

TIMING OF THE MAXIMUM EXTENT OF LATE PLEISTOCENE GLACIATION IN N.W. EUROPE: EVIDENCE FROM LUNDY

by

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ABSTRACT

This paper presents geomorphological and cosmogenic isotope evidence for the glaciation of Lundy. ²⁶Al/¹⁰Be analyses from glaciated bedrock surfaces reveal an exposure age of c. 35-40ka. This challenges the long-established view that the last glaciation this far south must belong to Middle Pleistocene, such as the Anglian Stage (c. 480-420 ka), when ice reached as far south as London. Instead, the findings suggest glaciation of Lundy during the last ice age (Devensian Stage). However, the ages from Lundy suggest that the ice sheet in this area was at its largest extent well before the global Last Glacial Maximum at c. 26-21 ka.

Keywords: *Lundy, British-Irish Ice Sheet, Devensian, Glaciation, Cosmogenic*

INTRODUCTION

A great deal of controversy has surrounded the extent, age and origin of glacial features and landforms in the southwest British Isles for over 170 years. The established view by most geoscientists is that the most extensive ice sheet in the British Isles occurred during the Anglian/Elsterian Stage (c. 480-430ka; ka=kilo annum, or thousands of years) and reached as far south as the north Devon and Cornish coasts. However, Scourse (1991) has argued that glacial deposits as far south as the Isles of Scilly belong to the last cold stage (Devensian; c. 110-11.7ka).

Lundy is situated in a uniquely strategic position for understanding the glacial history of the British Isles. The small (4.5×0.8km) granitic island (Thorpe *et al.*, 1990; Stone, 1990) lies close to the southernmost limits of the most extensive Pleistocene glaciation in the British Isles (Figure 1), 18km off the N.W. coast of Devon at the entrance to the Bristol Channel in S.W. England. Previous studies have suggested that the island displays evidence of ice sheet glaciation and was last glaciated by ice moving from the northwest – from the southern Irish Sea (Stephens, 1966; Mitchell, 1968; Taylor, 1975).

