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Exposure-age constraints on the extent, timing and rate of retreat of the last Irish Sea ice stream

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ABSTRACT

We report 23 cosmogenic isotope exposure ages (^{10}Be and ^{36}Cl) relating to the maximum extent and deglaciation chronology of the Irish Sea Ice Stream (ISIS), which drained the SW sector of the last British–Irish Ice Sheet. These show that the ISIS failed to reach the Preseli Hills of North Pembrokeshire yet extended southwards to impinge on northern Isles of Scilly (50°N) during the last glacial maximum. Four samples from western Anglesey demonstrate deglaciation of the southern Irish Sea Basin by *c.* 20–18 ka, and two from the Llŷn Peninsula in northwest Wales, if valid, suggest deglaciation by *c.* 23–22 ka followed by gradual oscillatory northwards retreat of the ice margin for over 3000 years. An alternative interpretation of our data suggests that ice reached Scilly as late as 22–21 ka then retreated 450 km northwards within the following three millennia, possibly in response to sea level rise and/or intrinsic reorganisation within the last British–Irish Ice Sheet. Samples from upland source areas of the ISIS in NW England and SW Scotland produced exposure ages ≤14.3 ka, suggesting possible persistence of ice in such areas into the Lateglacial Interstade of 14.7–12.9 ka.
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1. Introduction

During the last glacial maximum (LGM) of 26–21 ka (Peltier and Fairbanks, 2006) the Irish Sea basin was the main conduit for southwards drainage of the British–Irish Ice Sheet (BIIS). Both field evidence (Ó Cofaigh and Evans, 2001a, 2001b; Roberts et al., 2007; Thomas and Chiverrell, 2007) and recent climate-driven thermo-mechanical coupled models (Boulton and Hagdorn, 2006; Hubbard et al., 2009) indicate development of a high-velocity Irish Sea ice stream (ISIS) that flowed southwards under low shear stresses, at its maximum extent reaching a grounding line SW of the Scilly Isles (Scourse et al., 1990; Scourse, 1991; Scourse and Furze, 2001; Hiemstra et al., 2006). There is geomorphological and sedimentological evidence for the western limit of the ISIS along the south coast of Ireland (Ó Cofaigh and Evans, 2001a, 2001b, 2007), and former ice margin positions have been identified on topographical barriers that lie athwart the direction of flow in north Pembrokeshire (Walker and McCarroll, 2001), the Llŷn Peninsula (Young et al., 2002; McCarroll, 2001; Thomas and Chiverrell, 2007) and the Isle of Man (Thomas et al., 2004; Roberts et al., 2007; Fig. 1), but dating control for these former ice limits is weak. Here we present 23 cosmogenic isotope exposure dates that constrain the extent and retreat chronology of the ISIS.

2. Sample collection and analysis

Nineteen samples for surface exposure dating were collected from four topographic barriers that lay in the path of the ISIS: the Isles of Scilly, north Pembrokeshire, the Llŷn Peninsula and Anglesey, as well as from upland source areas in Wasdale (NW England) and upper Glen Trool in SW Scotland (Fig. 1; Table 1); the Wasdale and Glen Trool samples were obtained from sites several kilometres outside the limits of the glaciers that formed in these areas during the Loch Lomond (Younger Dryas) Stade of *c.* 12.9–11.7 ka (Sissons, 1980; Cornish, 1981). Four further samples were collected from sites in the Isles of Scilly and Pembrokeshire that lie outside the inferred LGM limits of the ISIS (Bowen et al., 1986, 2002; Scourse, 1991; Walker and McCarroll, 2001; Hiemstra

