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The deglaciation of the western sector of the Irish Ice Sheet from the inner continental shelf to its terrestrial margin

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This paper provides a new deglacial chronology for retreat of the Irish Ice Sheet from the continental shelf of western Ireland to the adjoining coastline, a region where the timing and drivers of ice recession have never been fully constrained. Previous work suggests maximum ice-sheet extent on the outer western continental shelf occurred at ~26–24 cal. ka BP with the initial retreat of the ice marked by the production of grounding-zone wedges between 23–21.1 cal. ka BP. However, the timing and rate of ice-sheet retreat from the inner continental shelf to the present coast are largely unknown. This paper reports 31 new terrestrial cosmogenic nuclide (TCN) ages from erratics and ice-moulded bedrock and three new optically stimulated luminescence (OSL) ages on deglacial outwash. The TCN data constrain deglaciation of the near coast (Aran Islands) to ~19.5–18.5 ka. This infers ice retreated rapidly from the mid-shelf after 21 ka, but the combined effects of bathymetric shallowing and pinning acted to stabilize the ice at the Aran Islands. However, marginal stability was short-lived, with multiple coastal sites along the Connemara/Galway coasts demonstrating ice recession under terrestrial conditions by 18.2–17. ka. This pattern of retreat continued as ice retreated eastward through inner Galway Bay by 16.5 ka. South of Galway, the Kilkee–Kilrush Moraine Complex and Scattery Island moraines point to late stage re-advances of the ice sheet into southern County Clare ~14.1–13.3 ka, but the large errors associated with the OSL ages make correlation with other regional re-advances difficult. It seems more likely that these moraines are the product of regional ice lobes adjusting to internal ice-sheet dynamics during deglaciation in the time window 17–16 ka.

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In recent years our understanding of the extent, chronology and dynamics of the last British–Irish Ice Sheet (BIIS) has undergone significant advances. This is particularly the case on the continental shelves surrounding Britain and Ireland where our knowledge of ice-sheet extent has improved due to the acquisition of new sedimentary, geophysical and geomorphological data sets, and our understanding of the timing and style of BIIS retreat has developed as new chronological data sets have become available. Earlier models of ice-sheet extent in western Ireland depicted unglaciated enclaves on land and very limited extension of the ice margin beyond the present coastline (e.g. Bowen *et al.* 2002). However, it is now evident that during the global Last Glacial Maximum (26.5–19 ka BP; Clark, P.U *et al.* 2009c) the BIIS expanded to the continental shelf edge west of Ireland and Britain (Benetti *et al.* 2010; Dunlop *et al.* 2010, 2011; Ó Cofaigh *et al.* 2012, 2019; Peters *et al.* 2015, 2016; Praeg *et al.* 2015). The marine-based sectors of the ice sheet were highly dynamic, with major shelf-edge terminating ice streams delivering sediment to the continental margin during phases of maximum ice extent (e.g. Callard *et al.* 2018; Scourse *et al.* 2019). Well-developed suites of grounding-zone wedges and moraines record grounding-line recession across the continental shelf as the ice sheet retreated in response to climatic, oceanic and sea-level forcing. These landforms and associated sedimentary records indicate that retreat was interrupted by periods of quasi-stability or grounding-line re-advance. To the northwest of Ireland on the Malin Shelf the ice sheet reached the shelf edge at ~26.7 cal. ka BP but retreat was underway by ~25.9 cal. ka BP or earlier (Callard *et al.* 2018; Ó Cofaigh *et al.* 2019). In contrast, offshore of central western Ireland, existing data indicate that the ice sheet reached the outer Porcupine Bank sometime after 24.1 cal. ka BP but retreated much later and was still grounded on the mid-shelf at ~18.5 cal. ka BP (Peters *et al.* 2015, 2016).

On the Atlantic shelf offshore of Galway Bay, western Ireland, the 'Galway Lobe' (Peters *et al.* 2016) was

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sourced by ice from the Irish Midlands flowing along a southwest trajectory (Greenwood & Clark 2009a). Recession of this lobe across the continental shelf has been a focus of recent work (Peters *et al.* 2015, 2016; Callard *et al.* 2019) but other than regional bedform mapping, very little is known about the timing of the marine to terrestrial transition of the ice sheet in western Ireland. From Galway Bay to southern County Clare (Fig. 1) only three ^{36}Cl cosmogenic exposure ages constrain deglaciation of the coast (20.9–15.3 ka; Bowen *et al.* 2002), but are all single samples making assessment of age uncertainties difficult. Additionally, they provide no insights into local deglacial conditions. Further north terrestrial cosmogenic nuclide (TCN) ages show that a marine embayment had developed along the north coast of Ireland by ~22–21 ka, though much of Donegal Bay remained ice-covered until ~17.0 ka (Small *et al.* 2017; Wilson *et al.* 2019).

Evidence for regional re-advances during deglaciation is largely unreported in central western Ireland, with only Greenwood & Clark (2009a) identifying a late phase re-organization of regional ice flow into southern County Clare. To the north of Connemara in Mayo and Donegal (Fig. 1), some authors have argued for deglaciation of the coastline under glaciomarine conditions at ~20.0 cal. ka BP (McCabe *et al.* 1986, 2005). However, this hypothesis is contentious and recent reconstructions of relative sea level during deglaciation suggest that while parts of the northwest coast of Ireland may have experienced glaciomarine conditions the central coastal areas of western Ireland more likely deglaciated under terrestrial conditions (Evans *et al.* 2015; Edwards *et al.* 2017).

This paper provides a new deglacial chronology for retreat of the BIIS from the inner continental shelf offshore of western Ireland to the adjoining coastline. To allow integration of the offshore chronology with terrestrial deglaciation chronology, the paper focuses on dating sites between Connemara and the Shannon Estuary, where westerly ice flow from the Irish Midlands fed the Galway Lobe Grounding Zone Wedge (GLGZW) and Galway Lobe Readvance Moraine (GLRM) identified by Peters *et al.* (2016). Particular aims include: (i) establishing when the ice margin retreated across the present coastline to become land-based; (ii) determining any change in the rate of ice-margin retreat as it became grounded on land; and (iii) exploring the implications of our age data for the interpretation of proposed regional re-advances of the Irish component of the BIIS. The paper provides 31 new terrestrial cosmogenic nuclide (TCN) dates on samples from glacially transported, erratic boulders and ice-moulded bedrock, supplemented by three new optically stimulated luminescence (OSL) dates on deglacial outwash. This chronology constrains the timing of the marine–terrestrial transition in ice-sheet retreat along 200 km of coastline from Connemara, County Galway in the north to the Shannon estuary in Country Clare to the south (Figs 1, 2).

Regional ice-sheet history

During the Last Glacial Maximum (LGM) the Irish Ice Sheet (IIS) ice flowed from a number of terrestrial source areas onto the western Irish continental shelf (Fig. 1). From the evidence provided by the dispersal of erratic boulders and the alignment of striae and glacial bedforms, several researchers have identified ice-flow patterns in western Ireland. This was dominated by radial ice movement centred on the Connemara mountains in the north of the area, and westwards or southwestwards movement of ice from the Irish Midlands between southern Connemara and the Shannon Estuary (e.g. Synge & Stephens 1960; Synge 1979; McCabe 2008; Smith *et al.* 2008 Smith & Knight, 2011; Fig. 2A). A more nuanced interpretation has been provided by Greenwood & Clark (2009a, b) on the basis of sequential (cross-cutting) flowsets derived from bedform alignments detected on satellite imagery and digital elevation models. Their interpretation suggests that southwestwards ice flow persisted across the area south of the Connemara mountains during and after the LGM, and was succeeded by southwards ice movement as the IIS shrank towards a residual ice divide located over the mountains of northern Connemara and southern County Mayo (Fig. 2B). In the Connemara area, flowset Fs54 clearly relates to the offshore movement of outlet glaciers across the coast from the Connemara mountains. Flowsets Fs17 and Fs18, which supplied ice into Clew Bay, also appear to have been sourced from the northern Connemara mountains. However, the dominant regional advance phase flowset is Fs6, which shows ice fed from central Ireland moving southwest across Galway Bay and County Clare (Fig. 2B). The convergent pattern of lineations led Greenwood & Clark (2009a) to infer that 'fast' and thick ice flow may have characterized this flowset, but a definitive ice stream signal is not discernible (cf. Stokes & Clark 1999). End moraine complexes in southern County Clare led Greenwood & Clark (2009b) to suggest that Fs6 shifted to a more southerly flow trajectory as deglaciation progressed and ice divides re-orientated west to east north of Galway Bay (Fig. 2B).

During the LGM the IIS grew rapidly after 32 ka BP and extended offshore on to the western continental shelf (Ballantyne & Ó Cofaigh 2017). Before the present century, most models of the extent of the BIIS placed the limit of the last ice sheet a short distance offshore from western Ireland. The presence of moraines near the shelf edge was first documented by Haflidason *et al.* (1997) on the basis of reflection seismic profiles, and those moraines were assumed by Sejrup *et al.* (2005) to mark the westward extent of the BIIS. C.D. Clark *et al.* (2012) subsequently employed the Olex bathymetric database to conduct more detailed mapping of the shelf west of