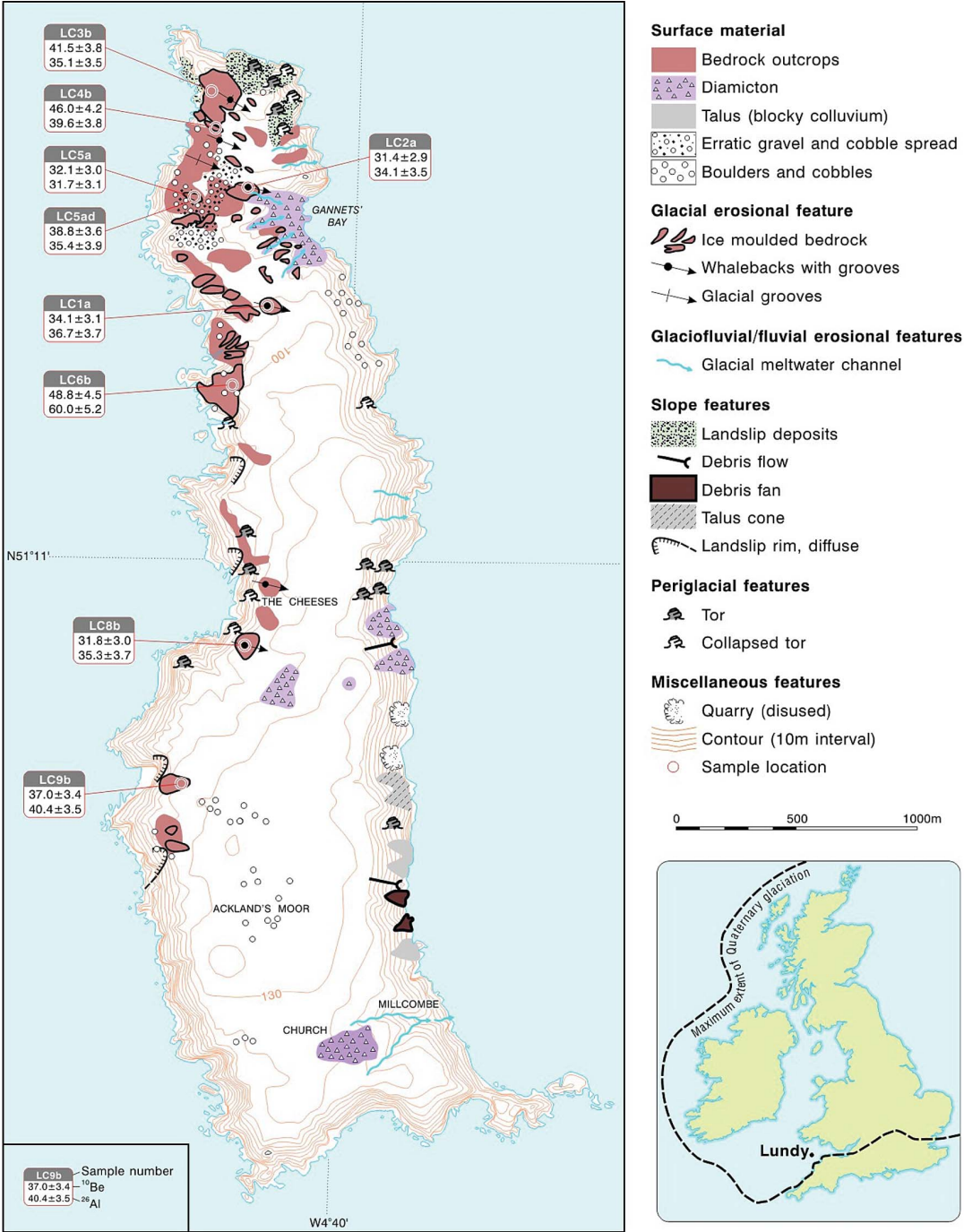


Figure 1: Geomorphological map of Lundy showing location within the British Isles. Sample locations are illustrated on this map. Reproduced from Rolfe *et al.* (2012) with permission from Elsevier

The primary aim of this paper is firstly to present the geomorphological evidence of the glaciation of Lundy, and secondly, to establish the exposure history of Lundy and relate this to the former extent of the British-Irish ice sheet. This summary paper is an abridged version of a more detailed paper published in Quaternary Science Reviews (Rolfe *et al.*, 2012).

METHODS

The glacial geomorphology of Lundy Island was examined in three separate fieldtrips in September 2008, July 2009 and April 2010. The fieldwork incorporated geomorphological mapping of glacial landforms, such as ice-moulded bedrock (grooves, large-scale stream-lining and lineations), the position and morphology of meltwater channels, large glacially-transported perched boulders, and the distribution of till (Figure 1).

The quartz-rich granite bedrock is suitable for ^{10}Be exposure dating. This technique is based on the fact that cosmic radiation is continually bombarding the Earth. A majority of this radiation originates from within our galaxy (including from our own Sun) with a small proportion of higher energy radiation originating from elsewhere in the universe. When it reaches the upper atmosphere of the Earth this galactic cosmogenic radiation interacts with the planet's magnetic field producing secondary radiation that reaches the Earth's surface. The primary radiation reaching the earth from space is dominated by protons whilst the secondary radiation reaching the earth's surface consists predominantly of neutrons (Cockburn and Summerfield, 2004). These neutrons (along with much smaller amounts of muons) interact with minerals in rock surface producing *in situ* terrestrial cosmogenic nuclides, such as ^{10}Be in quartz. The longer the exposure of the rock surface the greater the quantity of *in situ* terrestrial cosmogenic nuclides in that rock surface (Hughes *et al.*, 2014).