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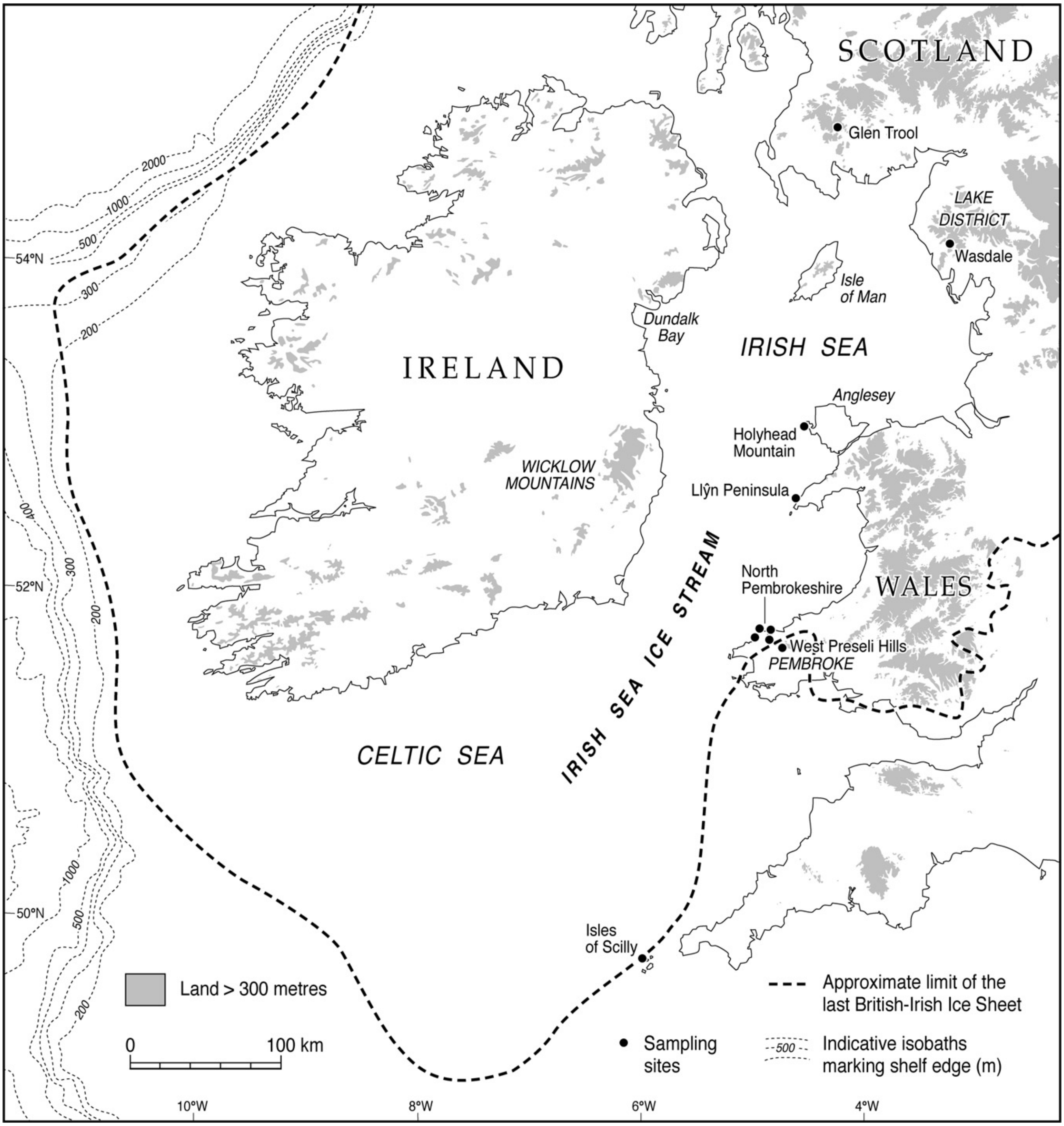

Fig. 1. Approximate limit of the last British–Irish Ice Sheet in the area of the Irish Sea and Celtic Sea (based on Sejrup et al., 2005) showing the location of sampling sites and other locations mentioned in the text.

et al., 2006). All but five samples were obtained from resistant quartz-rich lithologies (granite, quartzite and vein quartz), allowing ^{10}Be exposure dating of quartz. The exceptions are two samples (PF-01, PM-01) from ice-moulded outcrops of volcanic rock in north Pembrokeshire, and three samples (MC-01, MC-02, MC-03) from basaltic and rhyolitic tors on the western Preseli Hills (Mynydd Carningli). These were analysed as whole-rock samples using cosmogenic ^{36}Cl. All samples were chiseled from horizontal or near-horizontal bedrock or boulder surfaces, and, where appropriate, corrections for obstruction of incoming cosmic rays by surrounding topography were calculated from skyline measurements. Sample locations are given in Table 1 and discussed further below.

For ^{10}Be analyses, quartz separation and beryllium extraction followed Kohl and Nishiizumi (1992) and Ditchburn and Whitehead (1994); see also Stone (2004). Blanks and carrier contributions to measured ^{10}Be were $<10^4$ atoms, necessitating corrections $<1\%$. Samples for ^{36}Cl dating were crushed to 125–250 μm grainsize, leached in deionised water and dilute nitric acid to remove weathering products, then split into aliquots for ^{36}Cl extraction (Stone et al., 1996; Stone, 2001), chloride measurement by isotope dilution and bulk chemical analysis. Chlorine was

Table 1
Sample location and ^{10}Be analytical data.

