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Last Glacial Maximum cirque glaciation in Ireland and implications for reconstructions of the Irish Ice Sheet

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ABSTRACT

Reconstructions of the extent and height of the Irish Ice Sheet (IIS) during the Last Glacial Maximum (LGM, ~19–26 ka) are widely debated, in large part due to limited age constraints on former ice margins and due to uncertainties in the origin of the trimlines. A key area is southwestern Ireland, where various LGM reconstructions range from complete coverage by a contiguous IIS that extends to the continental shelf edge to a separate, more restricted southern-sourced Kerry-Cork Ice Cap (KCIC). We present new ^{10}Be surface exposure ages from two moraines in a cirque basin in the Macgillycuddy's Reeks that provide a unique and unequivocal constraint on ice thickness for this region. Nine ^{10}Be ages from an outer moraine yield a mean age of 24.5 ± 1.4 ka while six ages from an inner moraine yield a mean age of 20.4 ± 1.2 ka. These ages show that the northern flanks of the Macgillycuddy's Reeks were not covered by the IIS or a KCIC since at least 24.5 ± 1.4 ka. If there was more extensive ice coverage over the Macgillycuddy's Reeks during the LGM, it occurred prior to our oldest ages.

1. Introduction

Establishing the impact of an ice sheet on regional and global climate (Hostetler et al., 2000; Braconnot et al., 2012) and sea level (Lambeck et al., 2014; Peltier et al., 2015) requires an accurate reconstruction of the extent and the height (or thickness) of the ice sheet. Reconstructing the extent of a former ice margin is generally straightforward in terrestrial environments but more difficult where the margins extended offshore, particularly with respect to establishing their age (Weber et al., 2011; Hillenbrand et al., 2014). Reconstructing the height of former ice sheets is more challenging. Direct evidence comes from trimlines, formed where underlying topography projected above the ice surface as nunataks, but their interpretation is often controversial (Carlson and Clark, 2012). Modeling the response of the solid Earth to ice-loading history so as to match relative sea-level (RSL) histories or GPS data is commonly used to estimate ice thickness (Lambeck et al., 2014; Peltier et al., 2015), but the absence of constraining RSL data in many regions, the short length of most RSL records relative to the total deglacial history, and limited constraints on the properties of the solid Earth that influence isostatic rebound introduce uncertainties in these reconstructions.

At the Last Glacial Maximum (LGM, 19–26 ka) (Clark et al., 2009), Ireland was predominantly covered by the Irish Ice Sheet (IIS), which was among the smallest of the LGM ice sheets. Despite its small size, an accurate reconstruction of the LGM IIS is critical for characterizing its response to climate forcing, particularly the abrupt changes in the North Atlantic (Clark et al., 2012b). The LGM configuration of the IIS, however, remains widely debated. To a large extent, this debate reflects the differing methods used to reconstruct the IIS and their associated uncertainties, making it a microcosm of the issues involved in reconstructing other, larger ice sheets. This includes uncertainties in establishing the extent of the LGM margin on the continental shelf (Greenwood and Clark, 2009; Clark et al., 2012a) and in determining its thickness from trimline data (Rae et al., 2004; Ballantyne et al., 2011) and from modeling of post-glacial rebound (Lambeck, 1996; Shennan et al., 2006; Brooks et al., 2008). In general, however, we can identify three reconstructions of the LGM IIS (Fig. 1): (1) a minimal version with restricted, largely terrestrial margins and a separate KCIC (Bowen et al., 1986; McCabe, 1987; Ballantyne et al., 2011), (2) an