RESULTS

Geomorphological evidence

The geomorphology of Lundy can be interpreted as largely the product of glacial processes, modified by periglacial and post-glacial surface processes. Widespread smoothing and W.N.W.-E.S.E. lineations of granite bedrock surfaces and grooved whaleback bedrock forms can be interpreted as the product of sub-glacial ice moulding (Plates 1 and 2). Dry channels visible over the entire island can be also interpreted as subglacial meltwater channels. Large areas of erratic gravels and cobbles in the north part of the island provide the clearest sedimentological evidence of transport by ice. The erratic clasts were first identified by Mitchell (1968) and some of the clasts sampled in the study presented here match bedrock lithologies present to the N.W. of Lundy in Pembrokeshire in S.W. Wales, such as limestone, andesite, rhyolite, tuff, granophyre, gabbro/metafelsite and red granite (EDINA Geology Digimap 2009). The preferential sorting of these clasts to gravels and cobbles, along with their position on the watershed on Lundy (Figure 1) between areas of dry channels, supports interpretation of these materials as the remnants of subglacial meltwater deposits. Many large boulders of local granite scattered over the island (Plates 3, 4 and 5) appear to have been transported several tens to hundreds of metres in distance, often uphill, from bedrock outcrops including tors on the western side of the island. The presence of c.4m-thick

accumulations of blue clays into which these boulders are emplaced on the watershed of south side of the island (Figure 1) is consistent with the production of fines as a result of subglacial clast crushing. Granite tors often weather to produce subrounded boulders on plinths. These settings were viewed with caution when mapping boulders and only those that appeared to have been moved significant distance (tens of metres) from a bedrock obstacle were deemed to be ‘glacially-transported’. Furthermore, boulders that could have simply rolled downslope to their positions due to gravity were also avoided. Many of the boulder clusters mapped schematically in Figure 1 were situated slightly upslope and westwards of bedrock obstacles. The only exceptions are some of those that were mapped on the eastern side of the island, although even here, many boulders were perched close to the tops of hills well away from any bedrock plinths (Plate 4).



Plate 1: Ice-moulded whaleback bedrock on the north west coast of Lundy
(Photo © Chris Rolfe)

Exposure ages

The ^{10}Be and ^{26}Al results are shown in Table 1. 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 five of the eight sampling locations give exposure ages which agree within a one-sigma error range with the production rate ratio line, and there is approximate agreement between ^{26}Al and ^{10}Be ages (Figures 2 and 3). 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.

Plate 2: W.N.W.-
E.S.E. lineations of
granite bedrock
surfaces and grooved
whaleback bedrock
(Photo © Chris Rolfe)