Sample	OS Grid Reference	Latitude (°N)	Longitude (°W)	Altitude m OD	Thickness mm	Density g cm^{-3}	Shielding correction	[^{10}Be] 10^5 atoms g^{-1}
Sites inside the LGM glacial limit								
Glen Trool, SW Scotland								
GT-01	NX438821	55.109	4.449	340	38	2.65	0.998	0.922 ± 0.039
GT-2.1	NX437816	55.105	4.450	390	15	2.65	1.000	1.009 ± 0.020*
GT-2.2	NX437816	55.105	4.450	390	12	2.65	1.000	0.999 ± 0.031
GT-03	NX439815	55.104	4.447	390	28	2.65	1.000	0.904 ± 0.026*
Wasdale, SW Lake District								
W-13	NY153063	54.445	3.307	190	16	2.65	0.896	0.739 ± 0.020
Holyhead Mountain, Anglesey, NW Wales								
HM-01	SH215808	53.294	4.679	210	13	2.65	1.000	1.269 ± 0.041
HM-2.1	SH216808	53.294	4.679	205	10	2.65	0.997	1.104 ± 0.032
HM-2.2	SH216808	53.294	4.679	205	10	2.65	0.999	1.165 ± 0.044
HM-03	SH216808	53.294	4.679	200	10	2.65	0.999	1.143 ± 0.037
HM-04	SH216808	53.294	4.679	190	10	2.65	0.996	1.075 ± 0.025*
Mynedd Mawr, Lleyn Peninsula, NW Wales								
MM-01	SH141259	52.798	4.757	135	28	2.65	0.999	1.282 ± 0.031
MM-02	SH142261	52.800	4.756	125	33	2.65	1.000	1.193 ± 0.037
Pembroke, SW Wales								
CF-01	SM977376	52.000	4.947	130	19	2.65	1.000	2.007 ± 0.053
CO-01	SM889380	51.999	5.078	119	15	2.65	0.998	1.881 ± 0.081
PF-01	SM999374	51.998	4.915	95	62	2.65	1.000	^{36}Cl analysis
PM-01	SM883396	52.013	5.085	88	40	2.65	1.000	^{36}Cl analysis
Scilly Isles								
SC-1B	SV922177	49.980	6.293	20	77	2.65	1.000	3.304 ± 0.093*
SC-07	SV903170	49.972	6.320	20	32	2.65	1.000	3.896 ± 0.077*
SC-08	SV874163	49.965	6.360	15	120	2.65	1.000	0.974 ± 0.033*
Sites outside the LGM glacial limit								
Scilly Isles, outside glacial limit								
SC-06	SV913095	49.905	6.300	15	64	2.65	1.000	5.568 ± 0.133*
West Preseli Hills, Pembroke, SW Wales								
MC-01	SN052374	52.000	4.838	290	30	2.65	1.000	^{36}Cl analysis
MC-02	SN055372	51.998	4.833	330	63	2.65	0.975	^{36}Cl analysis
MC-03	SN054365	51.992	4.835	295	36	2.65	1.000	^{36}Cl analysis

^{10}Be concentrations are all normalized to the KNSTD ^{10}Be/^{9}Be standard, traceable to the ICN ^{10}Be standard. Those without an asterisk were measured relative to this standard, and those marked with an asterisk were measured relative to the Lawrence Livermore National Laboratory in-house standard LLNL3000. In the latter case, the measured values have been normalized to the KNSTD by multiplying by a factor of 0.965. See Balco (2007) for a more detailed discussion of the ^{10}Be/^{9}Be standards. Uncertainties (±1σ) include all known sources of analytical error.

analysed for ^{36}Cl using the 14UD accelerator at the Australian National University (Fifield et al., 2010). Procedural blanks run in parallel had ^{36}Cl/Cl ratios $<10^{-15}$ (*c.* 10^4 atoms ^{36}Cl), requiring blank corrections ≤1%. Chloride concentrations were measured by isotope dilution with ^{37}Cl on 0.5–1 g aliquots of crushed rock. Whole-rock chemical compositions were measured by X-ray fluorescence. Trace element neutron producers (U and Th) and absorbers (B, Sm, Gd) were analysed by ICP-MS.

We used the CRONUS online calculator (Balco, 2007; Balco et al., 2008) to calculate ^{10}Be exposure ages. ^{10}Be production rates are affected by altitude, and both latitudinal and temporal variations in the Earth's magnetic field. The CRONUS calculator allows determination of exposure ages based on four scaling models (De, Du, Li and Lm) that correct for these effects. These models account for time variation in ^{10}Be production rate and produce better agreement with high-precision calibration measurements than the original scaling factors of Lal (1991). Differences between exposure ages calculated with the four models range from 3.9% to 4.6%. To bracket the range of exposure age outcomes, Table 2 shows ages calculated using the Li model (Lifton et al., 2005), which yields the youngest ages, and the Du model (Dunai, 2001), which gives the oldest ages. As concentration of cosmogenic ^{10}Be diminishes with depth, post-exposure erosion of rock surfaces results in underestimation of exposure age (Gosse and Phillips, 2001). To accommodate this effect, we calculated exposure ages for assumed erosion rates (ε) of 0 and 1 mm ka^{-1}, the latter representing a reasonable upper limit for most quartz-rich igneous and metamorphic rocks (André, 2002; Nicholson, 2009). We adopt the convention that the youngest possible age is represented by Li scaling with $\varepsilon = 0$, and the oldest by Du scaling with $\varepsilon = 1$ mm ka^{-1}, and cite both ages with accompanying ± 1 σ external (total) uncertainties (Table 2). The difference between ages calculated using $\varepsilon = 0$ and $\varepsilon = 1$ mm ka^{-1} is 1–2% of sample age for all ages between 12.5 and 25.0 ka, and calculation of $\varepsilon = 2$ mm ka^{-1} (not shown in Table 2) adds a further 1–2% to ages within the same range. The ^{36}Cl exposure ages are based on production rates scaled using the original correction factors of Lal (1991) for spallation and muon capture reactions, without adjustment for past magnetic field variation. By analogy with ^{10}Be, these uncorrected ^{36}Cl exposure ages are likely to be 5–7% younger than ages that would be obtained from a variable production rate calculation. For samples collected outside the inferred ice limits (MC-01, MC-02, MC-03) this difference is of no importance; for sample PF-01, it would bring the ^{36}Cl age into closer agreement with the ^{10}Be ages of samples CF-01 and CO-01. Full details of ^{36}Cl production rates and of the underlying calibrations are given in the online data (http://depts.washington.edu/cosmolab/data). Table 3 gives uncorrected exposure ages assuming $\varepsilon = 0$, together with the minimum possible ages of Cl-rich samples for which any surface erosion would lower the apparent age (cf. Liu et al., 1994). Mean ages shown in Table 2 and cited below are weighted means with weighting factor $1/\sigma_i^2$ where σ_i is the internal (analytical) uncertainty. Weighted means rather than

Table 2
^{10}Be exposure ages.

