The evidence of glacial features on Lundy combined with the presence of what was originally reported as till in the Barnstaple area has been used to argue that ice was present in Barnstaple Bay during the Pleistocene (Stephens, 1966; Mitchell, 1968; Taylor, 1974). Although subsequently re-interpreted as proglacial lake sediments with dropstones (Croot et al., 1996), the sediments still imply a nearby ice-sheet margin. This evidence has also been used to support claims of ice reaching the Cornish coast to the southwest, such as at Trebetherick (Clarke, 1969), although some of the largest clasts at this site are now thought to be sourced from an inland area near Bodmin Moor (Scourse, 1996, p. 45).

Bowen et al. (2002) used ^{36}Cl to provide exposure ages for glacial landforms around Ireland and demonstrated that the most extensive phase of glaciation in many areas dates from the Early Devensian. A ^{10}Be exposure age of 19.8 ka from an upturned boulder on the Isles of Scilly (McCarroll et al., 2010), at the

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Fig. 1. Geomorphological map of Lundy showing location within the British Isles. Sample locations are illustrated on this map.

southernmost limit of an Irish Sea Ice Stream (ISIS), may suggest a Late Devensian age close to the global Last Glacial Maximum (LGM; 21 ka) a date which is supported by radiocarbon and thermoluminescence dates (Wintle, 1981; Scourse, 1991, 2006).

Furthermore, this age for the glacial and related sediments on the Isles of Scilly is independently supported by ice rafted debris of Celtic Sea sources in continental margin cores from the Goban Spur that date to Heinrich Event 2 (Scourse et al., 2000, 2009;

Haapaniemi et al., 2010). This pulse may well represent the Celtic Sea advance to Scilly during the LGM, as discussed in Scourse and Furze (2001).

In Wales, some areas of Pembrokeshire (such as the Preseli Hills) appear to have been ice-free during the Devensian (McCarroll et al., 2010). However, a glacial boulder on the Gower Peninsula, 70 km to the north of Lundy, has been dated to the last cold stage (Devensian) using ^{36}Cl exposure-age dating (Phillips et al., 1994), although this site (Arthur's Stone) displays evidence of interference by humans and may not be *in situ*. Nevertheless, the presence of raised beach deposits to the south of this ice limit, thought to belong to the Last Interglacial, support arguments for a Devensian Stage ice limit in South Wales (Bowen, 1994). However, this does not preclude ice overriding and the preservation of older beach deposits as has occurred on the northern parts of the Isles of Scilly (Scourse, 1991). To the east of Gower, a southern offshore ice limit reached into Swansea Bay, then trended back inland north of Bridgend and the Vale of Glamorgan with a southeastern lobe reaching into Cardiff Bay. However, older Irish Sea till and associated erratics are well known south of this limit, such as in the Pencoed area of Bridgend (Bevins and Donnelly, 1992) and underlying the North Somerset Levels (Hawkins and Kellaway, 1971; Kellaway, 1971; Andrews et al., 1984; Campbell et al., 1998), thus confirming glaciation of the Bristol Channel area by ice from the west on at least one occasion during the Pleistocene.

This paper investigates the evidence for glaciation on Lundy, at the western entrance to the Bristol Channel. The main objective is to utilise the strategic position of Lundy to establish the extent and timing of glaciation in this region, which is crucial for understanding the geometry of former ice sheets during the different glaciations in the British Isles. This objective can be achieved by answering two basic inter-related research questions:

- 1) Is there conclusive evidence that Lundy was glaciated?
- 2) If there is conclusive evidence of glaciation, then when did ice last retreat from Lundy?

These questions can be approached by testing various hypotheses, a primary hypothesis and a couple of dependent alternative sub-hypotheses:

Primary hypothesis: Lundy has been glaciated at some point in the Pleistocene.

Sub-hypothesis 1: Lundy was last glaciated during the Devensian (Weichselian) cold stage (MIS 5d-2; 110–11.7 ka).

Sub-hypothesis 2: Lundy was last glaciated during the Middle Pleistocene, during either the 'Wolstonian Interval' (Saalian) cold stage complex (MIS 10–6; 390–120 ka), the Anglian (Elsterian) cold stage (MIS 12; 480–420 ka), or earlier.

2. Study area

Lundy, approximately 4.5×1 km in size, is an exhumed Tertiary granite pluton with a small area of Devonian Morte Slate in its southeastern corner. The quartz-rich granite bedrock covers most of the island (Stone, 1990; Thorpe et al., 1990). Pegmatite veins are present within the granite and in addition to quartz, contain beryl and topaz (McIntock and Hall, 1912). The Lundy granite contains a swarm of dykes of dolerite/basalt, minor trachyte and rhyolite composition (Thorpe and Tindall, 1992). Quaternary deposits consist mainly of colluvium (head), clay-rich lake/pond sediments, surface gravels and boulders. Whilst no till has been reported, the identification of glacial erosional and associated deposition features has been used to argue that Lundy was overridden by glacial ice during the Pleistocene (Mitchell, 1968; Taylor, 1974).

3. Geomorphological mapping

3.1. Methods

The geomorphology of Lundy was mapped onto 1:10,000 Ordnance Survey base maps during three separate field visits in September 2008, July 2009 and April 2010 (Fig. 1). Field mapping was supplemented by aerial photographs obtained from the Cambridge University Collection of Aerial Photographs and an aerial survey of Lundy was also undertaken by CJR in a light aircraft in 2008. Subsurface sediments were investigated, where present, and retrieved using a gouge auger at a total of 50 sites across the island. Fourteen different types of erratic cobbles and pebbles were sampled from cobble/gravel (pebble–granule) spreads in the north part of the island (Fig. 1). A batch of eight siliceous samples were analysed using X-Ray Fluorescence (XRF). These samples were crushed and sieved at the University of Cambridge. The $<63 \mu\text{m}$ fractions were then mixed with binding wax and pressed into pellets and analysed for major elements using XRF at The University of Manchester. The remaining six samples were broken-up in the laboratory and lithologies identified based on close visual inspection of the mineral fragments using a low-power light microscope. Clasts suspected to be carbonates were confirmed using a simple hydrochloric acid effervescent test in the laboratory.

3.2. Results – description of the geomorphology

In this section groups of landforms are described and characterised below. This is followed by a separate section outlining interpretations of their genetic origin.