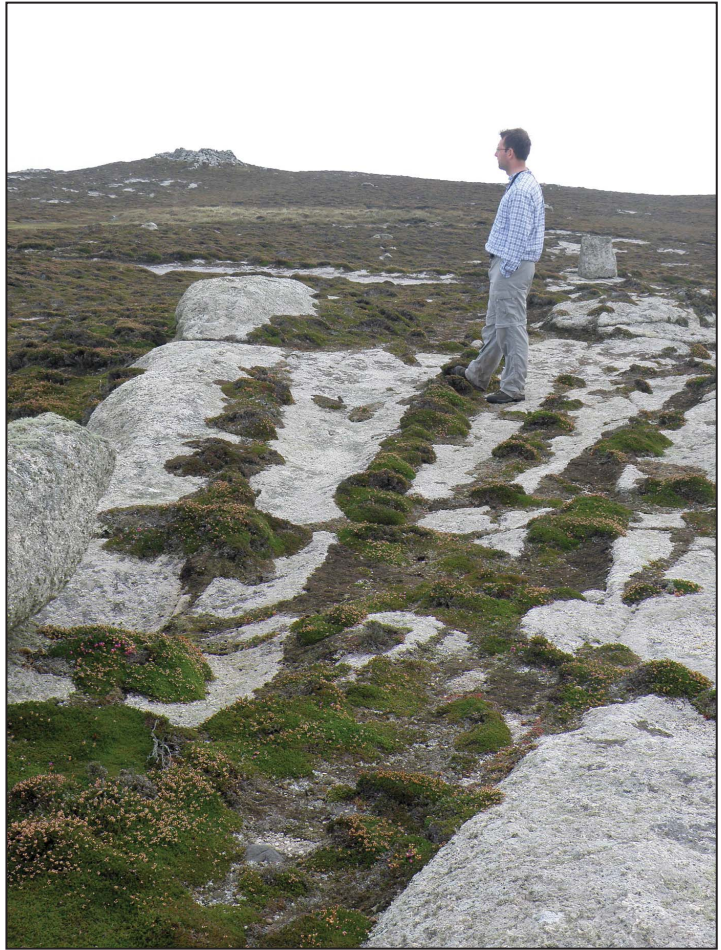


Plate 3: Glacially
transported boulder on
Ackland's Moor in the
southern part of Lundy
(Photo © Philip Hughes)





Plate 4: Glacially-transported boulder on the watershed of the north island north of Gannet's Bay. Reproduced from Rolfe *et al.* (2012) with permission from Elsevier (Photo © Philip Hughes)



Plate 5: A large perched boulder in the northwest part of the island. Reproduced from Rolfe *et al.* (2012) with permission from Elsevier (Photo © Chris Rolfe)

Table 1: $^{10}\text{Be}/^{26}\text{Al}$ 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 at 2.4 cm g^{-1} . (Rolfé *et al.*, 2012)

Sample ID	AMS ID	Latitude (°N)	Longitude (°W)	Altitude (m)	Sample thickness (cm)	Radionuclide conc. (10^5 at/g)	Exposure age (ka) no erosion	Exposure age (ka) 1 mm ka^{-1} erosion rate	Exposure age analytical uncertainty (ka) no cross.	$^{26}\text{Al}/^{10}\text{Be}$ (at/at)
	SUEC...					$^{10}\text{Be}^b$				
						$^{26}\text{Al}^c$				
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 Wrapper script 2.2; Main calculator 2.1; Constants 2.2.1; Muons 1.1										
^b NIST SRM4325 with a $^{10}\text{Be}/^{26}\text{Be}$ ratio of 2.79×10^{-11} was used for normalization.										
^c Normalization is in agreement with standards provided by K. Nishizumi (KNSTD in the Cronus-webcalculator)										

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 with averages of 37.9ka [standard deviation: 6.4] (^{10}Be) and 38.7 ka [standard deviation: 8.4] (^{26}Al), assuming zero erosion rates. If the oldest outlier is removed (sample Lc6b is significantly older than all other samples), then the average exposure ages of eight remaining samples are 36.6 ka [standard deviation: 5.3] (^{10}Be) and 36.0 ka [standard deviation: 2.8] (^{26}Al). Erosion rates of 1mm ka^{-1} would mean that the exposure ages could be very slightly older (<3% older – see Table 1). However, Rolfe *et al.* (2012, p.68) argued that erosion rates would have been minimal on Lundy granite since deglaciation.