Sample	Lifton (Li) scaling, $\varepsilon = 0$			Dunai (Du) scaling, $\varepsilon = 1$ mm ka^{-1}		
	Exposure age (ka)	Internal uncertainty (ka)	External uncertainty (ka)	Exposure age (ka)	Internal uncertainty (ka)	External uncertainty (ka)
Sites inside LGM ice limit						
Glen Trool, SW Scotland						
GT-01	13.38	0.57	1.44	14.11	0.60	1.79
GT-2.1	13.54	0.27	1.37	14.29	0.29	1.73
GT-2.2	13.53	0.43	1.40	14.28	0.46	1.76
GT-03	12.30	0.36	1.27	12.95	0.38	1.59
GT weighted mean	13.20	0.18	1.32	13.92	0.19	1.68
GT wm (less GT-03)	13.51	0.21	1.35	14.26	0.23	1.73
Wasdale, NW England						
W-13	13.50	0.37	1.39	14.22	0.39	1.74
Holyhead Mountain, Anglesey. NW Wales						
HM-01	20.48	0.66	2.14	21.79	0.72	2.72
HM-2.1	17.94	0.51	1.85	19.03	0.55	2.35
HM-2.2	18.88	0.72	2.01	20.05	0.78	2.53
HM-03	18.62	0.61	1.94	19.76	0.65	2.46
HM-04	17.71	0.43	1.80	18.77	0.45	2.29
HM weighted mean	18.44	0.25	1.84	19.56	0.27	2.36
HM wm (less HM-01)	18.11	0.27	1.81	19.20	0.29	2.32
Mynydd Mawr, Llŷn Peninsula, NW Wales						
MM-01	22.55	0.56	2.30	23.57*	0.58	2.84
MM-02	21.27	0.66	2.21	22.62	0.71	2.81
MM weighted mean	22.01	0.43	2.22	23.19	0.45	2.82
North Pembroke coast, SW Wales						
CF-01	35.28	0.93	3.63	38.04	1.04	4.77
CO-01	33.37	1.45	3.62	35.93	1.61	4.67
Scilly Isles, south Celtic Sea						
SC-1B	68.03	1.94	7.09	75.48	2.29	9.90
SC-07	77.55	1.55	7.95	86.93	1.86	11.4
SC-08	20.93	0.71	2.19	22.13	0.76	2.77
Sites outside LGM ice limit						
Scilly Isles, south Celtic Sea						
SC-06	114.9	2.82	12.0	133.8	3.73	18.6

*Calculated with $\varepsilon = 0$, since this sample was obtained from a striated surface, indicating that post-exposure erosion has been negligible. wm: weighted mean. Scaling from CRONUS online calculator (Balco, 2007; Balco et al., 2008): wrapper script version 2.2; main calculator version 2.1; constants version 2.2; muons version 1.1. Internal error reflects analytical uncertainty on ^{10}Be measurements only. External errors incorporate in addition uncertainties in the calibration and scaling procedures ($\pm 1\sigma$). Calculation of ages using $\varepsilon = 2$ mm ka^{-1} adds 1–2% for ages between 12 ka and 25 ka.

arithmetic means are appropriate because analytical uncertainties vary by up to a factor of two among samples from the same site. Production rate and scaling uncertainties, which amount to 9.9% and 12% respectively for Li and Du scaling (Balco, 2007; Balco et al., 2008), were added in quadrature to the internal errors to obtain the total (external) uncertainties on the weighted means. Tests of difference between samples from the same site were performed using the two sample difference of means (t) test, with $\nu = \infty$, differences being tested on the basis of analytical uncertainties (Table 2), as production rate uncertainties affect all samples from similar altitudes at the same site equally.

Table 3
^{36}Cl exposure ages.

Sample	Internal uncertainty (ka)	Conventional exposure age (ka)	Minimum possible exposure age (ka)
Samples inside the LGM glacial limit			
Pembroke, SW Wales			
PF-01	1.9	33.51 ± 2.56	33.44 ± 2.56
PM-01	4.4	76.82 ± 7.20	68.13 ± 6.38
Samples outside the LGM glacial limit			
West Preseli Hills, Pembroke, SW Wales			
MC-01	5.0	107.1 ± 7.70	107.1 ± 7.70
MC-02	8.6	152.6 ± 15.7	142.6 ± 14.7
MC-03	6.9	129.5 ± 14.1	108.7 ± 11.9

Conventional exposure ages assume negligible rock erosion. Minimum possible exposure ages were obtained for samples that show evidence of erosion by calculating production profiles for the combined reactions and solving for the range of exposure ages and steady erosion rates consistent with measured ^{36}Cl concentrations (cf. Phillips et al., 2001). Complete analytical results for these samples can be obtained from the University of Washington Cosmogenic Nuclide Laboratory website:http://depts.washington.edu/cosmolab/data/Irish_Sea_data.html.