3.2.1. Widespread streamlining and moulding of granite bedrock landforms

There is widespread smoothing and WNW–ESE lineations of granite bedrock surfaces, especially in the northern half of the island. At the smallest scale, lineations are in the form of grooves 10–20 mm deep and 10–50 mm wide, cut into the bedrock and visible by eye in the field. At the largest scale, lineations are visible from the air and incorporate regular alignment of whaleback bedrock outcrops (Fig. 2), pavements (Fig. 3) and channel-forms (>1 m in width).

3.2.2. Erratic gravels in the north island watershed

Large spreads (400×200 m) of erratic cobbles and gravels are present to a depth of 30 cm over bedrock pavements on the watershed of the northern part of the island (Fig. 3). Clasts are predominantly rounded–subrounded (Well-rounded 10%; Rounded 40%; Subrounded 30%; Sub-angular 20%). Some of the clasts exhibit shapes similar to dreikanterers (ventifacts) – see Sections 3.2.6 and 3.3.6. The results of XRF analyses from 7 of these samples (PH 1–7) are presented in Table 1 alongside geochemical results from local Lundy granite (PH 8). The local Lundy granite (PH 8) has a distinctive geochemistry with 71% SiO_2 , 16% Al_2O_3 and 9% combined Na_2O and K_2O (3 and 6% respectively) and also a distinctive physical appearance (Table 1). The erratics samples analysed by XRF are all siliceous but have contrasting geochemical and physical characteristics compared with the local Lundy granite. Three samples (PH 2, 3 & 7) contain $>90\%$ SiO_2 and these have a geochemical and physical properties similar to quartzites (Table 1). Two clasts (PH 4 and 6) have 75–80% SiO_2 with $>2.5\%$ combined Na_2O and K_2O and $>10\%$ Al_2O_3 and have geochemical and physical properties similar to rhyolites (Table 1). Two samples (PH 1 and 5) had SiO_2 contents of $>81\%$ and had geochemical and physical characteristics consistent with a sedimentary origin. The fine-grained mineralogy indicates that these are mudstones.

Fig. 2. A. Ice-moulded whaleback bedrock on the northwest coast of Lundy. B. Ice-moulded whaleback bedrock in Gannets' Combe, which drains into Gannets' Bay on the northeast coast of Lundy.

However, these pebbles had differing geochemistries (Table 1) and are likely to have different origins. In addition to the 7 siliceous erratics identified using XRF analyses, several erratic sedimentary clasts were also identified from hand specimens including limestone ($n = 3$), sandstone ($n = 2$) and quartzite ($n = 1$).

3.2.3. Widespread scattered large subrounded boulders

Large subrounded boulders (1–2 m diameter) of local granite are present in many parts of the island, often well away from tors and resting on elevated ground (Fig. 4A and B). In the north of the island boulders are found scattered over bedrock pavements (Fig. 3). They are also present in the south of the island, especially over the area of Ackland's Moor (Fig. 1). Here, the widely scattered boulders either rest on or are emplaced into the thin regolith on the moors and fields (Fig. 4B).

3.2.4. Blue clay–silt deposits in the southern half of the island

Augering revealed that blue clays and silts reach a maximum thickness of 4 m in parts. The thickest accumulations of these blue clays and silts are found in the southern half of the island in the vicinity of the church. This area is close to the highest watershed of

the island. The blue clay–silts contained very little organic material and are closely associated with diamicton deposits marked on Fig. 1.

3.2.5. Dry channels

Dry channels (5–10 m width) are present on the west and east coasts of the north island. Larger dry channels (50–100 m width, 300–400 m length) are present at Gannets' Combe (draining into Gannets' Bay) in the north of island and at Millcombe in the south (Fig. 1). The channels trend from west to east.

3.2.6. Tors, breccia, angular colluvium and ventifacts

Upstanding bedrock tors are present on the coastal fringes of Lundy especially in the west and northeast of the island, close to coastal cliff edges such as at The Cheeses (Fig. 1). Some of these tors have collapsed. Many of the tors have collapsed in an easterly direction and lines of blocks can be traced from the tors and appear to have been transported tens of metres from their origin in an easterly direction. Angular clast-rich deposits mantle the southern and western coastal slopes along with surface talus. On the rock pavements of northern Lundy many of the erratic clasts described above exhibit shapes similar to ventifacts, such as dreikanterers.

Fig. 3. A. Ice-moulded rock pavements with perched boulders in the northwest part of the island. This area also contains a large spread of erratic gravel and cobbles. Photograph is looking north. B. A large perched boulder in the northwest part of the island. Photograph is looking south.

Table 1

Dominant major element geochemical data (% of total composition) from a sample of the local Lundy granite (PH 8) and from 7 pebble clasts on the watershed in the NW part of Lundy (PH 1–7).

	PH 8	PH 7	PH 6	PH 5	PH 4	PH 3	PH 2	PH 1
Elements/ rock type	Lundy granite	Quartzite	Rhyolite	Sedimentary (mudstone)	Rhyolite	Quartzite	Quartzite	Sedimentary (mudstone)
Physical appearance	Coarse-grained grey, white and black mineral crystals	Fine-grained pink pebble with quartz veins	Fine-grained light blue-grey pebble. Homogenous crystals	Fine-grained dark grey pebble. Homogenous crystals	Fine-grained light blue-grey pebble. Homogenous crystals.	Light grey fine-grained pebble	Light grey fine-grained pebble	Fine-grained dark grey pebble. Homogenous crystals
SiO ₂	70.984	94.171	79.527	81.944	75.798	96.166	98.433	84.827
Al ₂ O ₃	15.901	3.321	10.160	6.871	12.361	1.452	0.346	7.699
Na ₂ O	3.297	0.066	0.802	0.863	1.469	0.025	0.025	0.133
K ₂ O	5.938	0.457	1.798	0.601	1.835	0.358	0.048	2.671
Fe ₂ O ₃	2.232	1.547	5.944	8.010	6.219	1.004	0.712	3.420

3.3. Results – interpretations of the geomorphology

3.3.1. Widespread streamlining and moulding of granite bedrock landforms

The widespread streamlined and moulded granite bedrock surfaces are interpreted as ice-moulded landforms and Lundy has striking similarities to upland ice-moulded granite landscapes (e.g. Cowton et al., 2009). However, whilst these erosional surfaces provide the most striking evidence of glaciation on the island, evidence of smoothed and lineated bedrock surfaces alone is insufficient to substantiate a glacial interpretation. This is because granite can often weather subaerially to form smooth surfaces and lineations can form as a result of preferential weathering along structural fractures.