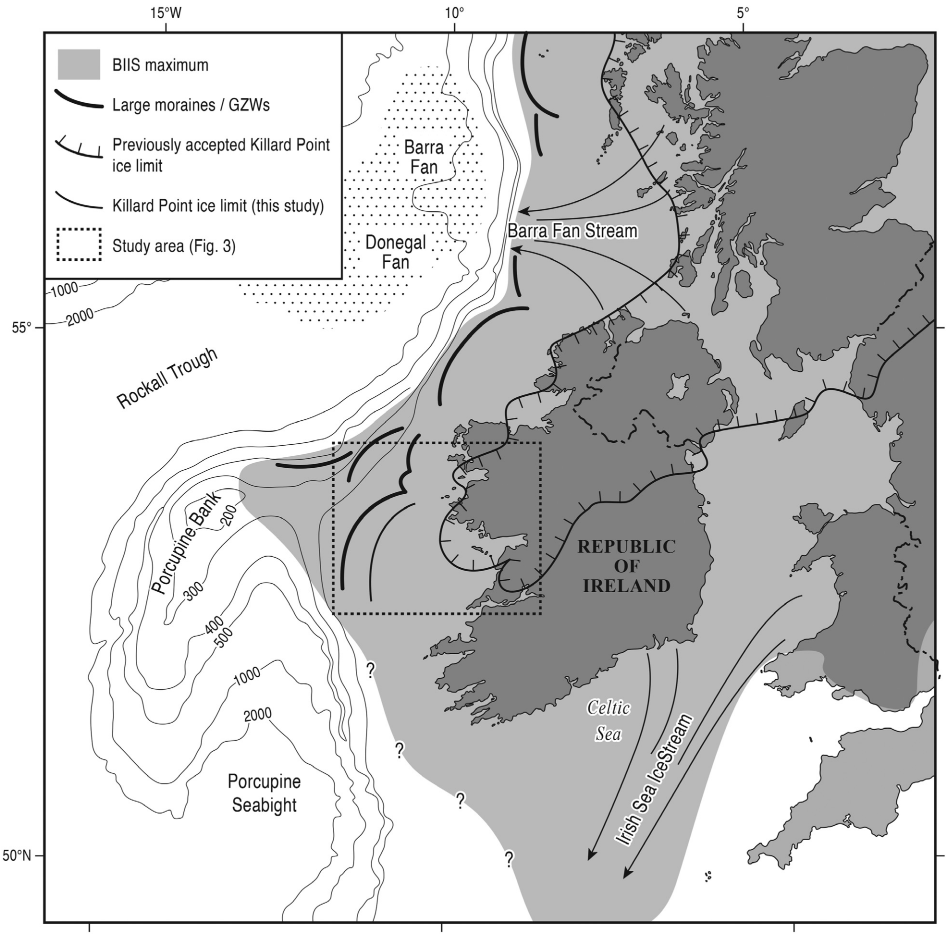
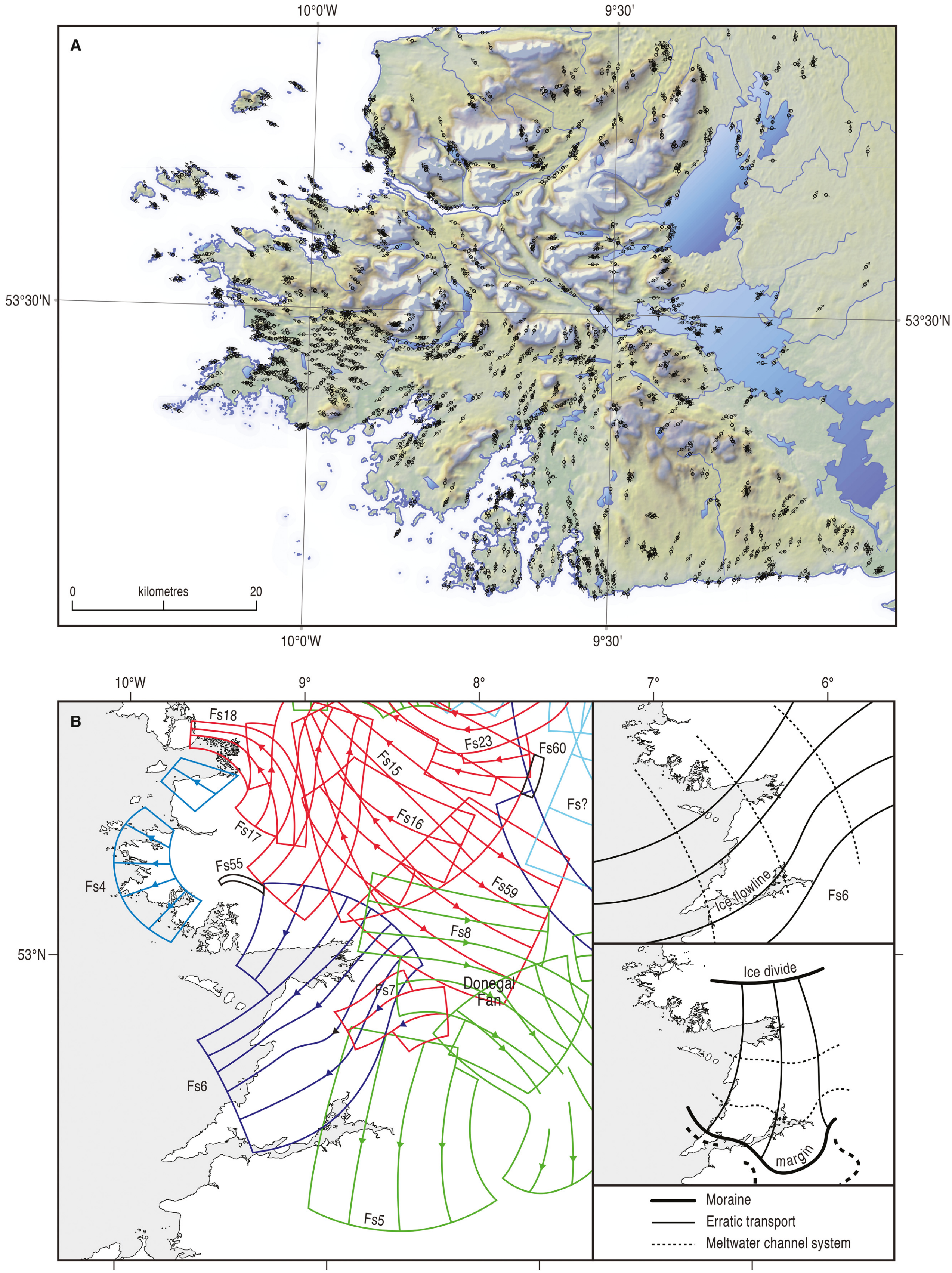


Fig. 1. The configuration of the BIIS at the Last Glacial Maximum. Maximum ice extent offshore from western Ireland is likely to have been reached at ~26–24 cal. ka BP. Ice retreat and re-advance across the mid-shelf is dated to between 21 and 18.5 cal. ka BP and is marked by the Galway Lobe Grounding Zone Wedge (GLGZW) and the Galway Lobe Re-advance Moraine (GLRM) (see Fig. 3). Deglaciation of the inner shelf back to the Galway and County Clare coast is poorly constrained.

Ireland, and depicted moraines (or grounding zone wedges) extending along the shelf edge. These were interpreted as indicating that during the LGM the last ice sheet had extended to the shelf break, with the advance of the ice margin being limited by calving at a deep-water marine-terminating margin. Peters *et al.* (2015) confirmed that the BIIS extended westwards to the shelf edge, and provided stratigraphical, morphological and chronological evidence that the ice margin had extended onto the Porcupine Bank, some 80 km farther west than previously mapped (Fig. 1), sometime after ~24.1 cal. ka BP.

Peters *et al.* (2016) showed that an 80-km-long arcuate moraine, the West Ireland Moraine (WIM), marks the westward limit of a grounded ice margin near the shelf break at ≤24.1 cal. ka BP (Fig. 3). They also described two major features deposited during subsequent eastward retreat of the ice margin towards Galway Bay. The older of these, the Galway Bay grounding-zone wedge (GLGZW), is located 120–140 km west of the mouth of Galway Bay, extends north–south for ~150 km and represents a prolonged stillstand or oscillating grounded ice margin, apparently buttressed by an extensive ice shelf to the west. Deposition of this grounding zone wedge is constrained by radiocarbon dates to within the period ~21.2 to ~18.5 cal. ka BP. Nested inside this feature, approximately 100 km west of the mouth of Galway Bay, is a recessional or re-advance moraine, the Galway Lobe recessional moraine (GLRM), deposited after ~18.5 cal. ka BP.

Information regarding the timing of ice-margin retreat on land between Clew Bay and the Shannon Estuary has previously been limited to a handful of TCN exposure ages, all obtained from single samples collected from exposed bedrock surfaces; all previously published cosmogenic ^{10}Be ages listed below have been recalibrated according to the protocol outlined in the following section. These published ages exhibit little consistency. Two samples obtained by Bowen *et al.* (2002) for coastal sites north of the Shannon Estuary yielded cosmogenic ^{36}Cl ages of 20.3±1.9 and 15.3±1.0 ka, and a single


A
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Fs18
Fs23
Fs60
Fs15
Fs?
Fs16
Fs17
Fs55
Fs4
Fs59
Fs8
Donegal Fan
Fs7
Fs6
Fs5
Ice flowline
Ice divide
margin
Moraine
Erratic transport
Meltwater channel system

Fig. 2. A. Regional striae patterns showing ice radiating from the Connemara mountains (Smith *et al.* 2008). B. Regional ice flowlines based on subglacial bedforms (Greenwood & Clark 2009b). Note Fs6 and Fs54 denoting ice flow offshore toward the southwest and west, respectively. However, the inset panels in B show a late southerly flow switch (Fs5) across County Clare during deglaciation that may be associated with moraine complexes at Kilrush-Kilkee and Scattery Island.

sample obtained from near the mouth of Galway Bay gave a ^{36}Cl exposure age of 20.9±2.7 ka (Fig. 3). A bedrock surface sampled by Ballantyne *et al.* (2008) near the head of Clew Bay produced a single cosmogenic ^{10}Be exposure age 18.9±0.9 ka, and another from 305 m altitude near Killary Harbour gave an exposure age of 16.9±0.8 ka. North of Clew Bay, Ballantyne *et al.* (2008) obtained two consistent ^{10}Be ages (19.1±1.0 and 19.2±1.0 ka) for ice-moulded bedrock on a col at 440 m altitude, which they interpreted as representing the timing of ice-sheet thinning.

The most comprehensive suite of TCN ages hitherto reported for western Ireland consists of eight ^{10}Be ages obtained by Clark *et al.* (2009a) from boulder samples on low ground near Furnace Lough, north of the head of Clew Bay. These (recalibrated) ages range from 15.8±1.3 to 19.4±1.8 ka, with an uncertainty-weighted mean (UWM) age of 16.9±1.0 ka, but the wide scatter of ages suggests that some may be compromised by transient sediment shielding or nuclide inheritance. Ballantyne & Ó Cofaigh (2017) suggested that the timing of deglaciation at this site may be equally represented by the three oldest ages (UWM = 18.4±1.0 ka) or the three youngest (UWM = 15.7±1.0 ka). The wide range of TCN ages hitherto obtained for western Ireland allows little confidence to be placed on their accuracy, particular as only a single sample of uncertain validity was dated at most sites.

Material and methods

Terrestrial cosmogenic radionuclide analysis and age calculation

The sampling procedures followed in this paper follow Roberts *et al.* (2008). All the samples for exposure dating were collected from heavily glacially abraded terrain with perched boulders. The vast majority of samples came from erratics, with only three samples taken from bedrock exposures. None of the samples was related to specific ice-marginal geomorphology (e.g. moraines), but in all cases the sites mark ice recession across a bedrock, subglacial surface (Small *et al.* 2017). In all, 31 samples were collected and analysed (Tables 1–3, S1). Sample locations and elevations were recorded using a hand-held GPS. The sample lithologies are predominantly granites with a few metasandstones or quartzites. Target samples were subglacial in origin, being subangular to subrounded and clearly abraded/striated. Large stable boulders standing >50 cm above local ground level were chosen to minimize potential sediment, vegetation and snow cover. Sample surfaces were over 30 cm from all edges. Heavily weathered, disintegrated or spalled surfaces were not sampled. Surface dip and strike were recorded. Shielding was recorded and corrected for using the CRONUS-Earth online calculator (Balco *et al.* 2008; accessed 23/03/2016; http://hess.ess.washington.edu/math/general/skyline_input.php).

Sample preparation for surface exposure ages follows the methods outlined in Small *et al.* (2017) and was executed at the Cosmogenic Isotope Analysis Facility – Scottish Universities Environmental Research Centre (CIAF - SUERC) and the Cosmogenic Nuclide Laboratory at the University of Glasgow. Full sample details including data on quartz (g), carrier (μg g^{-1}), ^{10}Be/^{9}Be and blank ^{10}Be/^{9}Be with related uncertainties are provided in Table S1. The 250–500 μm size fraction was used. The ^{10}Be/^{9}Be ratios were measured and calculated on the 5 MV accelerator mass spectrometer (AMS) at SUERC (Xu *et al.* 2010). ^{10}Be exposure ages were calculated using the CRONUS-Earth calculator (developmental version, accessed 02/06/2019; Wrapper script 2.3, Main calculator 2.1, constants 2.2.1, muons 1.1; http://hess.ess.washington.edu/math/al_be_v22/al_be_calibrate_v22.php; Balco *et al.* 2008) and, for comparison, the CRONUScalc calculator (http://web1.ittc.ku.edu:8888/2.0/html; accessed 02/06/2019; Marrero *et al.* 2016; Table 2). Ages calculated in the CRONUS-Earth calculator are calibrated using a local production rate from Scotland (LL LPR; reference production rate 4.02±0.18 atoms g^{-1} a^{-1}; Fabel *et al.* 2012). The CRONUScalc calculator allows users to calculate exposure ages using the Lifton-Sato-Dunai scaling scheme (SA) (Lifton *et al.* 2014) with a reference production rate of 3.92 atoms g^{-1} a^{-1}. All previously reported ^{10}Be ages were recalibrated using the CRONUS-Earth online calculator as per above. ^{36}Cl ages are not re-calculated but should be viewed with caution as regional production rates are unknown. We use an erosion rate of 1 mm ka^{-1}. Assuming erosion rates of 2 and 0 mm ka^{-1} produces ages up to ~2% older and ~1% younger, respectively, and does not alter our interpretations. Additionally, erosion rates on glaciated crystalline rocks are generally quite low at <2 mm ka^{-1} (André 2002). Uncertainties are cited as full (external) uncertainties and mean ages presented as uncertainty weighted means (UWMs; Table 3). All TCN ages are given as 'ka'.