Additional considerations that affect interpretation of exposure dates are (1) a former cover of sediment may have shielded some sampled surfaces, leading to underestimation of exposure age, and (2) some sampled surfaces may contain ^{10}Be or ^{36}Cl produced by pre-LGM exposure to cosmic radiation. This effect, the result of insufficient glacial erosion during the LGM to remove existing nuclide profiles, is likely to be most problematic in our southernmost samples obtained close to the former margin of the ISIS, from sites where ice cover was thin, flow was divergent and ice cover was of limited duration. Anomalously 'old' exposure ages, resulting from nuclide inheritance are more common in resistant lithologies such as the volcanic rocks of the Pembrokeshire coast (e.g. Stone and Ballantyne, 2006; Ballantyne et al., 2009b).

3. Results

3.1. The Scilly Isles, south Celtic Sea

A distinct limit of till and soliflucted till derived from the Irish Sea basin and associated with moraine ridges and glacially-eroded

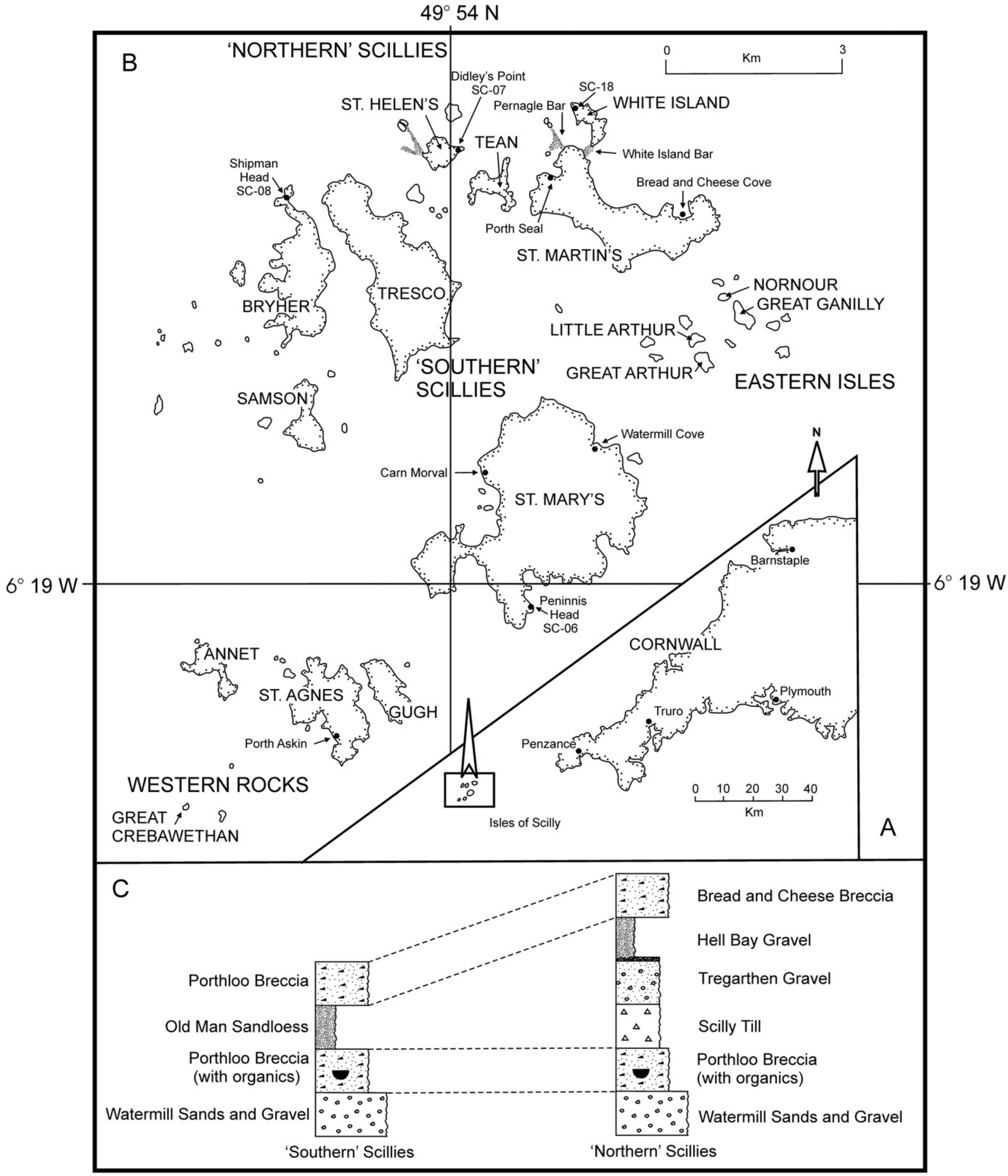

Fig. 2. A and B: Location and map of the Isles of Scilly showing the location of sites and sampling locations mentioned in the text, and the southern limit of the Hell Bay Gravel taken as the limit of ice advance during the Late Devensian (Scourse, 1991). C: Schematic lithofacies logs from north (right) and south (left) of the Hell Bay Gravel limit (Scourse, 1991) showing defined stratigraphic units and their correlation. The Porthloo Breccia underlies the glacial sequence (Scilly Till, Tregarthen Gravel, Hell Bay Gravel) and contains organic sediments (at Carn Morval, Watermill Cove, Porth Seal, Bread and Cheese Cove, Porth Askin) ^{14}C dated to between 34,500 + 885/800 (Q-2410) and 21,500 + 890/800 (Q-2358) ^{14}C years BP (Scourse, 1991). The Old Man Sandloess has been dated by thermoluminescence to 18,600 ± 3700 ka (QTL 1d and 1f; Wintle, 1981) and by optically-stimulated luminescence to 20,000 ± 7000 ka and 26,000 ± 10,000/9000 (738 al and 741 al; Smith et al., 1990).

tors was used by Scourse (1991) to define the southernmost extent of the grounded ISIS across the northern part of the Isles of Scilly. Hiemstra et al. (2006) substantiated this inferred glaciation limit when they identified seemingly relatively recent additional moraine ridges and glacitectonic structures in sediments exposed in the northernmost parts of Scilly. TL, OSL and radiocarbon dates relating to the Scilly ice limit on balance support moraine formation and till deposition during the last glacial cycle (Fig. 2; Scourse, 1991; Scourse and Furze, 2001; Hiemstra et al., 2006; Scourse et al., 2006), though this remains controversial (e.g. McCabe, 2008). To test this conclusion, one sample was obtained from outside the glacial limit and three inside the limit. Sample SC-06, from a granite tor outside the limit produced a minimum ^{10}Be age of 115 ± 12 ka to 134 ± 19 ka, consistent with exposure throughout the last glacial cycle. However, two samples (SC-1B, SC-07) from granite outcrops on northern headlands just within the glacial limit also produced pre-LGM exposure ages, of 68.0 ± 7.1 to 75.5 ± 9.9 ka and 77.6 ± 7.9 to 86.9 ± 11.4 ka respectively. By contrast, a