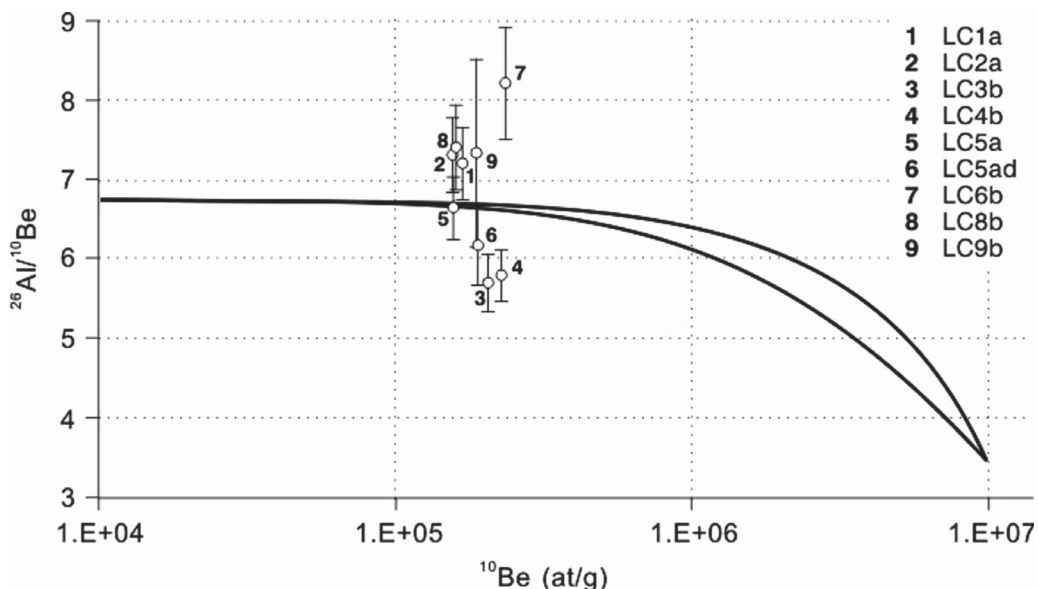


Figure 2: 'Banana' plot for ^{10}Be and ^{26}Al ages of samples collected on Lundy. Six out of nine of the ^{10}Be and ^{26}Al ages are statistically indistinguishable and the $^{26}\text{Al}/^{10}\text{Be}$ ratios overlap (within two-sigma uncertainty) the constant-exposure production-rate ratio line. This indicates that most of the samples do not have complex exposure histories detectable by the $^{26}\text{Al}/^{10}\text{Be}$ system. Reproduced from Rolfe *et al.* (2012) with permission from Elsevier

DISCUSSION

The findings from Lundy confirm that the island has been glaciated in the Quaternary, as originally proposed by Mitchell (1968) and reiterated in reviews such as that by Harrison and Keen (2005). This fact, and especially the timing of the last glaciation of this island, has important ramifications for our understanding of the south western margins of the British-Irish Ice Sheet during the last cold stage. The glaciation of Lundy has long been associated with clay deposits at Fremington, near Barnstaple in Devon, and associated erratics along the Devon coast (Kidson and Wood, 1976). However, the last glaciation of Lundy is not necessarily associated with a more extensive phase of glaciation that may have reached land inside Barnstaple Bay, which has yet to be dated.