Optically stimulated luminescence analysis and age calculation

Samples for optically stimulated luminescence (OSL) dating were collected from exposures of glacigenic

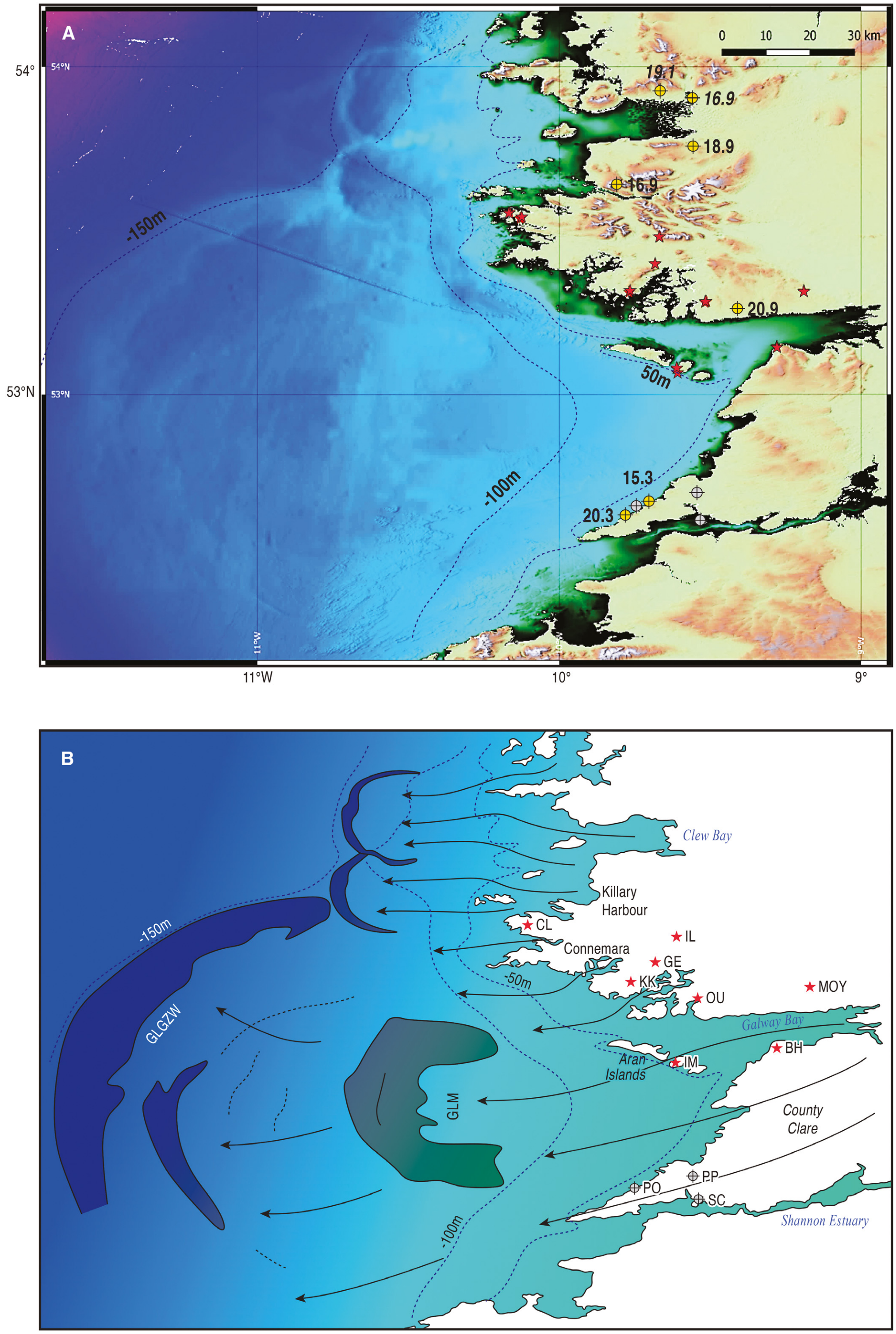


Fig. 3. A. The physiography and bathymetry of western Ireland and the adjacent continental shelf. The Connemara mountains are situated between Galway Bay and Clew Bay and would have harboured an independent ice cap later subsumed by the main Irish Ice Sheet as ice expanded westwards on the continental shelf. Pre-existing TCN ages form the region are indicated by yellow symbols (italicized ages represent uncertainty weighted means of multiple samples). New TCN ages are marked in red and new OSL ages in grey. B. The Galway Lobe Grounding Zone Wedge (GLGZW), the Galway Lobe Re-advance Moraine (GLRM) and the Galway Lobe Moraine (GLM) mark ice recession from the continental shelf. The Aran Islands are located offshore at the mouth of Galway Bay. Site name abbreviations for TCN and OSL sites are detailed in Table 1.

sediment, selecting lithofacies with the greatest potential for exposure to daylight in order to maximize the likelihood of identifying grains that had their OSL signal reset at deposition. Opaque plastic tubes were hammered into the sediment and then returned to the Aberystwyth Luminescence Research Laboratory for analysis.

External beta dose-rates were determined for OSL dating using inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectroscopy (ICP-AES), while the external gamma dose-rates were determined using *in situ* gamma spectrometry (Table 4). Quartz grains were isolated from the bulk sediment samples and used for OSL analysis following the protocols outlined in Smedley *et al.* (2017a). All luminescence measurements were performed using a Risø TL/OSL DA-15 automated single-grain system equipped with a $^{90}Sr/^{90}Y$ beta source (Bøtter-Jensen *et al.* 2003). Stimulation was performed using a green laser and detected through a 2.5-mm-thick U-340 filter and convex quartz lens placed in front of the photomultiplier tube. The signal was recorded at 125 °C for a total of 1 s, where the OSL signal was summed over the first 0.1 s of stimulation and the background calculated from the final 0.2 s. Instrument reproducibility of 2.5% was incorporated into the calculation of the equivalent dose (D_e) values. Preheat plateau tests were used to determine the preheat temperature (180 °C) used in the single aliquot regenerative dose (SAR) protocol (Murray & Wintle 2000) for OSL analysis.

Grains were mounted into 10 by 10 grids of 300-μm-diameter holes in a 9.8-mm-diameter aluminium single-grain disc for analysis. The grain size analysed for OSL dating varied between the three samples due to a lack of grains >180 μm in diameter in samples T5SCAT02 and T5PYNE02. Single-grain analysis was performed on sample T5TULA01 (grain size = 180–250 μm) to determine D_e values for dating. However, micro-hole analyses were performed on samples T5SCAT02 (125–180 μm) and T5PYNE02 (90–125 μm) as up to four and nine grains, respectively, were located in each during OSL analysis. The OSL signal-intensities emitted by quartz grains in these samples were very dim, making OSL analysis extremely challenging. D_e values were determined from only 0.4–0.5% of the total grains analysed, and so up to 11 700 grains needed to be analysed to characterize the single-grain D_e distribution. However,

Table 1. TCN sample codes, locational data, outcrop and rock type, sample thickness and density and shielding.

Sample code	Location	Lat.	Long.	Elevation (m a.s.l.)	Outcrop type	Sample lithology	Thickness (cm)	Density (g cm^{-3})	Shielding
T5BH01	Black Head (BH)	53.14528	−9.27667	12.00	Erratic	Granite	4	2.6	0.9999
T5BH02	Black Head	53.14528	−9.27883	7.00	Erratic	Granite	4	2.6	0.9939
T5BH03	Black Head	53.14362	−9.27833	15.00	Erratic	Granite	4	2.6	0.9939
T5CL01	Claddaghduff (Cl)	53.53500	−10.1300	25.00	Erratic	Granite	4	2.6	0.9991
T5CL02	Claddaghduff	53.5372	−10.1304	32	Erratic	Granite	4	2.6	0.9970
T5CL03	Claddaghduff	53.5395	−10.1261	35	Erratic	Granite	4	2.6	0.9987
T5CL04	Claddaghduff	53.5382	−10.1270	26	Erratic	Granite	4	2.6	1.0000
T5CL06	Claddaghduff	53.55333	−10.1647	19.00	Erratic	Granite	4	2.6	1.0000
T5CL07	Claddaghduff	53.55467	−10.1644	19.00	Erratic	Granite	4	2.6	1.0000
T5IE01	Illion East (IE)	53.48133	−9.66740	105.00	Erratic	Meta sandstone	4	2.6	0.9938
T5IE02	Illion East	53.48136	−9.6674	105	Erratic	Meta sandstone	4	2.6	0.9970
T5IE03	Illion East	53.48150	−9.66740	105.00	Erratic	Quartzite	4	2.6	0.996
T5IE04	Illion East	53.48148	−9.66735	107	Erratic	Meta sandstone	4	2.6	0.9984
T5IM01	Inis Meáin (IM)	53.06722	−9.60805	15.00	Erratic	Granite	4	2.6	1
T5IM02	Inis Meáin	53.07805	−9.61278	33.00	Erratic	Granite	4	2.6	0.9999
T5IM03	Inis Meáin	53.07830	−9.61260	34.00	Erratic	Meta sandstone	4	2.6	0.99
T5IM04	Inis Meáin	53.07972	−9.61028	43.00	Erratic	Granite	4	2.6	1
T5KK01	Kilkieran (KK)	53.31180	−9.76940	89.00	Erratic	Granite	4	2.6	1
T5KK02	Kilkieran	53.31140	−9.76970	82.00	Bedrock	Granite	4	2.6	1
T5KK03	Kilkieran	53.31100	−9.76980	75.00	Bedrock	Granite	4	2.6	0.9939
T5KK04	Gowlan East (GE)	53.39730	−9.68250	35.00	Erratic	Granite	4	2.6	0.9988
T5KK05	Gowlan East	53.39760	−9.68220	37.00	Erratic	Granite	4	2.6	0.9988
T5KK06	Gowlan East	53.39920	−9.68320	34.00	Erratic	Granite	4	2.6	0.9994
T5MOY01	Moycullen (MOY)	53.31550	−9.18910	72.00	Erratic	Granite	4	2.6	0.9994
T5MOY02	Moycullen	53.31518	−9.18855	70.00	Erratic	Granite	4	2.6	0.9994
T5MOY03	Moycullen	53.31572	−9.18877	73.00	Erratic	Granite	4	2.6	0.9998
T5MOY04	Moycullen	53.31473	−9.18915	73.00	Erratic	Granite	4	2.6	0.9989
T5MOY05	Moycullen	53.31540	−9.18890	73.00	Erratic	Granite	4	2.6	0.9927
T5OU04	Rossaveel (OU)	53.28083	−9.51862	59.00	Erratic	Granite	4	2.6	0.9988
T5OU05	Rossaveel	53.28278	−9.51722	70.00	Erratic	Granite	4	2.6	0.9999
T5OU06	Rossaveel	53.28333	−9.51305	54.00	Bedrock	Granite	4	2.6	0.9939

Table 2. TCN age calculations. Note both CRONUS 2.3 LLPR LM and 2.0 LM version are provided for comparative purposes. Assuming erosion rates of 2 and 0 mm ka^{-1} makes our ages ~2% older and ~1% younger, respectively, and does not alter our interpretations. Erosion rates on glaciated crystalline rocks are generally low at <2 mm ka^{-1} (André 2002).