further sample (SC-08) from a boulder inside the glacial limit produced a post-LGM exposure age of 20.9 ± 2.2 to 22.1 ± 2.8 ka, consistent with deposition by the last ice sheet. This sample was obtained from the top of a ~9 m^3 granite boulder from a moraine on Shipman Head, Bryher (Fig. 3). A network of weathering pits and drainage channels on the underside of the boulder demonstrates that it had been inverted, providing a fresh surface at the time of deposition. However, an incipient drainage network on the top surface implies post-depositional erosion, so the age range for this sample may slightly underestimate true exposure age. We attribute the conflict between the post-LGM age of SC-08 and the ages obtained for SC-1B and SC-07 to the effects of nuclide inheritance in the latter, as it is unlikely that glacial erosion could have removed 2–3 m of bedrock from these sites during the brief period that the ISIS impinged on the Scilly Isles, particularly if southwards extension of ISIS to the Scillies represented a short-lived surge event (Scourse et al., 1990; Hiemstra et al., 2006).

Fig. 3. Upper: boulder moraine located on eroded granite surface, Shipman Head, Bryher, Isles of Scilly (see Fig. 2 for location), viewed looking northeastwards towards the island of Men-a-vaur; the large boulder sampled (SC-08) is clearly visible on the left. Lower: boulder of local granite sampled for ^{10}Be rock exposure dating (sample SC-08), rucksack for scale. Weathering pits and drainage channels are visible on the underside of the boulder indicating that this boulder was probably eroded from a nearby granite tor and inverted during deposition.

3.2. The north Pembroke coast, southwest Wales

Geomorphological evidence (Catt et al., 2006) indicates that the eastern LGM limit of the ISIS lay along the north Pembroke coast (Fig. 1). East of the proposed ice limit, the western Preseli Hills (Mynydd Carningli) show no evidence of glaciation, and the landscape is dominated by tors rising above autochthonous blockfields (Walker and McCarroll, 2001). Closer to the coast, however, rocky knolls are conspicuously ice-scoured and glacial deposits derived from the Irish Sea basin are widespread (Hiemstra et al., 2005). Three samples collected from basaltic tors on the west Preseli Hills (MC-01, MC-02, MC-03) all yielded minimum ^{36}Cl ages >100 ka (Table 3), consistent with the inference that this area escaped glaciation during the LGM. Two samples (CF-01, CO-01) from ice-moulded outcrops on coastal headlands just within the proposed glacial limit produced ^{10}Be ages of 35.3 ± 3.6 to 38.0 ± 4.8 ka and 33.4 ± 3.6 to 35.9 ± 4.7 ka and two further samples (PF-01 and PM-01) gave ^{36}Cl ages of 33.5 ± 2.6 ka and 76.8 ± 7.2 ka. Although three of these ages are internally consistent and all are significantly younger than those obtained from the Preseli tors, all are significantly older than the LGM, and thus conflict with the geomorphological evidence for over-running of the north Pembroke coast by the ISIS during the LGM. We infer that all four ages are augmented by nuclide inheritance due to insufficient removal of bedrock by glacial erosion, and thus provide no information on the timing of ice retreat.