3.3.2. Erratic gravels in the north island watershed

The gravels that are widely spread over the northern island watershed include numerous clasts that are foreign to the local lithologies. Mitchell (1968) identified 100 rounded clasts. The methods used by Mitchell to identify these clasts is not stated in his paper only that they “were collected and identified as follows”:

“Possibly of island origin” 35 clasts including quartz: 22; miscellaneous igneous: 9; mica schist: 2; haematite: 1; limonite: 1

“Probably not of island origin” 38 clasts including grey quartzite: 25; pink quartzite: 13

“Certainly not of island origin” 27 clasts including coarse sandstone: 9; flint: 8; chert: 3; micaceous sandstone: 2; sandstone with carbonaceous debris: 1; greywacke: 1; ignota: 3

The physical and geochemical differences between the erratics and the Lundy granite are clear from the XRF analysis of 8 clasts in this study (Table 1). The sample of Lundy granite had the following major element composition: 71% SiO₂; 16% Al₂O₃; 6% K₂O, and; 3% Na₂O. This is representative of Lundy granite and is broadly consistent with major element data from Lundy granite presented in Stone (1990). Three clasts had very different SiO₂ contents of 94–98% (PH 2, 3 & 7). These are interpreted as quartz or quartzite erratics. All of the clasts were fine-grained but varied in colour and appearance (PH 2 and 3: light grey; PH 7: pink with quartz veins). Some of the most extensive quartzite formations in the southern Irish Sea area are present on the coasts of both northwest Wales in Anglesey and the Llyn Peninsula (Phillips, 1992) whilst quartz pebbles are widespread in the Millstone Grit of the Pembrokeshire coalfield (Archer, 1965). The very high SiO₂ content of these clasts is higher than some quartzites in Wales (e.g. Phillips, 1992) and it may be that these clasts are quartz erratics reworked from conglomerates such as Millstone Grit. Pink quartz veins are also present in Morte slate, which is present in the SE corner of the island and some of the quartz-rich samples may be of local origin. Nevertheless, there are no quartz or quartzite outcrops in the area of the gravel spreads on Lundy and these clasts are clearly erratic to where they are found. Two other clasts had SiO₂ contents of 82%

Fig. 4. A. Glacially-transported boulder on the watershed of the north island north of Gannets' Bay. B. Glacially-transported boulder on Ackland's Moor in the southern part of Lundy.

(PH 5) and 85% (PH 1). This suggests that the clasts are not volcanic since even the most quartz-rich rhyolites rarely exceed 80% SiO₂. The clasts are more siliceous with lower aluminium oxide contents than most sandstones and mudstones of the southern Welsh basin, for example (cf. McCann, 1991). The clasts have no comparable equivalent within the Lundy volcanics. As noted in the previous paragraph, the southeast tip of Lundy is formed of Morte Slate and this lithology is likely to be present offshore. However, Upper Devonian slates of this region contain much less SiO₂ (c. 55–60%) and much more aluminium oxides (>20%) and potassium oxides (≥4%) (Cattell, 1998). Thus, these clasts have not been derived from the Lundy country rocks and can be considered to be erratics.

Two samples had similar physical properties (fine-grained light blue-grey clasts) with similar geochemistry with SiO₂ contents of 75.8% and 79.5% and combined Na₂O and K₂O of 2.6% and 3.3%. These samples are similar to some rhyolites. On Lundy, rhyolite dykes are known to be present – including in the north of the island near the gravel spreads where the clasts were found (Thorpe and Tindall, 1992). However, the local rhyolites have much higher values of combined Na₂O and K₂O (7.8–10.5%). Furthermore, the clasts have much higher iron oxide content (Fe₂O₃: 6%) than most of the Lundy rhyolites that have otherwise comparable geochemistries (Fe₂O₃: 1–2%). The clasts have a closer geochemical composition to rhyolites from the thick rhyolite sequences of the Skomer Volcanic Group off the westernmost coast of Pembrokeshire (e.g. Thorpe et al., 1989) although the precise origin remains unknown.

In addition to the siliceous clasts analysed using XRF, several limestone clasts collected from the gravel spreads are clearly erratics since no carbonate bedrock lithologies are found on or near Lundy. Given that rhyolites, quartz/quartzites, siliceous sedimentary and carbonate limestones are common lithologies, a wide range of sources are possible as noted in the previous paragraphs. Nevertheless, the presence of these erratic clasts is consistent with transport and deposition in association with an Irish Sea Ice Sheet. The fact that the clasts are well-sorted into cobbles and gravels and predominantly rounded suggests deposition by water. The presence of these deposits on the watershed is consistent with sediment release at the apex of bedrock obstacles in subglacial channels (cf. Lesemann and Brennand, 2009).

3.3.3. Widespread scattered large subrounded boulders

The large subrounded boulders present on bedrock pavements in the northern part of the island, and widely scattered all over the southern half of the island, are interpreted as glacially-transported boulders.

3.3.4. Blue clay–silt deposits in the southern half of the island

The thick blue clay–silt deposits around St Helena's Church in the southern half of the island are interesting because they are present close to the watershed of Lundy and not in a topographic basin. This does not support a theory of deposition in a subaerial lake basin. It is possible that these inorganic clay–silt deposits formed in a subglacial tunnel during ice sheet retreat under low water pressures. Although the clays are not in a basin, they are adjacent to the Millcombe meltwater channels.

3.3.5. Dry channels

The dry channels are interpreted as subglacial meltwater channels. The channels are likely to have exploited structural weaknesses in the bedrock, such as along major joints. In the north, a network of some of the largest and interconnected channels can be found at Gannets' Combe. Immediately upslope of these channels to the west are the large spreads of erratic cobbles and gravels,

further supporting the idea that this area was a major subglacial meltwater route over the Lundy obstacle.