Sample code	AMS ID	Erosion rate (cm a^{-1})	^{10}Be (atoms g^{-1})	+/– (atoms g^{-1})	CRONUS 2.3 LLPR LM (ka)	Int. uncert. (ka)	Ext. uncert. (ka)	CRONUS 2.0 LM (ka)	Int. uncert. (ka)	Ext. uncert. (ka)
T5BH01	b8679	0.0001	54832	3655	13.9	0.9	1.1	13.9	0.9	1.4
T5BH02	b8680	0.0001	65848	4793	16.8	1.2	1.4	16.8	1.2	1.8
T5BH03	b8681	0.0001	46974	3566	11.8	0.9	1.1	11.8	0.9	1.3
T5CL01	b8684	0.0001	60499	6202	15.0	1.6	1.7	15.0	1.6	2.0
T5CL02	b10296	0.0001	69900	2213	17.5	0.6	1.0	17.5	0.6	1.5
T5CL03	b10297	0.0001	69150	2261	17.3	0.6	1.0	17.3	0.6	1.5
T5CL04	b10298	0.0001	69221	2236	17.3	0.6	1.0	17.4	0.6	1.5
T5CL06	b8685	0.0001	74342	7295	18.7	1.9	2.0	18.7	1.9	2.4
T5CL07	b8686	0.0001	66010	6531	16.5	1.7	1.8	16.5	1.7	2.1
T5IE01	b9961	0.0001	62107	3996	16.6	0.8	1.1	14.3	0.9	1.1
T5IE02	b10647	0.0001	83291	5136	19.3	1.2	1.5	19.0	1.2	2.0
T5IE03	b10424	0.0001	78652	4244	18.2	0.8	1.2	18.2	0.8	1.7
T5IE04	b10658	0.0001	45174	2901	10.3	0.7	0.8	10.3	0.7	1.1
T5IM01	b8675	0.0001	67412	3864	17.0	1.0	1.2	17.0	1.0	1.7
T5IM02	b8677	0.0001	76133	4173	19.0	1.0	1.3	19.0	1.0	1.8
T5IM03	b10300	0.0001	89161	2918	22.3	0.8	1.3	22.0	0.8	2.0
T5IM04	b8678	0.0001	81179	4537	20.1	1.1	1.4	20.0	1.1	2.0
T5KK01	b10301	0.0001	72234	2370	16.9	0.6	1.0	16.9	0.6	1.5
T5KK02	b10425	0.0001	73327	3273	17.2	0.6	1.0	17.3	0.6	1.5
T5KK03	b10302	0.0001	72805	3271	17.2	0.8	1.1	17.3	0.8	1.6
T5KK04	b10303	0.0001	78033	2979	19.3	0.8	1.2	19.3	0.8	1.7
T5KK05	b10306	0.0001	67407	2358	16.6	0.6	1.0	16.6	0.6	1.5
T5KK06	b10307	0.0001	70822	2175	17.5	0.6	1.0	17.5	0.6	1.5
T5MOY01	b10308	0.0001	66723	2255	15.8	0.6	0.9	15.8	0.6	1.4
T5MOY02	b9653	0.0001	66008	2705	15.7	0.6	0.9	15.7	0.6	1.4
T5MOY03	b9654	0.0001	69037	2622	16.4	0.6	0.9	16.4	0.6	1.4
T5MOY04	b9657	0.0001	72383	2900	17.2	0.6	1.0	17.2	0.6	1.5
T5MOY05	b10319	0.0001	74225	2419	17.6	0.6	1.0	17.7	0.6	1.5
T5OU04	b8687	0.0001	67480	6607	16.3	1.6	1.8	16.3	1.6	2.1
T5OU05	b8688	0.0001	56926	5548	13.5	1.3	1.5	13.5	1.3	1.7
T5OU06	b8567	0.0001	76604	3185	18.4	0.8	1.1	18.4	0.8	1.6

the very dim OSL signal intensities likely meant that the OSL signals emitted by micro-hole analyses were dominated by a single brighter grain in each hole, and so the D_e distributions would be similar to single grain measurements. The very dim OSL signal-intensities emitted by the quartz grains from this region in comparison to the rest of the BIIS (e.g. Smedley *et al.* 2017a, b; Chiverrell *et al.* 2018; Bradwell *et al.* 2019) are likely because the grains were eroded locally from carbonate bedrock, with little opportunity for sensitization of the OSL signal.

Successful dose-recovery experiments were performed on samples T5SCAT02 and T5KSW01 and demonstrated that the SAR protocol was appropriate for OSL analysis. Six screening criteria were applied to the data throughout the analyses; associated uncertainties were included for each test. Grains were only accepted if the response to the test dose was greater than three sigma above the background; the test dose uncertainty was <20%, the recycling ratios and OSL-IR depletion ratios were within the range 0.8–1.2; recuperation was <5% of the response from the largest regenerative dose (150 Gy) and the single-grain D_e values were not part of a population of very low doses that were identified by the finite mixture model (FMM) to be inconsistent with the geological context of the sample. The single-grain D_e values determined for each sample are given in Tables S2–S4. To determine OSL ages, D_e values were calculated using the minimum age model (MAM) as the single-grain D_e distributions were asymmetrically distributed and therefore deemed to have been heterogeneously bleached prior to burial. The overdispersion determined from dose-recovery experiments (Table 5) estimated the scatter in the single-grain D_e distributions arising from intrinsic sources of uncertainty that were beyond measurement uncertainties. The intrinsic overdispersion was then added in quadrature to the extrinsic overdispersion arising from external microdosimetry (~20%) to determine σ_b for the MAM (after Smedley *et al.* 2017b). The MAM D_e values were divided by the environmental dose-rates to determine an age for each sample (Table 5). All OSL ages are given as 'ka'. It should be noted that all radiocarbon ages are quoted as cal. ka BP with reference to 1950.

Table 3. Statistical analysis of T5 TCN ages. Sample code numbers that have been underlined represent the samples used to calculate uncertainty-weighted means (UWM) = uncertainty-weighted mean; U_U = external (total) uncertainty associated with UWM; AM = arithmetic mean; U_A = arithmetic mean of external (total) uncertainties; χ^2_R = reduced Chi-squared value; υ = degrees of freedom (= $n - 1$).

Site name	Sample code	CRONUS v2.3 LLPR LM (ka)	Int. uncert. (ka)	Ext. uncert. (ka)	χ^2_R	UWM (ka)	Ext. uncert. (ka)
Black Head	T5BH01	13.9	0.9	1.1	11.81 ($n = 3$)	N/A	N/A
	T5BH02	16.8	1.2	1.4			
	T5BH03	11.8	0.9	1.1			
Claddaghduff	T5CL01	15.0	1.6	1.7	0.73 ($n = 6$)	17.3	0.8
	T5CL02	17.5	0.6	1.0			
	T5CL03	17.3	0.6	1.0			
	T5CL04	17.3	0.6	1.0			
	T5CL06	18.7	1.9	2.0			
	T5CL07	16.5	1.7	1.8			
Illion East	T5IE01	16.6	0.8	1.1	2.55 ($n = 4$)	18.1	1.1
	T5IE02	19.3	1.2	1.5			
	T5IE03	18.2	0.8	1.2			
	T5IE04	20.0	1.3	1.8			
Inis Meáin	T5IM01	17.00	1	1.2	6.85 ($n = 4$)	19.5	1.2
	T5IM02	19.00	1	1.3			
	T5IM03	22.3	0.8	1.3			
	T5IM04	20.1	1.1	1.4			
Kilkieran	T5KK01	16.9	0.6	1	0.13 ($n = 3$)	17.1	0.8
	T5KK02	17.2	0.6	1			
	T5KK03	17.2	0.8	1.1			
Gowlan East	T5KK04	19.3	0.8	1.2	0.13 ($n = 3$)	17.1	0.8
	T5KK05	16.6	0.6	1			
	T5KK06	17.5	0.6	1			
Moycullen	T5MOY01	15.8	0.6	0.9	1.94 ($n = 5$)	16.5	1.9
	T5MOY02	15.7	0.6	0.9			
	T5MOY03	16.4	0.6	0.9			
	T5MOY04	17.2	0.6	1			
	T5MOY05	17.6	0.6	1			
Rossaveel	T5OU04	16.3	1.6	1.8	6.86 ($n = 3$)	18.2	1.0
	T5OU05	13.5	1.3	1.5			
	T5OU06	18.4	0.8	1.1			

New constraints on the timing of deglaciation

The aim of the sampling rationale employed in this paper was to date ice retreat along the local flowlines as the ice margin retreated from offshore to onshore. Flowline reconstruction is based on mapping of subglacial bedforms as reported by Greenwood & Clark (2009a). The geomorphic setting of each sample site is outlined below. The Aran Islands offshore from Galway Bay provide a clear set of pinning points on the inner shelf as the ice margin migrated eastward towards the coast. Claddaghduff is the most westerly sampling site, capturing ice retreat back to the Connemara coast. The TCN ages from Kilkieran, Gowlan East and Illion East track the timing of ice recession in a northeasterly direction back towards the Connemara Mountains, while those obtained for Rossaveel and Oughterard constrain the timing of ice retreat further east. The sites at Moycullen and Black Head were sampled to establish the timing of

Table 4. Environmental dose-rates determined using ICP-MS and ICP-AES analysis and *in situ* gamma spectrometry. The chemical concentrations are presented with decimal points relevant to detection limit. The dose-rates were calculated using the conversion factors of Guerin *et al.* (2011) and beta dose-rate attenuation factors of Guerin *et al.* (2012). Water contents were estimated considering the field and saturated water contents, and the environmental history for each sample; these values are expressed as a percentage of the mass of dry sediment. Cosmic dose-rates were determined after Prescott & Hutton (1994). Dose-rates were calculated using the Dose Rate and Age Calculator (DRAC; Durcan *et al.* 2015).

Sample	Depth (m)	Water content (%)	U (ppm)	Th (ppm)	K (%)	Rb (ppm)	Beta dose-rate (Gy ka^{-1})	Gamma dose-rate (Gy ka^{-1})	Cosmic dose-rate (Gy ka^{-1})	Total dose-rate (Gy ka^{-1})
T5SCAT02	1.5	30±5	3.30±0.33	10.4±1.0	1.6±0.2	84.0±8.4	1.33±0.13	0.83±0.05	0.17±0.02	2.40±0.14
T5PYNE02	5.2	20±5	3.08±0.31	9.5±1.0	1.3±0.1	65.6±6.6	1.32±0.10	0.81±0.05	0.11±0.01	2.52±0.13
T5KSW01	1.0	23±5	2.88±0.29	10.6±1.1	1.9±0.2	93.1±9.3	1.52±0.14	0.92±0.06	0.18±0.02	2.67±0.15

eastward migration of the ice margin through inner Galway Bay into the interior lowlands of Ireland (Fig. 3).

In southern County Clare a series of sites with exposed glacial sediments were also investigated in order to obtain OSL ages to constrain the timing of ice-margin retreat. Two sites (Scattery Island and Pynes Pit) exhibit outwash and glaciolacustrine sediments associated with moraine ridges and thus constrain the ages of ice-marginal positions during overall retreat. The third site on the southwest coast of County Clare (Portacarron) has no distinctive geomorphology to demarcate the ice margin, but glacifluvial sediments were used to provide a deglacial OSL age.