3.3. The Llŷn peninsula, northwest Wales

The Llŷn Peninsula forms a major topographic barrier (Fig. 1) crossed by ice-marginal sediment-landform assemblages that reflect oscillatory retreat of the ISIS and decoupling from ice radiating from Snowdonia (McCarroll and Ballantyne, 2000; Thomas and Chiverrell, 2007). Two samples (MM-01 and MM-02) were obtained from ice-scoured quartzite outcrops at Mynydd Mawr near the western end of the peninsula. Sample MM-01 was obtained from a striated surface, indicating that post-exposure erosion has been negligible and thus that the effective age range is 22.6 ± 2.3 ka (Li scaling, $\varepsilon = 0$) to 23.6 ± 2.8 ka (Du scaling, $\varepsilon = 0$) for this sample. Sample MM-02 yielded exposure ages of 21.3 ± 2.2 ka

(Li scaling, $\varepsilon = 0$) to 22.6 ± 2.8 ka (Du scaling, $\varepsilon = 1$ mm ka^{-1}). The exposure ages for the two samples yield a weighted mean age of 22.0 ± 2.2 ka to 23.2 ± 2.8 ka. Despite the consistency of the two ages, we cannot exclude the possibility of nuclide inheritance, and these ages should be considered maximal for deglaciation of western Llŷn.

3.4. Holyhead mountain, Anglesey, north Wales

Five samples of vein quartz (HM-01, HM-2.1, HM-2.2, HM-03, HM-04) collected near the ice-moulded quartzite summit of Holyhead Mountain yielded a fairly closely clustered group of ages with a mean age of 18.4 ± 1.8 to 19.6 ± 2.4 ka. However, the greatest individual age in this group (HM-01: 20.5 ± 2.1 to 21.8 ± 2.7 ka) differs from the weighted mean of all others in the group at $p < 0.01$, suggesting that the age obtained for HM-01 may reflect slight nuclide inheritance, and that the mean age of the other four samples (18.1 ± 1.8 to 19.2 ± 2.3 ka) should be considered representative for the timing of deglaciation at this site.

3.5. Upland source areas: Wasdale, northwest England and Glen Trool, southwest Scotland

The samples from the two upland source area sites produced much younger exposure ages than the others reported here. Vein quartz from the lee side of a roche moutonnée in Wasdale (sample W-13) yielded ^{10}Be exposure ages of 13.5 ± 1.4 ka to 14.2 ± 1.7 ka, and four samples from the tops of granite boulders in Glen Trool (GT-01, GT-2.1, GT-2.2, GT-03) produced a mean age of 13.2 ± 1.3 ka to 13.9 ± 1.7 ka. However, the exposure age of sample GT-03 (12.3 ± 1.3 to 13.0 ± 1.6 ka) is significantly younger ($p < 0.1$) than the weighted mean age of the other three Glen Trool samples, possibly reflecting former shielding by sediment cover. We infer that the mean age of the other three samples (13.5 ± 1.4 to 14.2 ± 1.7 ka) is more representative for deglaciation of this site.

4. Discussion

Although some of the exposure ages reported above (samples SC-1B, SC-07, CF-01, CO-01, PF-01, PM-01) appear to be compromised by nuclide inheritance and others may represent maximal ages for deglaciation (MM-01, MM-02, HM-01), our results allow several conclusions to be drawn regarding the extent and deglaciation chronology of the ISIS. First, the exposure ages obtained for tors on the Preseli Hills and Scilly all exceed 100 ka, confirming that these sites lay beyond the limits of the ISIS at the LGM (Scourse, 1991; Hiemstra et al., 2006; Catt et al., 2006). Second, the four youngest samples (HM-2.1, HM2.2, HM-03, HM-04) obtained for Holyhead Mountain yield an uncertainty-weighted mean age of 18.1 ± 1.8 to 19.2 ± 2.3 ka, suggesting deglaciation of the southern Irish Sea basin by 18–20 ka. This inference is consistent with three ^{10}Be ages averaging 18.8 ± 1.9 ka to 20.1 ± 2.4 ka for downwastage of the Wicklow ice dome on the opposite side of the Irish Sea (ages recalculated from Ballantyne et al. (2006)), and with AMS ^{14}C ages that indicate open marine conditions in and NW of Dundalk Bay (Fig. 1) by *c.* 18.5–19.0 cal ka (McCabe et al., 2005, 2007). Collectively, these dates suggest deglaciation of most of the Irish Sea basin by *c.* 18–19 ka.