3.3.6. Tors, angular colluvium, talus and ventifacts

The upstanding bedrock outcrops (tors) of Lundy are formed by the preferential subaerial weathering of existing weaknesses within the granite. The evidence of perched blocks immediately east and southeast of these tors suggests that they have been modified by ice (Stephens, 1966; Mitchell, 1968). This is similar to the displacement of granite blocks from tors by former ice sheets observed on the summits of the Cairngorms (Phillips et al., 2006). Angular breccia deposits that mantle the steep coastal slopes in the east of the island are interpreted as colluvial material. Evidence for a prolonged period of periglacial environment is indicated by the presence of numerous dreikanter clasts in the north of the island. These dreikanter are formed in erratic clasts and along with the tors, breccia, angular colluvium and talus, may illustrate that a prolonged period of periglacial conditions prevailed on Lundy after the last ice disappeared from the island (cf. Knight, 2008). Alternatively, these clasts may be reworked from pre-existing sediments, although preservation of such clear clast morphologies seems unlikely at the base of an eroding ice sheet.

4. Terrestrial cosmogenic nuclide analyses

The quartz-rich granite samples are suitable for examining the exposure history using ²⁶Al and ¹⁰Be analyses. A complicating factor is that Lundy may have experienced a complex exposure history in the past. For example, the island may have been covered by cold-based (non-erosive) ice, till, soil or other material for unknown periods after the sampled landforms were formed, possibly resulting in a complex (i.e. multiple) exposure history. It is, however, possible to test such a possibility by applying multiple cosmogenic nuclide analyses such as ¹⁰Be and ²⁶Al in combination on the same landform surface (e.g. Bentley et al., 2006; Miller et al., 2006). Thus, this study utilised both ¹⁰Be and ²⁶Al analyses for each of our samples. Paired nuclide analyses are useful because ¹⁰Be and ²⁶Al have different half-lives and very different production rates and the ratios between the two nuclides present in a rock surface can help tease out a complex exposure history, which cannot be done by just relying on a single nuclide approach.

4.1. Field methods

Rock samples were collected using a club hammer and chisel, each sample being 500 g–1 kg and approximately 60% quartz. Samples were taken from bedrock landforms interpreted as glacial in origin. These were largely grooved whaleback bedrock forms. Low-lying bedrock pavements prone to burial and chemical solution were avoided. The latter was often clearly expressed by the presence of gnammas. Large granite boulders that are scattered over the island were not sampled either. Whilst many of these boulders are interpreted as glacially-transported, the local granite lithology indicates that transport distances were small and it is possible that ice removed these boulders from tors on the west coast of the island. There is a risk, therefore, of an inherited signal in the terrestrial cosmogenic nuclide concentrations in the surfaces of these boulders.

Seven samples were taken from normal coarse-grained Lundy granite whilst one sample LC5a was taken from a pegmatite vein. A duplicate sample (LC5d) was analysed at the LC5a site in order to test for beryl and topaz in the pegmatite vein, since beryl and topaz are known to be present in the Lundy granite (McLintock and Hall, 1912). High levels of ⁹Be and ²⁷Al in beryl and ²⁷Al in topaz are

associated with pegmatic granites and can have an effect on surface-exposure ages (Bierman et al., 2002) – see below.

4.2. Laboratory methods: sample preparation and AMS measurement

The density of the whole granite samples was measured in the laboratory using water displacement. Samples were then crushed and dry-sieved in the Department of Earth Sciences, University of Cambridge, before submitting to SUERC.

Purified quartz was obtained from the 250–500 μm size fraction of the crushed rocks and BeO targets were prepared for $^{10}\text{Be}/^9\text{Be}$ analysis using the procedure described in Wilson et al. (2008) as modified in Glasser et al. (2009). Further modifications compared to Glasser et al. (2009) are: (1): the sample preparation was also carried out for ^{26}Al (see below); (2) c. 210 μg Be was added as carrier and (3) c. 12–30 g sample was dissolved.

4.2.1. ^{10}Be

The $^{10}\text{Be}/^9\text{Be}$ ratios were measured with the 5 MV accelerator mass spectrometer at SUERC (Xu et al., 2010). Ion currents of $^9\text{Be}^{16}\text{O}^-$ were between 3 and 7 μA . NIST SRM 4325 with a $^{10}\text{Be}/^9\text{Be}$ ratio of 2.79×10^{-11} (in agreement with Nishiizumi et al., 2007) was used for normalisation. The denominator of the $^{10}\text{Be}/^9\text{Be}$ ratios obtained in the AMS measurement was total Be and not only the amount of Be-carrier added. Corrections for native Be – most likely caused by beryl and/or topaz were high for some samples. The uncertainty of the total amount of Be (uncertainty of Be concentration in the carrier solution for the carrier amount and uncertainty of the ICP-MS measurement of native Be) was used for this correction. These corrected $^{10}\text{Be}/^9\text{Be}$ ratios were further corrected for $^{10}\text{Be}/^9\text{Be}$ of the processing blanks prepared with the samples. One-sigma uncertainties of the SUERC AMS measurement include the uncertainty of the sample measurement, the uncertainty associated with the correction for native Be, the uncertainty related to the measurement of the primary standard and the uncertainty of the blank correction.

4.2.2. ^{26}Al

No Al carrier was added to the dissolved samples. Native aluminium was determined with ICP-OES at SUERC. One-sigma uncertainties of total Al were typically 3%. The measurement procedures at the SUERC AMS are described in detail in Xu et al. (2010). Typical ion currents of ^{27}Al were 300 nA. Z92-0222 (donated from PRIME Lab, Purdue) and a nominal $^{26}\text{Al}/^{27}\text{Al}$ ratio of 4.11×10^{-11} was used as primary standard. The measurements of this material agree with the measurements of standard material supplied by Nishiizumi (2004). The treatment of the uncertainties that contribute to the uncertainty of the ^{26}Al concentration in atoms g^{-1} quartz is described in Roberts et al. (2008).

4.3. Minimising and accounting for the effects of beryl (and topaz)

Beryl and topaz are known to be present in the Lundy granite (McIntock and Hall, 1912) and naturally-occurring ^9Be in beryl (and similarly ^{27}Al in topaz) could have an effect on the surface-exposure ages of samples collected on Lundy. If abundant beryl is present within samples and a substantial amount is dissolved during sample preparation, then this can potentially produce an exposure age that is too young, by decreasing the $^{10}\text{Be}/^9\text{Be}$ ratio, presumably coming only from quartz. Most quartz mineral separates contain negligible Be (^9Be), but in some cases – in pegmatite granites – concentrations can be as high as 2–37 ppm (Bierman and Caffee, 2002). During sample processing, Be-carrier is added to dissolved “quartz” samples for the purpose of measuring

$^{10}\text{Be}/^9\text{Be}$ values by AMS. It is normally assumed that all ^{10}Be is cosmogenic and any ^9Be present in the analysis was added via the Be-carrier. If beryl were present in Lundy samples, additional ^9Be could be present in the $^{10}\text{Be}/^9\text{Be}$ system that was later measured on AMS. This effect can be corrected for by analysing the native Be concentration in the dissolved sample.