Cosmogenic surface exposure ages

The first six sites described below (Claddaghduff, Kilkieran, Gowlan East, Ilion East, Rossaveel and Moycullen) have common characteristics. All are situated on low (≤105 m a.s.l.), glacially scoured ground comprising small bedrock knolls and occasional roches moutonnées rising above peat and patchy drift cover, with abundant erratic boulders. The latter are generally subangular to subrounded, indicating that they experienced active subglacial transport prior to deposition. For brevity, and consistency with previously published papers from the BRITICE-CHRONO project, we go on to discuss ages as calculated using the LLPR and the CRONUS-Earth online calculator (Balco *et al.* 2008).

Claddaghduff. – Claddaghduff is situated on the western edge of the Connemara coastline to the south of Cleggan (Fig. 3). The alignment of subglacial bedforms suggests a strong west to southwest ice-flow direction. The area is littered with perched granite erratics, 1–2 m in diameter (Fig. 4). Striae are rare, due to granular disintegration (1–5 mm), pitting (3–5 mm) and spallation (~5–15 mm). The top surfaces of sampled boulders all sit over 1 m above the local ground level. Samples were collected from two adjacent locations (samples CL01–04, and CL06–07 in Tables 1 and 2). They provide age estimates of 15.0±1.7, 17.5±1.0, 17.3±1.0, 17.3±1.0, 18.7±2.0 and 16.5±1.8 ka, respectively. Taken together they produce a reduced Chi-square (χ^2_R) value of 0.73 with and a UWM of 17.29±0.82 ka. This is statistically indistinguishable from the UWM for the three most tightly constrained samples (CL02+03+04; UWM = 17.4±0.9 ka; Table 3); an age of 17.3±0.8 ka is adopted in the Discussion section.

Kilkieran and Gowlan east. – These sites are located 25 km east of that at Claddaghduff (Fig. 3). The granite surfaces of the numerous granite boulders have suffered minor granular disintegration (1–3 mm) and some spallation (up to 10 mm). Sample KK1 was obtained from a perched erratic, and samples KK2 and KK3 from the plucked lee-sides of roches moutonnées. The three samples provide ^{10}Be ages of 16.9±1.0, 17.2±1.0 and 17.2±1.1 ka, respectively (Tables 2, 3), and produce a χ^2_R value of 0.13 and a UWM of 17.1±0.8 ka.

Approximately 12 km inland to the northeast a further set of samples from Gowlan East (Fig. 3) provides further constraints on deglaciation in this area. Here large granite erratics were deposited as the ice margin retreated towards the Twelve Bens, in the heart of the Connemara Mountains. Some of these are 3 × 3 × 2 m in diameter and stand well clear of the surrounding peat. Samples KK04–06 yielded exposure ages of 19.3±1.2, 16.6±1.0 and 17.5±1.0 ka, respectively (Table 2). These ages yield a χ^2_R value of 4.26 suggesting a significant contribution from geological uncertainty. Sample KK04 cannot be identified as an outlier on the basis of an extreme studentized deviate (ESD) test (cf. Jones *et al.* 2019). However, as this site lies inland (i.e. up ice) of the Kilkieran site it would be expected to have deglaciated later than 17.1±0.8 ka (the UWM for Kilkieran), a scenario not consistent with the older age of KK04. Additionally, we note that the younger two ages (KK05 and KK06) are in agreement and are indistinguishable from the cluster of ages at Kilkieran. On this basis, we favour the interpretation that the UWM of KK05 and KK06 (17.1±0.9 ka) is the best estimate of the timing of deglaciation at this site (Table 3).

Illion East. – This site lies ~13 km north of Gowlan East, in the foothills of the Twelve Bens; the TCN ages for this site therefore mark retreat of the ice margin towards its mountain source area. The area is covered by subangular to subrounded metasandstone erratic boulders that exhibit minor granular disintegration (1–3 mm), surface pitting (3–5 mm) and spallation (up to 10 mm). Four samples from boulders (IE 01–04) provided ages of 16.6±1.1, 19.3±1.5, 18.2±1.2 and 20.0±1.8 ka, respectively (Table 2), and have a χ^2_R value of 2.55; however, no samples are flagged as statistical outliers (ESD or

Table 5. OSL analysis results, including the overdispersion of the data obtained from dose-recovery tests (DR OD), the total number of grains analysed for dating each sample, the number of grains (*n*) that yielded equivalent dose values, the overdispersion (OD) of this data, and the sigma-b value (σ_b) used in the minimum age model for calculating the equivalent dose (D_e) used to determine the age.

Sample	Grain size (μm)	DR OD (%)	Total analysed	*n*	OD (%)	σ_b	D_e (Gy)	Age (ka)
T5SCAT02	125–180	29	6500	35	52	0.35	33.0±6.9	13.7±3.0
T5PYNE02	90–125	–	11 700	43	66	0.35	30.5±5.9	13.3±2.7
T5KSW01	180–250	41	6900	43	61	0.40	37.5±9.3	14.1±3.6

Fig. 4. A. The Claddaghduff site is characterized by ice scoured terrain with subglacial bedform long axes trending west/southwest. The area is littered with perched, subglacial, granite erratics (CL 6 shown). B. Striae are rare, due to granular disintegration (1–5 mm), pitting (3–5 mm) and sometimes spallation (~5–15 mm). Sample surfaces were elevated over 1 m above the local ground level. C. Samples were taken from the upper surfaces of these boulders using a rock saw. Sample thickness was typically 3 cm. The UWM exposure age for this site is 17.3±0.8 ka.

Chauvenet test). We consider the UWM age of all four samples of 18.1±1.1 ka as a reasonable estimate of the timing of deglaciation.

Rossaveel. – At Rossaveel the alignment of ice moulded bedforms suggests ice movement in a southwesterly direction. Samples were taken from two erratics (OU4 and OU5) and the lee-side of a roche moutonnée (OU06; Fig. 5; Tables 1, 2). These returned ages of 16.3±1.8, 13.5±1.5 and 18.4±1.1 ka, respectively (Table 2). The samples have χ^2_R = 6.86. We note that OU05 is significantly younger than the other samples both at this site and within the data set as a whole but it is not a statistical outlier. Using only OU04 and OU06 provides an UWM of 18.2±1.0 ka, but this has a low confidence for the same reasons as outlined for the Illion East site (Table 3).

Moycullen. – Five samples were obtained from Killagoola, just south of Moycullen (Fig. 6). The terrain at this site is littered with large (1–2 m diameter) granite boulders that exhibit surface granular disintegration (2–5 mm) and pitting (1–3 mm) but are clearly subglacial in origin. The five samples (MOY 01–05) provided ages of 15.8±0.9, 15.7±0.9, 16.4±0.9, 17.2±1.0 and 17.6±1.0 ka, respectively (Table 2). No sample is a statistical outlier and the five samples together give a χ^2_R value of 1.94, which suggests they are from the same population at the 95% confidence interval. Using all five provides a UWM of 16.5±1.9 ka and this is used in discussion (Table 3).

Black Head. – At Black Head in County Clare, granite erratic boulders can be found resting on a limestone pavement situated just above sea level (samples range from 7–12 m a.s.l.; Fig. 7). The erratics are subangular to subrounded but devoid of striae due to surface weathering and pitting. Regional ice movement across Black Head has been mapped as flowing southwest initially with a possible late phase switch to a more southerly flow

(Greenwood & Clark 2009a). The three ages (BH01–03) obtained from this site are all significantly different and give a χ^2_R value of 11.81 (Table 4); the two closest (and youngest) ages of 13.8±1.1 and 11.8±1.1 ka would imply deglaciation around the time of the Younger Dryas, which is considered very unlikely for this site. Considering it within the context of all the geochronological data presented here and used with caution, the oldest age (16.8±1.4 ka) suggests the minimum age for deglaciation at this site. It is not easy to explain the 'young' ages for this site, but it is possible the erratics may have been shielded at some point by sediment or that despite trying to avoid spalled surfaces these were inadvertently sampled at this site.

Inis Meáin. – The Aran Islands lie at the mouth of Galway Bay approximately 40 km west of Galway City. They are composed of Carboniferous limestone and form spectacular glaciokarst. The passage of ice across the islands is represented by prominent granite erratics transported from the Galway mainland. They are ubiquitous on all three islands but sampling of four boulders was confined to the south side of Inis Meáin. Here the landscape is devoid of any sediment cover with perched erratics sitting directly on exposed limestone (Fig. 8). All the samples have suffered some surface granular disintegration, pitting and spalling. Many erratics sit on raised pedestals (10–25 cm above local ground level) indicating postglacial lowering of the surrounding limestone pavement.

Samples IM01–IM04 from Inis Meáin produced widely divergent ages (17.0±1.2, 19.0±1.3, 22.3±1.3 and 20.1±1.4 ka, respectively). Interpretation of the four exposure ages from this site is not straightforward. The four samples give a χ^2_R value of 6.85, indicating significant geological uncertainty but none is flagged as a statistical outlier. Only two ages (IM02+04) for this site are consistent within analytical uncertainties, yielding an UWM of 19.51±1.17 ka (Tables 2, 3). This is somewhat older than other TCN ages reported onshore. It could indicate earlier deglaciation; however, the youngest three ages have an acceptable χ^2_R value (2.20) and give an UWM 18.55±1.03 ka suggesting a later deglaciation age, more compatible with that implied by onshore sites. The three oldest ages (IM02–04) do not yield an acceptable χ^2_R value (4.08). IM03 (22.32±0.80 ka) may be compromised by nuclide inheritance as it is significantly older than the other samples. In the Discussion, we adopt the deglacial age of 18.5±1.0 ka for the Aran Islands, with the caveat that this may still overestimate the timing of deglaciation.

Optically stimulated luminescence ages

Three sites comprising sediment exposures in glacifluvial and glaciolacustrine outwash were investigated in southwest County Clare and sampled for OSL dating (Figs 9, 10).

The coastal plain south of Kilkee is relatively flat lying with few geomorphic features of note. However, at Portacarron, to the southwest of Kilkee, approximately 4 m of glaciogenic sediment overlies shale bedrock (Fig. 10A). Overlying the bedrock is 2.1 m of poorly sorted, massive to locally chaotic, subangular to subrounded bouldery gravel that fines upwards crudely and gradationally into trough cross-bedded, cobble-boulder gravel with localized zones of scour and fill. The gravels are interpreted as proximal glacifluvial outwash (Miall 1978, 1992). These are overlain by stratified and rippled coarse to medium sands overlain in turn by laminated sands. These mark a transition to more distal sandur conditions (Miall 1978; Smith 1985). An OSL age from 3.90 m depth within rippled sands in this unit provided a deglacial age of 14.1±3.6 ka (Tables 4, 5). Above this, a massive, grey diamicton with a silty-clay matrix and dispersed clasts of shale, limestone and sandstone is interpreted as a subglacial till marking ice advance back over the site.