Thirdly, the exposure age obtained for the large granite boulder at Shipman Head on Scilly (20.9 ± 2.2 to 22.1 ± 2.8 ka) appears to confirm that the ISIS reached the Scilly Isles during or shortly after the LGM. However, the Shipman Head exposure age and the mean exposure age of 22.0 ± 2.2 ka to 23.2 ± 2.8 ka for the two samples obtained from the Llŷn Peninsula appear incompatible (within the limits imposed by the associated uncertainties) as the former site must have been deglaciated before the latter. A maximal age of *c.* 24 cal ka for extension of ice southwards across the Celtic Sea to Scilly is provided by AMS ^{14}C dating of shell fragments incorporated in till deposited by the ISIS along the southern coast of Ireland (Ó Cofaigh and Evans, 2007), and supported by ice-rafted debris with ISIS lithological affinity that occurs in Heinrich layer 2 (*c.* 24 cal ka) in core OMEX-2K obtained from the adjacent continental slope (Scourse et al., 2000, 2009; Haapaniemi et al., 2010). Our dating evidence suggests two possible scenarios. First, if the Shipham Head exposure age is too young but the Llŷn Peninsula ages are valid, it is possible that the ISIS margin reached its southernmost limit around or shortly after 24 ka, then retreated rapidly to the central Irish Sea Basin at the latitude of the Llŷn Peninsula. The large difference between the mean exposure age obtained for Llŷn (22.0 ± 2.2 to 23.2 ± 2.8 ka) and that for Holyhead Mountain (18.1 ± 1.8 to 19.2 ± 2.3 ka) implies that under this scenario the ice margin then experienced gradual net northwards retreat over a period of roughly 3–4000 years. Some support for this is provided by structural and sedimentological evidence in northern Llŷn for an oscillating ice margin that underwent at least 11 readvances as it retreated northwards towards Anglesey (Thomas and Chiverrell, 2007), though these could have been of short duration. Similar evidence for ice-marginal oscillations occurs on the east coast of Ireland (Thomas and Summers, 1983, 1984; Evans & Ó Cofaigh, 2003).

If the Shipham Head exposure age is valid and ice impinged on the northern parts of the Scilly Isles at 20.9 ± 2.2 to 22.1 ± 2.8 ka, the exposure ages from the Llŷn Peninsula must be regarded as maximal (augmented by nuclide inheritance) and a different scenario unfolds, in which the margin of the ISIS withdrew northwards from Scilly to Anglesey, a distance of 370 km, within about 3 ka. Ice-free conditions in Dundalk Bay at *c.* 19 cal ka (McCabe et al., 2005, 2007) imply northwards retreat of the ice margin of over 450 km in 2–4 ka. On present evidence, there is no way to distinguish between the two scenarios. Both, however, involve rapid and early northwards retreat of the ISIS ice margin, suggesting that retreat may have been caused or enhanced by rise in relative sea level at the margins of the ISIS (McCabe and Ó Cofaigh, 1996) and/or reflect intrinsic ice sheet instability associated with the development of a fast, low-gradient ice stream (Hubbard et al., 2009).

The exposure ages obtained for samples from source areas of the ISIS in Wasdale (13.5 ± 1.4 ka to 14.2 ± 1.7 ka) and Glen Trool (weighted mean age 13.5 ± 1.4 to 14.3 ± 1.7 ka) suggest possible persistence of ice in these upland valleys during at least the early part of the Lateglacial Interstade (≈Greenland Interstade 1 of Lowe et al., 2008; 14.7–12.9 ka), despite rapid summer warming at *c.* 14.7 ka (Brooks and Birks, 2000). Exposure dating of boulders on moraines in NW Scotland has produced almost identical ages, and also indicates persistence of substantial ice masses during at least the early part of the Lateglacial Interstade (Bradwell et al., 2008; Ballantyne et al., 2009a). The Wasdale and Glen Trool dates suggest that survival of ice cover in upland source areas of the last ice sheet after *c.* 14.3 ka may have been a more widespread phenomenon.

5. Conclusions

1. Exposure ages >100 ka for samples obtained from tors on the Preseli Hills in north Pembroke and south of the inferred glacial limit on the Isles of Scilly confirm that these areas escaped glaciation during the last glacial stage. A single ^{10}Be exposure age of 20.9 ± 2.2 ka to 22.1 ± 2.8 ka supports the hypothesis that the ISIS impinged on northern Scilly during the LGM.
2. Four ^{10}Be exposure ages for samples obtained from Holyhead Mountain on the westernmost point of Anglesey average of 18.1 ± 1.8 ka to 19.2 ± 2.3 ka, implying deglaciation of the

southern Irish Sea Basin by 18–20 ka, and consistent with evidence for open marine conditions around Dundalk Bay in eastern Ireland by 18.5–19.0 cal ka. These dates imply that the margin of the ISIS retreated 450 km northwards following the LGM, possibly reflecting mass loss by accelerated calving as relative sea level rose (cf. Brooks et al., 2008) and/or intrinsic ice sheet instability following the development of a fast low-gradient ice stream that drained ice southwards through the Irish Sea basin into the area of the Celtic Sea (Roberts et al., 2007; Evans et al., 2009).
3. Two scenarios are proposed for ISIS ice margin retreat. Exposure ages obtained for ice-moulded rock outcrops on the Llŷn Peninsula average 22.0 ± 2.2 ka to 23.2 ± 2.8 ka, suggesting rapid retreat of the ISIS ice margin from its southernmost limit to the latitude of Llŷn, followed by a period of gradual oscillatory retreat lasting over 3000 years. Alternatively, if the Llŷn dates represent maxima, the exposure age of 20.9 ± 2.2 ka to 22.1 ± 2.8 ka for a boulder on Scilly implies evacuation of ice from most of the Irish Sea basin within the period *c.* 22–19 ka.
4. Five samples from upland source areas of the ISIS produced exposure ages ≤14.3 ka, suggesting possible persistence of ice during the early part of the Lateglacial Interstade.

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