However, since beryl and topaz are relatively resistant to dissolution by hydrofluoric acid (compared with quartz), this is unlikely to be a major factor in affecting calculated exposure ages. Nevertheless, steps were taken to minimise and account for these contributions, such that the uncertainty in age determinations will be mainly a result of surface processes, rather than of mineralogical or chemical complications. This was done in the field by limiting the number of samples from pegmatite veins where beryl and topaz minerals are abundant, and also by careful preparation and observation during chemical preparation of the samples in the laboratory. Other than LC3b, LC4b, and LC5a, all samples underwent heavy-liquid separation, in order to remove more dense topaz and beryl from the “pure” quartz separates prior to their HF-dissolution. Most samples had negligible residue after hydrofluoric acid treatment, and the carrier amount of ^9Be was corrected for the amount that native ^9Be dissolved. In some cases this correction was substantial and in other cases small. Substantial amounts of ^{27}Al in the sample to be dissolved can give rise to decreased $^{26}\text{Al}/^{27}\text{Al}$, and thus reduced $^{26}\text{Al}/^{10}\text{Be}$ ratios compared to the production rate line from quartz. The underlying reason is that the production-rate ratio $^{26}\text{Al}/^{10}\text{Be}$ in topaz is 16.4 (calculated based on elemental production rates from Masarik, 2002) – compared to 6.75 in quartz. The ($n,2n$) reaction on ^{27}Al dominates this effect. Moreover, ^{26}Al can be preferentially leached from residue compared to ^{27}Al – this is because ^{26}Al is located in distorted lattice positions due to its formation from high-energy reactions.

4.4. Results – ^{10}Be and ^{26}Al analyses

The ^{10}Be and ^{26}Al results are shown in Table 2. All ages cited in the main text are calculated in CRONUS-Earth webcalculator version 2.2 (constants 2.2.1) (Balco et al., 2008) using the time-dependent Lal/Stone production rate model (Lal, 1991; Stone, 2000).

Plots of the $^{26}\text{Al}/^{10}\text{Be}$ ratios versus ^{10}Be concentrations show that 6 of the 9 sampling locations give exposure ages that agree within a two-sigma error range with the production-rate ratio line, and there is approximate agreement between ^{26}Al and ^{10}Be ages (Figs. 5 and 6). This indicates that there is no evidence for complex exposure history in these samples and that Lundy has not been covered by cold-based ice, or any other material (i.e. thick soils) at time-scales accessible by the $^{26}\text{Al}/^{10}\text{Be}$ system, after the last phase of erosion (see Discussion section for more on this). Two samples (LC3b and LC4b) yielded nuclide data that falls entirely below the production-rate ratio line. Another sample (LC6b) yielded a $^{26}\text{Al}/^{10}\text{Be}$ ratio of 8.24 and agrees only within two standard uncertainties with the production-rate ratio line. This sample is located in the so-called ‘forbidden zone’ (Lal, 1991) indicating possible enhanced production of ^{26}Al from ^{27}Al compared to SiO_2 as well as preferential leaching of ^{26}Al compared to ^{27}Al from Al-bearing minerals. However, there were no enhanced ^{26}Al blanks in the laboratory analyses and, therefore, no evidence for contamination with ^{26}Al .

5. Discussion

The geomorphological evidence and results of $^{10}\text{Be}/^{26}\text{Al}$ analyses from Lundy provides important insight into the glacial history

Table 2
 $^{10}\text{Be}/^{26}\text{Al}$ cosmogenic nuclide results from ice-moulded bedrock on Lundy. Exposure ages are calculated in the CRONUS-Earth webcalculator using the time-dependent Lal/Stone scaling scheme (Lal, 1991; Stone, 2000). No topographic shielding correction needed to be applied to the samples. Uncertainties are at one sigma. Sample density was measured in the laboratory at 2.4 cm g^{-1} .

Sample ID	AMS ID SUERC...	Latitude (°N)	Longitude (°W)	Altitude (m)	Sample thickness (cm)	Radionuclide conc. (10^5 at/g) $^{10}\text{Be}^b$ $^{26}\text{Al}^c$	Exposure age (ka) no erosion ^a	Exposure age (ka) 1 mm ka^{-1} erosion rate ^a	Exposure age analytical uncertainty (ka) no eros.	$^{26}\text{Al}/^{10}\text{Be}$ (at/at)
LC1a (^{10}Be)	b3858	51.19	4.67	102	3	1.669 ± 0.055	34.1 ± 3.1	35.0 ± 3.3	1.1	7.22 ± 0.45
LC1a (^{26}Al)	a1067					12.05 ± 0.64	36.7 ± 3.7	37.7 ± 3.9	1.9	
LC2a	b3859	51.2	4.67	104	3	1.535 ± 0.053	31.4 ± 2.9	32.1 ± 3.0	1.1	7.33 ± 0.47
LC2a	a1068					11.25 ± 0.60	34.1 ± 3.5	35.0 ± 3.7	1.8	
LC3b	b3284	51.2	4.67	104	3	2.034 ± 0.069	41.5 ± 3.8	42.8 ± 4.1	1.4	5.72 ± 0.36
LC3b	a962					11.64 ± 0.61	35.1 ± 3.5	36.0 ± 3.7	1.8	
LC4b	b3288	51.2	4.68	106	3	2.247 ± 0.075	46.0 ± 4.2	47.6 ± 4.5	1.5	5.82 ± 0.32
LC4b	a963					13.08 ± 0.56	39.6 ± 3.8	40.8 ± 4.1	1.7	
LC5a	b3599	51.2	4.68	94	3	1.556 ± 0.058	32.1 ± 3.0	32.5 ± 3.5	1.2	6.66 ± 0.39
LC5a	a964					10.36 ± 0.48	31.7 ± 3.1	32.4 ± 3.2	1.4	
LC5ad	b3638	51.2	4.68	94	3	1.878 ± 0.070	38.8 ± 3.6	39.9 ± 3.8	1.4	6.19 ± 0.49
LC5ad	a982,a984					11.62 ± 0.81	35.4 ± 3.9	35.9 ± 4.5	2.5	
LC6b	b3860	51.19	4.68	97	5	2.329 ± 0.085	48.8 ± 4.5	50.6 ± 4.9	1.8	8.23 ± 0.70
LC6b	a1069					19.17 ± 1.48	60.0 ± 5.2	62.8 ± 7.8	4.6	
LC8b	b3861	51.18	4.67	115	3	1.583 ± 0.058	31.8 ± 3.0	32.6 ± 3.1	1.2	7.42 ± 0.53
LC8b	a1070					11.75 ± 0.72	35.3 ± 3.7	36.2 ± 3.9	2.1	
LC9b	b3864	51.17	4.68	124	3	1.853 ± 0.064	37.0 ± 3.4	38.0 ± 3.6	1.3	7.35 ± 1.17
LC9b	a1071					13.62 ± 2.11	40.4 ± 3.5	41.6 ± 7.7	6.2	