The terrain between Kilkee and Kilrush exhibits several linear and elliptical ridges running west to east that form a broad belt of hummocky terrain that can also be traced running northeast between Kilrush and Cooraclare. We term this the 'Kilkee–Kilrush Moraine Complex' (Fig. 9A, B). To the southwest of Cooraclare well-developed hummocky terrain with occasional flat-topped mounds occurs up to 41 m a.s.l. Pynes Pit, located 1.7 km southwest of Cooraclare, is a sand and gravel quarry within one of these flat-topped mounds. A 10-m-high section in the southeast face of the pit exposes a succession of stratified gravels, sands and fines (Fig. 10A, B). Three main lithofacies were identified. The lower 1.8 m of sediment is a crudely stratified, coarse sandy pebble gravel that dips generally southwards. It is interpreted as proximal glacifluvial outwash (Miall 1978). The gravels are overlain by a series of laminated silty sands and silt/clays with Type B, ripple-drift cross-lamination and draped lamination up to 4.57 m depth in the section log. In places, laminae exhibit rhythmic couplets with lower silty sands overlain sharply by silty clays (Fig. 10B). Between 3.24 and 4.18 m the sediments become more sandy and transition to Type A ripples. At ~4.0 m they also exhibit ball and pillow structures. Small-scale, sub-vertical faults are ubiquitous through this unit. These sediments point to deposition by a combination of low energy traction currents and suspension settling to produce the climbing ripples, draped lamination and rhythmically laminated fines (Gustavson *et al.* 1975; Smith & Ashley 1985). Such successions are consistent with a glaciolacustrine depositional environment and it is possible that they represent deltaic bottomsets or distal foresets; the flat top of the mound in which they are exposed supports a deltaic interpreta-

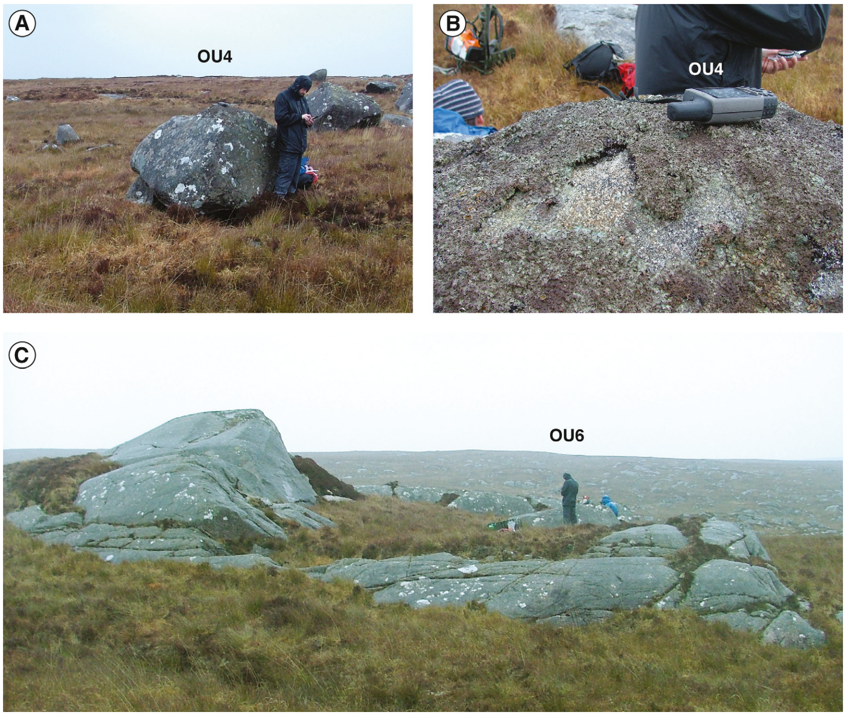


Fig. 5. The Rossaveel region is characterized by glacially scoured terrain with roches moutonnées and glacially sculpted bedrock bumps. Samples were taken from two erratics (OU4 and OU5) and the lee-side of a roche moutonnée (OU06; Tables 1–3). A, B. OU4, an erratic, provided an exposure age of 16.3±1.8 ka. Note the heavy lichen cover on this sample. C. Sample OU6 was taken from bedrock surface in the lee-side of a large roche moutonnée, which provided an age of 18.4±1.1 ka. Using only OU04+06 provides an UWM of 18.2±1.0 ka, but this has a low level of confidence.

tion. A high influx of fine sediment with rapid deposition from suspension is consistent with the ripple-drift lamination as well as soft-sediment deformation structures (faulting and ball and pillows; Gustavson *et al.* 1975; Teller 2003). The rhythmically laminated couplets may be varves and reflect a seasonal control on sedimentation (cf. Ashley 1975; Palmer *et al.* 2008) but confirmation of this requires further investigation. An OSL sample taken between 4.18–4.57 m from a rippled sand bed provided an age of 13.3±2.7 ka (Tables 4, 5). The sequence then coarsens upwards with beds of stratified gravel at 4.57 m and again at 5.40 m marking a return of more proximal sedimentation to the site. From 5.59 m to the top of the section at 8.59 m crudely bedded to massive cobble gravels, exhibiting locally developed imbrication, mark a full return to high energy glacifluvial conditions. These may represent delta topsets. These sediments clearly form part of the Kilkee–Kilrush Moraine Complex, but they are not significantly glaciotectonized at this locality.

The final site investigated in southwest Clare is Scattery Island in the Shannon Estuary (Figs 9A, 10A, C). Scattery Island has been previously interpreted as a thrust moraine formed during deglaciation at ~17–16 ka with ice pushing from east to west, subparallel to the estuary (McCabe 2008). It may represent a continuation of the Kilkee–Kilrush Moraine Complex further north (Fig. 9A). The lowest lithofacies is a folded and thrust laminated clay with large clasts. This unit is clearly waterlain (either glaciolacustrine or glaciomarine) with an ice-rafted component (McCabe 2008). Above the lower deformed clay up to 6 m of crudely stratified to massive, coarse cobble gravel forms the main coastal sediment exposure on the west coast of the island (Fig. 10A, C). In places stratified, discontinuous sand pods are interbedded with the gravel. The sand and gravels undoubtedly relate to increasingly proximal glacifluvial and ice-marginal conditions as ice re-advanced to form the Scattery Island moraine. McCabe (2008) reported several distinct thrusts cross-cutting the section and thrust ridges up to 12 m high trending NNE to SSW across the island. A single OSL sample from a sandy unit at 8.90 m up the section provided an age of 13.7±3.0 ka (Tables 4, 5).

Discussion

Ice-sheet retreat across the continental shelf offshore of central western Ireland

The arcuate planform of moraines and grounding zone wedges across the continental shelf demonstrate that the western sector of the IIS was composed of a series of confluent lobes that formed distinct flow elements within

Fig. 6. A, B. The area south of Moycullen is characterized by hilly terrain that is glacially scoured and littered with large granite erratics. These large erratics have flat upper surfaces that sit over 1 m above the local ground level that is often covered in peat. These erratics are not striated due to surface granular disintegration (2–5 mm) and pitting (1–3 mm). Using all five ages (MOY 1–5) provides a UWM age of 16.5±1.91 ka.

the ice sheet as it moved offshore. The onshore flowset mapping of Greenwood & Clark (2009a) indicates that ice crossing the area from the Connemara mountains to the Shannon Estuary flowed generally southwestwards on land and then westwards across the adjacent shelf as the Galway Lobe (Figs 2, 3). The footprint of the Galway Lobe dominates the offshore sea-floor geomorphology in the form of the GLGZW, the GLRM and the inner GLM (Fig. 3; Peters *et al.* 2016). North of the Connemara mountains westward ice flow was focused along the Killary Harbour fjord and Clew Bay to feed the offshore Connemara Lobe (Figs 2, 3).

Recent work offshore has shed new light on the timing of ice advance and subsequent retreat of the IIS back towards the Connemara, Galway and Clare coasts (Peters *et al.* 2016; Callard *et al.* 2019). At the LGM, Galway Lobe ice contributed to extension of the ice margin as far west as the Porcupine Bank, where the presence of multiple moraine complexes and grounding-zone wedges indicates an oscillating ice margin between ~26.4 and ~24.4 cal. ka BP. Oscillatory retreat of the ice margin to the mid-shelf was followed by a period of relative stability as the ice grounded at the GLGZW between ~23.0 and ~21.1 cal. ka BP, but the inner shelf appears to have been largely ice-free by 17.1 cal. ka BP (Callard *et al.* 2019; Fig. 11A).

Our sampling at Inis Meáin on the Aran Islands aimed to establish the timing of ice-margin retreat to the mouth of Galway Bay, but the TCN ages for this site are inconsistent. Using the youngest age (IM01) in isolation provides an age of 17.0±1.0 ka for deglaciation of this site (Table 3), which is consistent with an adjacent offshore deglacial age of 17.1 cal. ka BP reported by Callard *et al.* (2019). Collectively, however, the TCN ages for Inis Meáin suggest much earlier deglaciation, at 19.5±1.2 ka, or, more plausibly 18.5±1.0 ka (see above). The Aran Islands form a natural barrier across outer Galway Bay and are coincident with the –50 m contour close to shore. If ice retreated rapidly from the mid-shelf after ~21 ka, the combined effect of bathymetric shallowing and pinning on the Aran Islands may have stabilized the grounding line, slowing or halting ice-margin retreat (Fig. 11B).

The ice-sheet surface model simulations in Fig. 11B represent a central flowline from inner Galway Bay through the Aran Islands to the edge of the continental shelf (Fig. 11A). The ice-surface profiles are extracted from a three-dimensional ice-sheet model simulation, using the Parallel Ice Sheet Model (PISM; Winkelmann *et al.* 2011), which was forced to fit the empirically defined ice limits at the thousand year timesteps. The profiles are instructive in demonstrating change in steepness of

Fig. 7. A. At Black Head granite erratics rest on a limestone pavement. B. The granite erratic surfaces are weathered due to granular disintegration (~1–3 mm) and spallation on the flanks (~5–20 mm). Moderate lichen growth also is evident. C. The three ages (BH01–03) obtained from this site are all significantly different (Table 1); the oldest age is BH02 at 16.8±1.4 ka.

surface ice slopes as the ice margin underwent a transition from being marine-terminating (low slopes) to terrestrial terminating (higher slopes), likely arising from the dual consequence of change in basal shear stress from substrate contrasts and the loss of the marine margin. Ice-surface elevation would have been ~600–700 m a.s.l. across the inner continental shelf. This estimate concurs with geomorphic evidence from the Connemara mountains to the north (transposed in Fig. 11A) that suggests the summits (~650–700 m a.s.l.) were buried by ice during the LGM (Ballantyne *et al.* 2008).

The cosmogenic ^{36}Cl TCN ages of 20.9±2.7 and 20.3±1.9 ka from Galway Bay and Loop Head, respectively (Bowen *et al.* 2002), may also support early deglaciation (despite their large uncertainties). However, given the overwhelming evidence derived from this study for near-synchronous ice retreat from the coast at ~17.5–17.0 ka (Table 3) these single ages appear anomalous. Furthermore, the substantial moraine complex on the sea floor just to the west of the Aran Islands (the GLM, Peters *et al.* 2016; Figs 3, 11A) implies offshore ice-margin stability between ~21 and ~19 cal. ka BP, before ice retreated to the Aran Islands. Hence, a window of 19.5 to 18.5 ka for the deglaciation of the Aran Islands fits broadly with both the offshore geomorphology and chronology, and pre-dates the much younger ages obtained from the mainland.