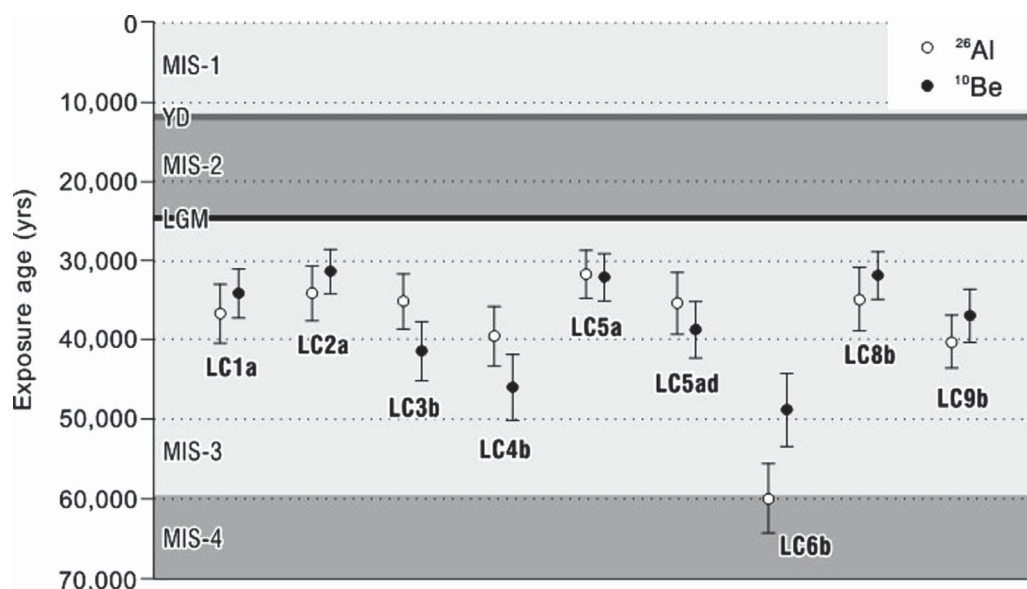


Figure 3: ^{26}Al and ^{10}Be ages from the Lundy bedrock samples. MIS: Marine Isotope Stage; YD: Younger Dryas; LGM: Last Glacial Maximum. Reproduced from Rolfe *et al.* (2012) with permission from Elsevier

This is discussed in detail by Rolfe *et al.*, (2012) who note that if ice did not reach the coast inside Barnstaple Bay during the last time Lundy was glaciated, then the ice limit must have existed somewhere in the 20-25km between the island and the coast.

Rolfe *et al.* (2012) argued that the exposure ages represent the timing of ice sheet retreat from the Lundy area revealing the island's granite surface between 35-40ka. The geomorphology and associated exposure ages from Lundy suggest that the British-Irish Ice Sheet in this area had retreated and exposed the island by 40-35ka as a result of climatic warming in marine isotope (MIS) 3. This would have facilitated the expansion of mammal fauna into S.W. England and Wales prior to climatic deterioration during MIS 2. It is now known that Woolly Rhinoceros were present just north of Lundy in South Wales (Paviland, Gower) at 38.5-36.3ka (Jacobi *et al.*, 2009) and cold-adapted megafauna have also been found along the north Devon coast at Doniford (90km east) which has a semi-continuously aggrading fluvio-periglacial 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 (42.9-39.2ka) (Jacobi *et al.*, 2009) and these age differences are consistent with a northward migration of Woolly Rhinoceros as ice retreated during MIS 3.

Several offshore records in the Celtic Sea have yielded radiocarbon ages that have been used to support a southern advance of the British-Irish Ice Sheet from the Irish Sea basin close to the global Last Glacial Maximum (LGM; 26,000 to 21,000 years ago) (Scourse *et al.*, 2009; Ó Cofaigh and Evans, 2007). Furthermore, in Wales, there is clear evidence that the Welsh Ice Cap was thick at this time and overran some of

the highest peaks at the LGM during MIS 2 (Glasser *et al.*, 2011). However, the evidence from Lundy of exposure several thousand years before the LGM means that the dynamics of the British-Irish Ice Sheet were complex with different marginal lobes exhibiting very different patterns of retreat (Figure 4). Thus, more work is required in order to understand the temporal and spatial history of the British-Irish Ice Sheet and in particular, more work is needed to elucidate the relationship between the glaciation of Lundy and the Pleistocene sedimentary record on the mainland in Devon and also in areas bounding the Bristol Channel.