^a CRONUS-Earth webcalculator; Wrapper script 2.2; Main calculator 2.1; Constants 2.2.1; Muons 1.1. (Balco et al., 2008).

^b NIST SRM 4325 with a $^{10}\text{Be}/^{26}\text{Be}$ ratio of 2.79×10^{-11} was used for normalisation.

^c Normalisation is in agreement with standards provided by K. Nishiizumi (KNSTD in the Cronus-webcalculator).

of the southwestern extension of the British Irish Ice Sheet. However, the results also pose apparent contradictions with other evidence from the British Isles, which require consideration. One interpretation of the exposure ages is that they simply reflect the subaerial weathering rates of the Lundy granite. However, the fact that samples were taken from both normal coarse-grained granite and also a pegmatite vein helps to falsify this possibility. Pegmatite veins tend to be upstanding from the rest of the Lundy granite by several centimetres suggesting that the veins are more resistant. This is important because similar ages from the pegmatite vein to the 'average' ages yielded from normal granite surfaces suggests that the ice-moulded bedrock surfaces on Lundy are stable and have undergone minimal erosion since exposure. In Table 2 exposure ages are presented based on erosion rates of zero and 1 mm ka^{-1} . The significance of erosion was tested by comparing the exposure ages yielded from normal granitic surfaces with those from the resistant pegmatite veins. As noted in the previous paragraph, the ^{26}Al and ^{10}Be exposure ages from the pegmatite vein sample (LC5a; $31.7 \pm 3.1/32.1 \pm 3.0 \text{ ka}$, and LC5ad; $35.4 \pm 3.9/38.8 \pm 3.6 \text{ ka}$ – see below for discussion of the difference in these duplicate ages) were no older (within uncertainty) than the ages from normal granite surfaces. It is possible that agreement of exposure ages simply illustrates that the erosion rates of the pegmatite veins and the surrounding granite are similar with upstanding veins being the result of step-wise erosion in contrast to steady erosion of the surrounding surfaces. However, the mineral topaz, which is a significant component of the pegmatite veins on Lundy (McIntock and Hall, 1912) is more resistant than quartz, which is a dominant mineral in the surrounding granite (topaz, Mohs scale hardness = 8; quartz, Mohs scale hardness = 7; Monroe and Wicander, 1995, p. 38). This suggests minimal erosion rates, and in this paper we refer to ages calculated assuming a zero erosion rate.

Near-zero erosion rates on Pleistocene glaciated surfaces are not unusual since in many parts of the British Isles many exposed glacial surfaces still preserve clear striae, such as in Snowdonia (e.g. Gemmell et al., 1986). The absence of similar striae on the Lundy

granite is not due to significant weathering but is because striae tend to form best on fine-grained bedrocks rather than coarse-grained granites and striae are also absent from the Isles of Scilly (Scourse, personal communication). Nevertheless, whilst there is no evidence of significant erosion based on similarities in exposure ages on the normal granite and resistant pegmatite veins, there is geomorphological evidence of localised weathering on the granite in the form of gnammas. The gnammas on Lundy have depths ranging from 26 to 106 mm with an average of 57 mm. Given a mean exposure age of c. 35 ka on intact surfaces outside of these gnammas, this implies an erosion rate of 1.6 mm ka^{-1} , which is very similar to erosion rates estimated for the Cairngorm granite in Scotland (Phillips et al., 2006). However, since all samples for cosmogenic nuclide analysis were taken from outside of gnammas on apparently intact surfaces, erosion rates at the sampling sites are

Fig. 5. "Banana" plot for ^{10}Be and ^{26}Al ages of samples collected on Lundy. Six out of nine of the ^{10}Be and ^{26}Al ages are statistically indistinguishable and the $^{26}\text{Al}/^{10}\text{Be}$ ratios overlap (within two-sigma uncertainty) the constant-exposure production-rate ratio line. This indicates that most of the samples do not have complex exposure histories detectable by the $^{26}\text{Al}/^{10}\text{Be}$ system.

Fig. 6. ^{26}Al and ^{10}Be ages from the Lundy bedrock samples. MIS: Marine Isotope Stage; YD: Younger Dryas; LGM: Last Glacial Maximum.

likely to have been significantly less than 1.6 mm ka^{-1} . Very old surfaces would produce wider and deeper gnammas eventually leading to variable breakdown of the rock surfaces and degradation of any previously ice-moulded bedrock. This would result in a wide scatter of exposure ages, unlike the data yielded from the surfaces of the Lundy granite, the majority of which is tightly scattered between 40 and 30 ka (Fig. 6, Table 2). This is further support for a Devensian rather than older glaciation and subsequent exposure of Lundy.

The comparison of the cosmogenic data from the normal Lundy granite and the pegmatite vein is also important for testing whether beryl and topaz minerals within these rocks have affected the cosmogenic nuclide signal. The presence of these minerals in the “purified” quartz used for age determinations can potentially produce an exposure age that is too young (see Section 4.3). Pegmatite granites are known to be at risk of higher levels of ^9Be and ^{27}Al in beryl and ^{27}Al in topaz than other granites (Bierman et al., 2002). If this is true for Lundy then we would expect to find a difference in the nuclide concentrations (and associated ages) between the normal granite and the pegmatite veins which are known to be richer in beryl and topaz (McLintock and Hall, 1912). The ^{26}Al and ^{10}Be exposure ages from the duplicate pegmatite vein samples (LC5a; $31.7 \pm 3.1/32.1 \pm 3.0 \text{ ka}$, and LC5ad; $35.4 \pm 3.9/38.8 \pm 3.6 \text{ ka}$) provide insights into the effects of beryl and topaz on the Lundy exposure ages. LC5a ages are nominally younger than LC5ad. This is most likely due to the presence of extra ^9Be and ^{27}Al from partially dissolved beryl and topaz; a heavy-liquid density separation was not part of the preparation of sample LC5a, unlike LC5ad. As noted in Section 4.3, other than LC3b, LC4b, and LC5a, all samples underwent heavy-liquid separation and the effects of beryl and topaz on the exposure ages are likely to be minimal.