The timing of ice retreat onshore

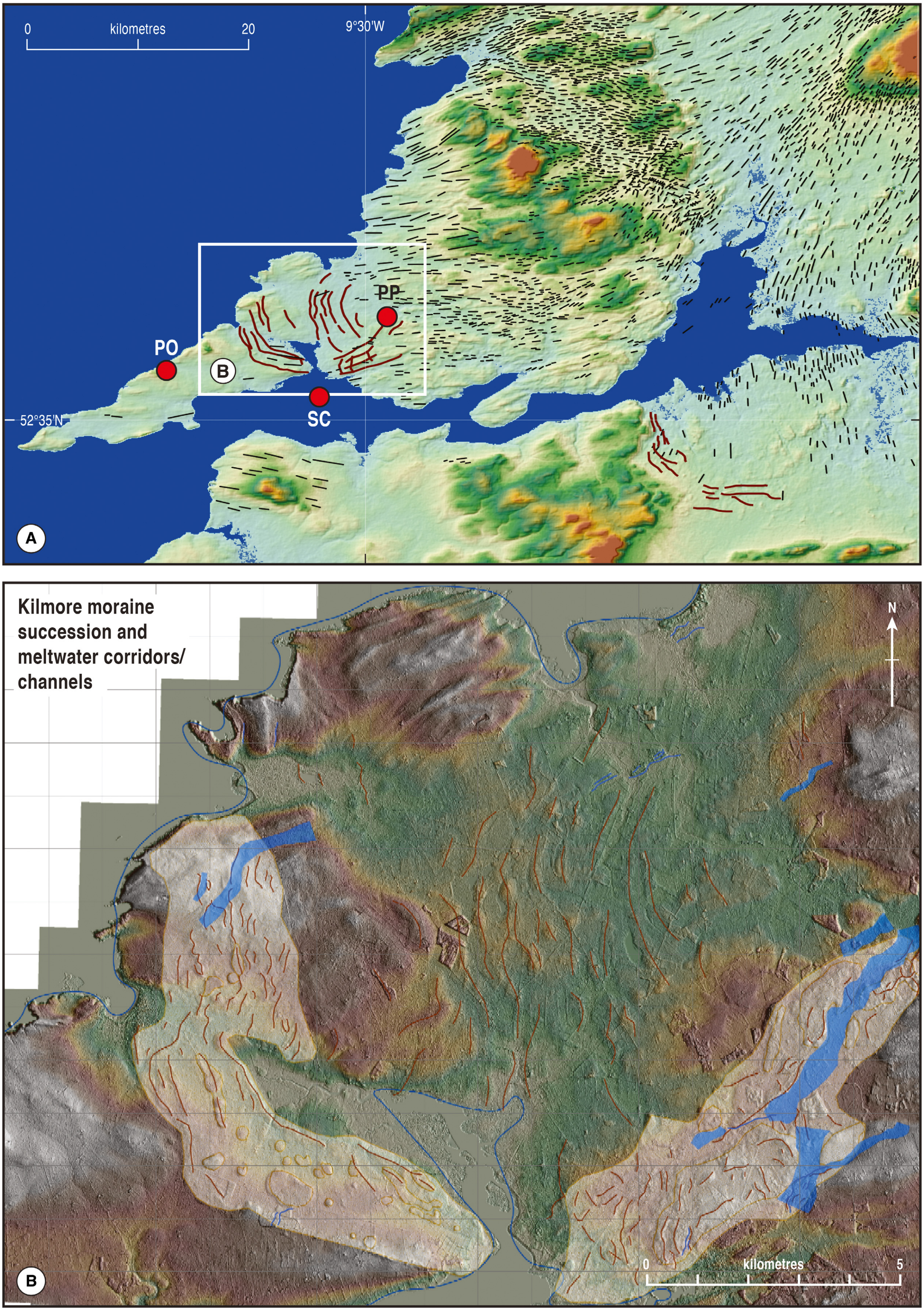
It is clear from the TCN ages that the ice around the Connemara and Galway coasts began to retreat inland between ~18.0 and 17.0 ka. On the outer coast at Claddaghduff the ice began to retreat at 17.3±0.8 ka, moving back into the western upland areas of the Connemara mountains (Fig. 11A). This is matched by ice retreat from the coast between Kilkieran and Ileon East (17.1±0.9 to 18.6±1.1 ka) and at Rossaveel at

Fig. 8. Carboniferous limestone pavement on Inis Meáin. Perched granite erratics on the pavement were transported from the Galway mainland. Both photographs (A, B) show sample IM02. Note the limestone pavement is completely devoid of sediment and vegetation cover. Ages for this site range from 17.0 to 22.3 ka. Using the two most consistent ages (IM02+04) yields an UWM of 19.5±1.1 ka. However, the youngest three ages have an acceptable χ^2_R value (2.20) and give an UWM of 18.5±1.0 ka.

18.2±1.0 ka. Ice flow in this area would have been partially guided by topography as it thinned back towards the southern edge of the central Connemara mountains, and this is supported by regional striae patterns (Fig. 2A). The ages from Black Head and Moycullen suggest a slightly later retreat of ice into inner Galway Bay, the mean age from Moycullen being well constrained at 16.5±1.9 ka by five TCN ages and giving some credence to the single Black Head age of 16.8±1.4 ka (Table 3). At this point the ice sheet would have been grounded and terrestrially based. Edwards *et al.* (2017) demonstrate that under most modelled scenarios relative sea level remained below present between 20 and 10 ka, although it is worth noting that under a 'kuchar max' GIA scenario areas deglaciated at ~20 ka would have been inundated by up to 20 m a.s.l. (the hypothetical marine limit). However, the coastal areas of Connemara and inner Galway remained glaciated until ~17 ka and, hence, glaciomarine conditions cannot have developed above present sea level around the coast between 20 and 17 ka (Fig. 11C).

With respect to regional deglacial ice-sheet dynamics there is some support for ice having retreated to the coast further north of Clew Bay prior to 20.0 cal. ka BP with deglaciation of outer Donegal Bay (e.g. Belderg and Fiddauntawnanoneen; McCabe *et al.* 1986, 2005 and see Ó Cofaigh *et al.* 2019). Two cosmogenic ages from the Nephin Beg mountains north of Clew Bay also show ice thinning north of Clew Bay at ~19.1 ka (Ballantyne *et al.* 2008). The timing of deglaciation through Clew Bay is similar to the chronology presented here (for Connemara and Galway Bay), with ice-free conditions in the inner part of Clew Bay between 18.8–16.9 ka (Ballantyne *et al.* 2008; Clark *et al.* 2009b). However, it should be noted that the deglaciation of Clew Bay was influenced by ice margin re-advances during final deglaciation (Clark

Fig. 9. A. A geomorphic overview of southwest County Clare and the Shannon estuary showing the Kilkee–Kilrush moraine complex and the Scattery Island Moraine. B. Distinctive elongated and circular ridges forming a moraine complex in the area between Kilkee and Kilrush.


0
kilometres
20
9°30'W
PP
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B
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A
Kilmore moraine succession and meltwater corridors/ channels
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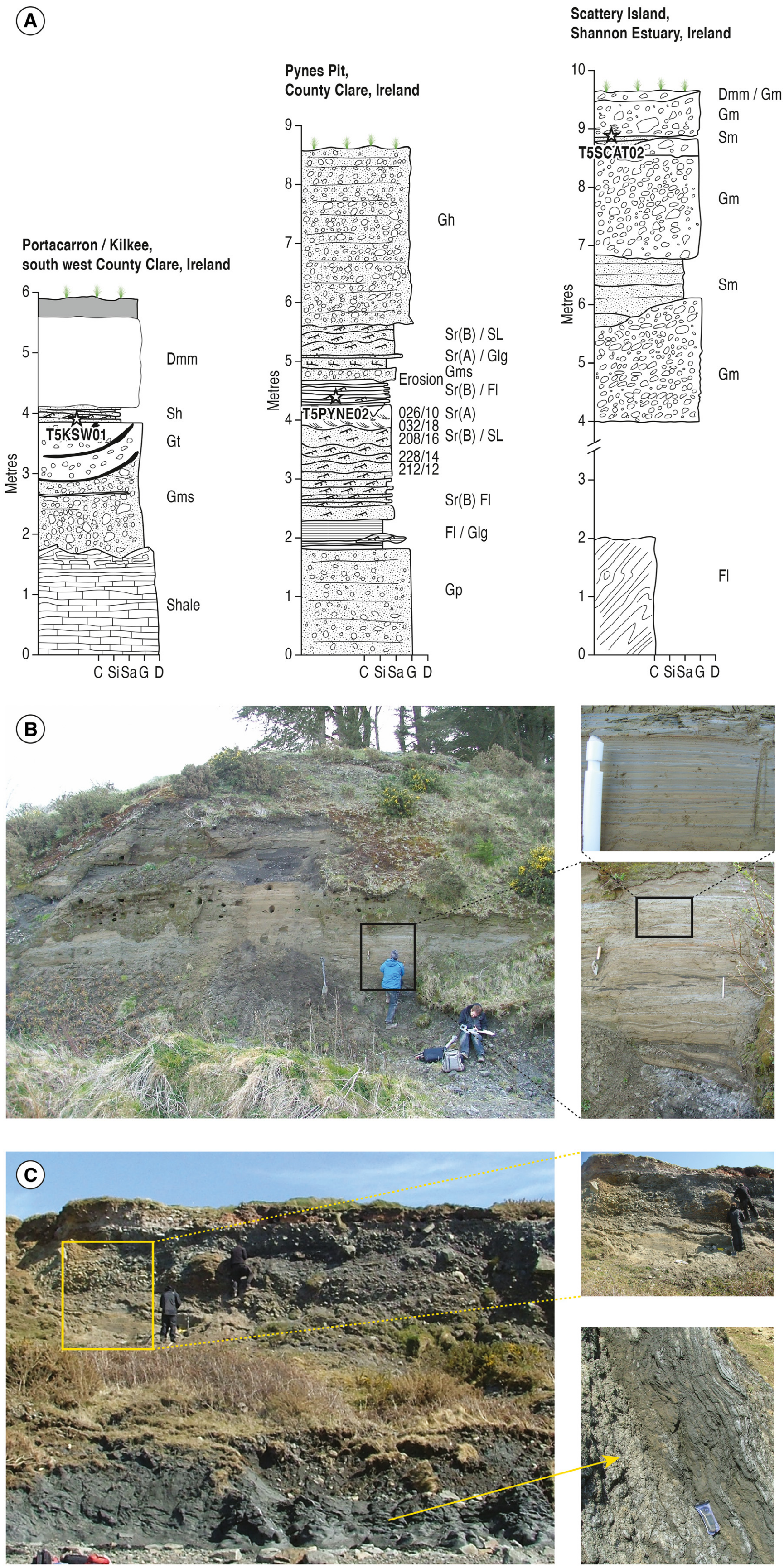
A
Portacarron / Kilkee,
south west County Clare, Ireland
Metres
Dmm
Sh
T5KSW01
Gt
Gms
Shale
C Si Sa G D
Pynes Pit,
County Clare, Ireland
Gh
Sr(B) / SL
Sr(A) / Glg
Gms
Erosion
Sr(B) / Fl
T5PYNE02
026/10
032/18
208/16
228/14
212/12
Sr(A)
Sr(B) / SL
Sr(B) Fl
Fl / Glg
Gp
Scattery Island,
Shannon Estuary, Ireland
Dmm / Gm
Gm
Sm
T5SCAT02
Gm
Sm
Gm
Fl
B
C

Fig. 10. A. Three sedimentary logs showing the glacial stratigraphy exposed at Portacarron (PO), Pynes Pit (PP) and Scattery Island (SC), respectively. B The glacial stratigraphy at Pynes Pit showing crudely bedded gravels overlain by rhythmically laminated fines and rippled sands with overlying planar stratified gravels. C. The glacial stratigraphy at Scattery Island with lower deformed laminated clays overlain by stratified sands and gravels that have been compressed and thrust.