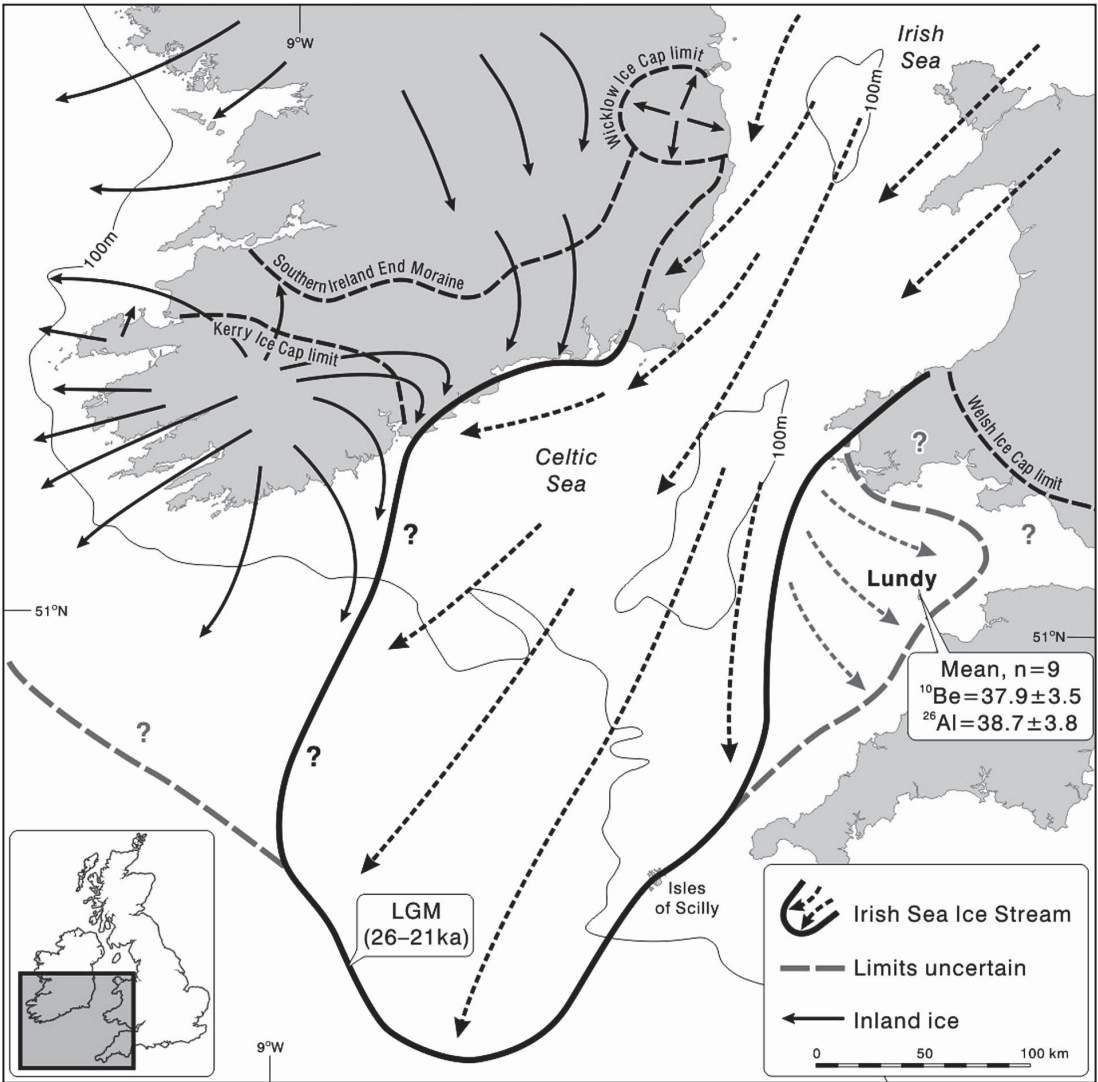


Figure 4: Ice margin configurations at the LGM and also during an earlier phase when Lundy was ice covered. The LGM position and ice directional indicators are based on a figure in Ó Cofaigh and Evans (2007, their Fig. 2). Reproduced from Rolfe *et al.* (2012) with permission from Elsevier

CONCLUSIONS

Lundy was glaciated during the Late Pleistocene, and paired $^{26}\text{Al}/^{10}\text{Be}$ nuclide analyses indicate that ice retreated from the area exposing the granite bedrock 35,000 to 40,000 years ago. The fact that Lundy is now known to have been glaciated during the last ice age is a major new finding since the previous established view was that the island was glaciated only during much earlier ice ages. The exposure ages also indicate that the ice sheet margins in this area retreated from maximum positions long before the global Last Glacial Maximum which occurred between c. 26,000 and 21,000 years ago. The evidence from Lundy therefore provides important new insights into the extent and timing of glaciation in the southwestern British Isles.

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