Another possible explanation of the results is that all of the exposure ages from Lundy are too old and that Lundy was last exposed following ice sheet retreat shortly after the global LGM at 26–21 ka – as has been argued for the Isles of Scilly and Pembrokeshire (McCarroll et al., 2010). If ages are affected by inheritance, due to the inability of the ice sheet to erode to sufficient depth, then a wide range of exposure ages would be expected since erosion would have been widely variable as the sites lie in a variety of positions: some on the stoss-side of the Lundy obstacle, some on the apex, and some on the lee-side. This is not the case for the majority of samples. The majority of ^{26}Al and ^{10}Be ages are within error of each other and there is only one sample that yielded exposure ages more than 10 ka different than all other samples (LC6b). Two samples (LC3b and LC4b) yielded nuclide data that falls entirely below the production rate line. Quartz from samples LC3b and LC4b was not processed with a heavy-liquid density separation,

as at the time of sample preparation, the presence of beryl and topaz was not yet known. The exposure ages yielded by these samples could thus be affected by the presence of “extra” ^9Be and ^{27}Al , and could thus be younger than the “actual” exposure ages. This may explain why the $^{26}\text{Al}/^{10}\text{Be}$ values fall below the constant-exposure line. Of course, the ages may be representative and unaffected by extra ^9Be and ^{27}Al , in which case, a geomorphological explanation must be considered. The low $^{26}\text{Al}/^{10}\text{Be}$ values for these two samples may indicate the surface from which they were sampled has experienced a complex history of irradiation and burial (Lal, 1991). However, since this is restricted to these samples and not evident in any of the other samples this complex exposure history is likely to be explained by the presence of “extra” ^9Be and ^{27}Al .

Whilst the $^{26}\text{Al}/^{10}\text{Be}$ data shows that 6 of the 9 samples show no signs of a complex exposure history (see Section 4.4. Results – ^{10}Be and ^{26}Al analyses, above), this interpretation is limited by the sensitivities of the time-scales accessible by the $^{26}\text{Al}/^{10}\text{Be}$ system. For example, if an exposed rock surface is later buried under ice for 50 ka the ^{10}Be concentration will be reduced by 2.5% and the ^{26}Al concentration by 4.8% (based on ^{10}Be and ^{26}Al decay constants from Nishiizumi, 2004; Chmeleff et al., 2010; Korschinek et al., 2010, respectively). Present measurement uncertainties means that such low reductions in concentration will not be detectable, and a 50 ka burial is therefore too short to be detected by $^{26}\text{Al}/^{10}\text{Be}$ measurements. This means that the exposure ages from Lundy could represent composite exposure ages and are potentially too old. The likelihood and implications of this issue are explored further below.

5.1. Implications of the Lundy findings for the glacial history of SW British Isles

This paper confirms that Lundy has been glaciated in the Quaternary, as originally proposed by Mitchell (1968) and reiterated in reviews such as that by Harrison and Keen (2005). The glaciation of Lundy and the timing of the glaciation have important implications for our understanding of the southwestern margins of the British Ice Sheet during the last cold stage. The glaciation of the Bristol Channel (and therefore Lundy) has long been associated with erratic-bearing clay deposits at Fremington, near Barnstaple in Devon, and associated erratics along the Devon coast (Maw, 1864; Dewey, 1910; Taylor, 1956, 1958; Vachell, 1963; Arber, 1964; Kidson and Wood, 1974). However, the chronostratigraphy of the Fremington deposits remains problematic. Raised beach deposits around Barnstaple Bay have been ascribed to the Middle Pleistocene and the Fremington ‘Till’ to the Anglian Stage (MIS 12) by Bowen et al. (1985), Bowen and Sykes (1988) and by Croot et al. (1996). However, Scourse and Furze (2001) have questioned the Anglian age of the Fremington clay deposits and also argued that the upper Fremington clay series was deposited in a glaciolacustrine environment. They noted that the presence of reworked palynomorphs of Tertiary age within these deposits suggest a grounding ice sheet over the Stanley Bank Basin, a highly organic mid Oligocene sequence situated immediately to the east of Lundy (Boulter and Craig, 1979). The cosmogenic exposure data from Lundy strongly implies that the last glaciation of this island occurred in the Devensian rather than the Anglian. However, further research is required in order to elucidate the relationship between the last Lundy glaciation and the Fremington clays.

Lundy presents a largely erosional record of glaciation. Whilst there are some glacially-transported boulders and erratic gravels on the island, true moraines or till are absent. Moraines and till marking the former margins and recessional positions of the former ice sheet, if present, are likely to be submerged offshore between Lundy and the north Devon coast – over the Stanley Bank

Basin. Prominent asymmetrical sediment ridges do exist off the east coast of Lundy. However, these have been interpreted as bifurcating high frequency sand waves (James et al., 2004, see their Fig. 14; Mackie et al., 2006, see their Fig. 4.1). Ice moving over Lundy would have also been moving up the Bristol Channel. Prominent asymmetrical sediment ridges also exist in this channel but, again, these are interpreted as sand waves in James et al. (2004) and Mackie et al. (2006), although several images of the bed material just to the east of Lundy appear to show poorly sorted mud-rich gravels which could be of glacial or glaciofluvial origin. Ice in the Bristol Channel would have formed a major barrier to drainage – possibly forming an ice-dammed lake. During retreat, the ice-sheet margin would have been separated from the modern coast of Devon by an ice-marginal drainage system. As with other potentially related evidence, this is submerged below the current sea level.