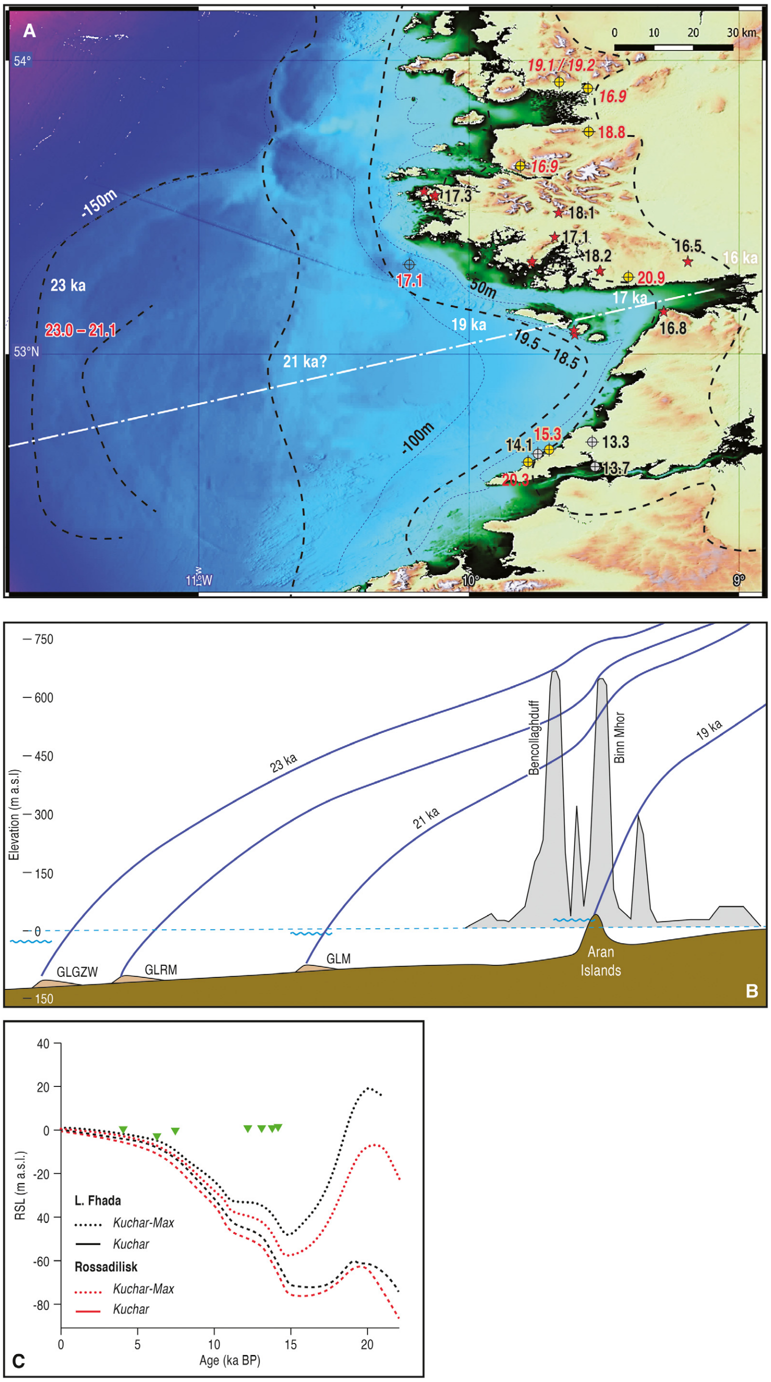

Fig. 11. A. Ice-sheet retreat chronology and isochrones (black dashed lines) from the Connemara, Galway and County Clare region based on new (black) and existing (red) cosmogenic exposures ages, OSL and ^{14}C ages. The white dotted line represents the modelled flowline for the ice-sheet surface profiles shown in (B). B. Modelled ice surface cross profiles of the Galway Bay Ice Lobe as it retreated from the mid-shelf to onshore. Note that maximum ice thickness at the LGM is estimated to have been in excess of 700 m (Ballantyne *et al.* 2008). Relative sea level is shown at 0 m a.s.l., with the wave symbols broadly indicating RSL when the ice margin was situated at GLGZW, GLM and the Aran Islands. C. Four possible sea-level curves (model output) from this region suggest that RSL rose to a maximum marine limit of ~20 m a.s.l. at ~20 ka. Thereafter, sea level fell until ~15 ka during deglaciation due to glacio-isostatic' uplift (Edwards *et al.* 2017). Green triangles are terrestrial limiting dates. Note L. Fhada is situated close to Kilkieran; Rossadillisk close to Claddaghduff.

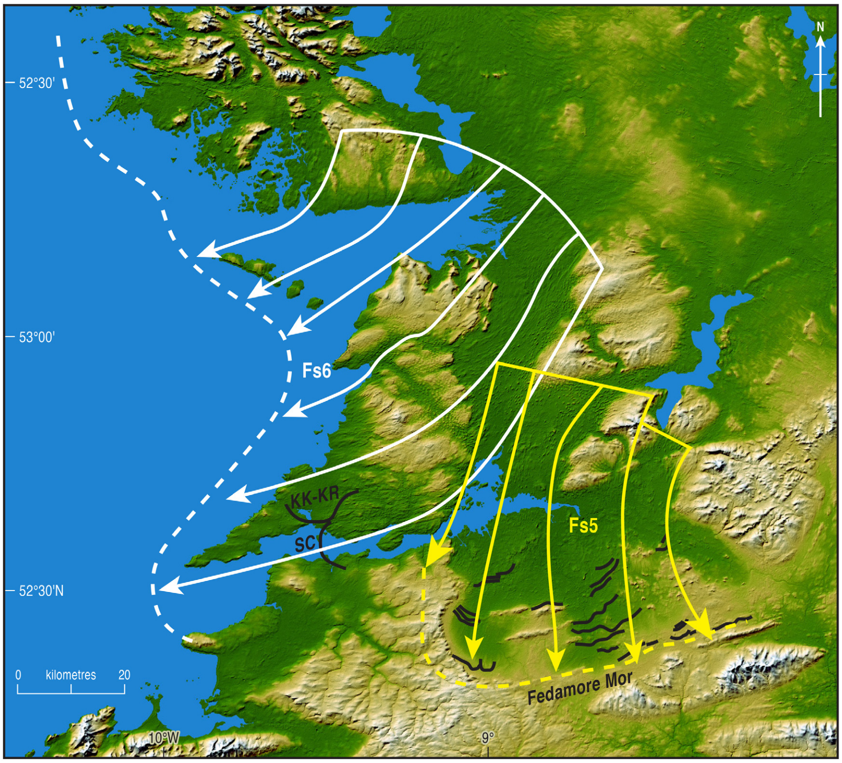

Fig. 12. Regional flow dynamics during peak LGM flow conditions were dominated by flowset Fs6 (based on regional bedform mapping; Greenwood & Clark 2009a, b). However, during deglaciation the trajectory of regional ice flow across County Clare and the River Shannon corridor is hypothesized to have shifted to a more southerly orientation (Fs5; Greenwood & Clark 2009a, b). Flowset Fs5 is clearly related to the Fedamore moraine complex, but determining which flow set, Fs5 or Fs6, was responsible for the formation of the Scattery Island and Kilkee–Kilrush moraines remains unresolved; as does the timing of this event.

et al. 2009b; see below). This also fits with evidence for ice thinning from Mweelrea to the north of Killary Harbour where terrain between 305 and 650 m a.s.l. became ice-free at ~16.9 ka (Ballantyne *et al.* 2008; Fig. 11A). This consistent pattern of retreat onto the coast and thinning in the Connemara mountains between ~18–17 ka suggests that both the ice sheet and local ice caps were responding synchronously to regional forcing mechanisms at the time.

Greenwood & Clark (2009a) mapped an extensive zone of 'terminal' moraine demarcating a late phase re-organization of flowset Fs6 into south County Clare (Fig. 2B) and this may be coincident with the Kilkee–Kilrush Moraine Complex and Scattery Island moraine (Fig. 12). The three OSL ages from this area suggest this is a possible later phase of ice re-advance in the region. At Portacarron, the glacifluvial outwash is dated to 14.1±3.6 ka, while the outwash associated with the Scattery Island moraine dates to 13.7±3.0 ka (Table 5). This fits well with Pynes Pit slightly further north, which dates to ~13.3±2.7 ka. If correct, these ages would infer the presence of ice in southwest Ireland during the Lateglacial. This seems very unlikely and, more feasibly, the large errors associated with these OSL ages (caused by the very dim OSL signal-intensities emitted by the quartz grains) imply this re-advance phase is older (errors would push the outer age range of these samples to 17.7–16.0 ka; Table 5). Clark *et al.* (2009b) inferred the Clew Bay re-advance to the north was linked to the Killard Point Stadial (McCabe *et al.* 1998). However, Ballantyne & Ó Cofaigh (2017) noted that the cosmogenic exposure age population from eastern Clew Bay could range from 18.4 ka (max.) to 15.7 ka (min.) (as a result of split populations of old and young samples). Hence, inferring regional (a)synchroneity between retreat/re-advance limits (and common external forcing mechanisms) is fraught with uncertainty. During the final phases of ice-sheet activity along the west coast of Ireland internal ice-sheet dynamics, ice divide migration, topography and a warming climate would have all been key controls on ice-margin behaviour as ice down-wasted and withdrew into central Ireland and local dispersal centres.

Conclusions

During the LGM ice from the IIS flowed offshore through Clew Bay, Galway Bay and County Clare sourced from the main ice sheet to the west. There is also clear evidence that Connemara and Mayo mountains fed local ice offshore that was confluent with the main ice sheet. The imprints of these distinct lobes are clear in sea-floor geomorphology. Maximum ice-sheet extent on to the outer western continental shelf was reached at ~26–24 cal. ka BP. The initial retreat of the ice from the shelf edge was marked by marginal oscillations and the production of grounding-zone wedges between 23–21.1 cal. ka BP as individual flow lobes advected subglacial material offshore.

The first clear evidence of deglaciation of the near coast comes from the Aran Islands where exposure ages suggest ice-free conditions by ~19.5–18.5 ka. This infers ice retreated rapidly from the mid-shelf after 21 ka BP, but the combined effects of bathymetric shallowing and pinning acted to stabilize the ice margin at the Aran Islands. From Clew Bay to southern Connemara, multiple coastal sites infer retreat inland between 18.2 and 17.1 ka with ice flow inland being guided by topography as it thinned landward towards its source areas. Cosmogenic exposure ages from Moycullen and Black Head, which fringe inner Galway Bay, show ice continuing to recede eastward by 16.5 ka.

The Kilkee–Kilrush Moraine Complex and Scattery Island moraines point to a late stage re-advance of the IIS into County Clare and along the Shannon estuary at ~14.1 to 13.3 ka, but the large errors associated with those OSL ages make correlation with other regional re-advances difficult. It seems more likely that these moraines are the product of regional ice lobes re-adjusting to changes in internal ice-sheet dynamics, ice divide migration and topography in the window 17–16 ka as ice down-wasted and receded into central Ireland.

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Author contributions. – DHR, CÓC and CKB wrote the manuscript. DHR, CÓC, DJAE, RCC, MB and CKB executed the fieldwork for this project. DS and DF carried out the TCN laboratory and statistical analysis. RKS and GATD carried out the OSL laboratory and statistical analysis. JE and CDC provided the PISM model output for the ice-sheet profile reconstructions and onshore geomorphic mapping in southern County Clare. SLC, CÓC and DHR provided the onshore/offshore correlations. All authors contributed to manuscript production.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at http://www.boreas.dk.

Table S1. Sample data including quartz (g), carrier (μg g^{-1}), ^{10}Be/^{9}Be and blank ^{10}Be/^{9}Be with related uncertainties.

Table S2. OSL D_e values for sample T5SCAT02.

Table S3. OSL D_e values for sample T5PYNE02.

Table S4. OSL D_e values for sample T5KSW01.