The geomorphology and associated exposure ages from Lundy suggest that the British Irish Ice Sheet (BIIS) in this area had retreated and exposed the island by 40–35 ka – as a result of climatic warming in MIS 3. This would have facilitated the expansion of mammal fauna into SW England and Wales prior to climatic deterioration during MIS 2. For example, radiocarbon evidence shows that Woolly Rhinoceros were present just north of Lundy in South Wales (Paviland, Gower) at 38.5–36.3 ka (Jacobi et al., 2009). Cold-adapted megafauna have also been found along the north Devon coast at Doniford (90 km east) which has a semi-continuously aggrading fluvioperiglacial sequence from 65 ± 5 ka to the early Holocene (Basell et al., 2011). South of this area, at Kent's Cavern in south Devon Woolly Rhinoceros bones yield older

ages (42.9–39.2 ka) (Jacobi et al., 2009). These age differences are consistent with a northward migration of Woolly Rhinoceros as ice retreated during MIS 3. Similarly, recent radiocarbon re-dating of hominid bones from Kent's Cavern indicates that modern anatomical humans were present in south Devon between 44.2 and 41.5 ka (Higham et al., 2011). Again, this could have coincided with the same period of warmer climate and retreat of the BIIS associated with the last exposure of Lundy.

Both the cosmogenic exposure ages from Lundy and the radiocarbon ages from cave sites in SW British Isles suggest climatic amelioration early in MIS 3 and deterioration late in MIS 3. This situation is well known from records around the British Isles (Brown et al., 2002) and wider Europe (van Andel, 2002) and it is not unexpected that ice should be retreating and mammal faunas expanding their range at this time. However, pin-pointing the climatic forcing that led to the build-up of the BIIS prior to this period is not easy because of the rapid and high amplitude climatic fluctuations that occurred during this interval. European glaciers would have been strongly influenced by millennial-scale climate changes driven by ocean-atmosphere perturbations in the North Atlantic region and this is especially evident in smaller ice masses at mid-latitudes (Hughes et al., 2006; Hughes and Woodward, 2008). However, given the size of the former BIIS, this ice mass would have been slow to respond to centennial- and millennial-scale climate changes since the rate of glacier response to changing mass balance is inversely related to glacier size (Bahr et al., 1998). Thus, it is highly likely that the dynamics of this former ice sheet would have been out-of-phase with such rapid climatic changes,

Fig. 7. The Lundy exposure ages plotted alongside the NGRIP ice core record (Wolff et al., 2010 and references therein). The grey shaded area represents the estimated period of exposure based on the median exposure ages. GI = Greenland Interstadial; HE = Heinrich Event.

Fig. 8. Ice margin configurations at the LGM and also during an earlier phase when Lundy was ice covered. The LGM position and ice directional indicators are based on a figure in Cofaigh and Evans (2007, their Fig. 2).

possibly by thousands to tens of thousands of years. For example it is possible that the ice sheet built-up during MIS 4 (Fig. 7). The ice sheet is likely to have then suffered irregular retreat following the prominent warming episodes experienced during Greenland Interstadials over the period between c. 64 and 35 ka (GI 18–8) (Fig. 7).

Several offshore records have yielded radiocarbon ages that have been used to support a southern advance of the BIIS from the Irish Sea basin close to the global LGM (Cofaigh and Evans, 2007; Scourse et al., 2009) (Fig. 8). Furthermore, in Wales, there is clear evidence that the Welsh Ice Cap was thick at this time and warm-based ice overran and eroded some of the highest peaks at the LGM during MIS 2 (Glasser et al., 2011). As noted in the previous section, there is a theoretical possibility that Lundy experienced a complex exposure history over timescales that are too short to be picked up in the paired $^{10}\text{Be}/^{26}\text{Al}$ technique. In this situation it is possible, for example, that Lundy was eroded by an ice sheet during MIS 4 (c. 74–59 ka), exposed during MIS 3 (c. 59–29 ka) and then later covered by non-erosive cold-based ice during MIS 2 (29–14 ka) when the ISIS extended down through the Celtic Sea as far as the Isles of Scilly (stage ages from Martinson et al., 1987). Unfortunately, this cannot be proved nor disproved based on the existing $^{10}\text{Be}/^{26}\text{Al}$ data because the timescales are too short. However, even if Lundy was covered by cold-based ice during MIS 2, the data does support the assertion that the island's last phase of erosive glaciation occurred well before the LGM, much earlier in the last glacial cycle.

On land, the application of cosmogenic nuclide analyses has enormous potential for testing the extent and timing of the last BIIS predicted by ice-sheet models. Models are currently best-constrained in the north and west (Scotland and Ireland) where a large number of cosmogenic nuclide analyses have been applied (Ballantyne, 2010; Chiverell and Thomas, 2010; Clark et al., in press). In contrast, only a limited number of cosmogenic isotope analyses have been presented for the southernmost sector of the BIIS (McCarroll et al., 2010). The wide geographical distribution of these sites along with a large scatter in the ages poses problems of interpretation – especially with regard to the significance of outliers in the geochronological datasets. For example, ages from single ^{10}Be measurements in SW Wales are very similar to those obtained using paired isotope analyses on Lundy but have been dismissed as inherited ages by McCarroll et al. (2010). This may not necessarily be the case. As always, however, the data must always be considered and if the Pembrokeshire ages were accepted then this potentially leaves major problems reconciling these ages with radiocarbon dates from the adjacent marine record in the Celtic Sea (e.g. Cofaigh and Evans, 2007).

6. Conclusions

The data presented in this paper supports the view that Lundy was glaciated during the Late Pleistocene, and paired $^{26}\text{Al}/^{10}\text{Be}$ nuclide analyses indicate that ice-moulded bedrock on this island has an exposure history of c. 35–40 ka. It follows that the BIIS in

this area was more erosive before 35–40 ka than during MIS 2. The exposure ages represent a period of ice sheet retreat during MIS 3. Climatic amelioration associated with this ice retreat coincided with expanded ranges of mammals including modern anatomical humans and cold-adapted megafauna. Changing subglacial dynamics caused by the interaction of eustatic sea levels and coastal shelf topography are likely to have caused a change in the configuration of the ISIS during subsequent readvance culminating at the LGM (26–21 ka). At this time, a fast-flowing ice stream would have reached the close to the continental shelf in the Celtic Sea leaving Lundy and the Bristol Channel area ice free. The evidence from Lundy provides important new insights into the extent and timing of glaciation in the southwestern British Isles and illustrates the spatially- and temporally-complex response of the BIIS to rapid large amplitude climate changes during the last glacial cycle.

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