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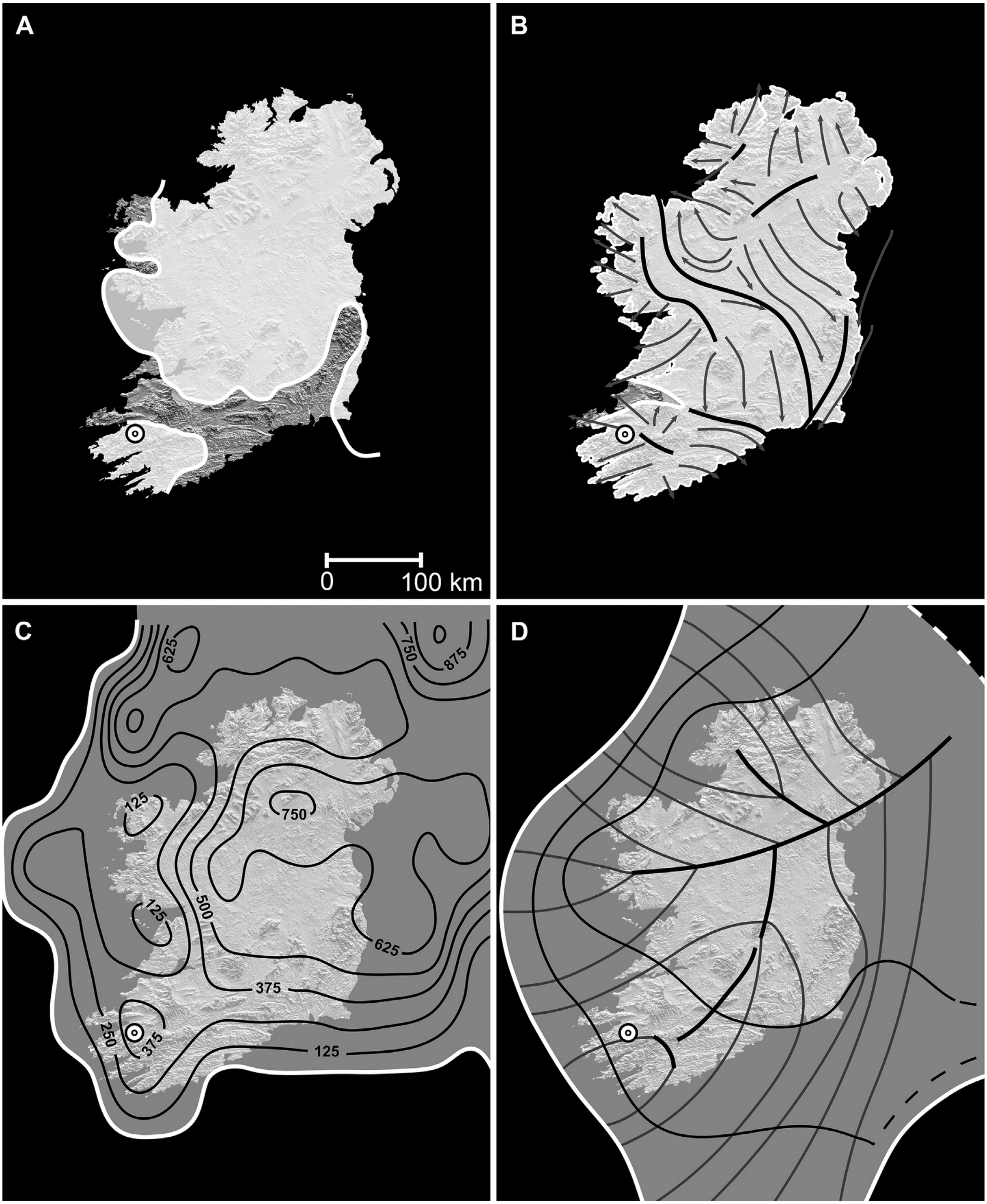

Fig. 1. Last Glacial Maximum ice sheet reconstructions from A) Bowen et al. (1986), B) Ballantyne et al. (2011), C) Brooks et al. (2008) (for 21 ka), and D) Greenwood and Clark (2009) (for 24 ka) showing varying interpretations of the IIS extent. White shaded areas indicate ice cover. Thick black lines represent ice divides. Thin black lines represent ice thickness contours – numbers indicate topography corrected ice-sheet thickness. Gray lines represent proposed ice flow lines. The location of the Alohart cirque is indicated by the circle on each map.

intermediate version which is also relatively thin and with a separate KCIC but has more extensive marine margins (Shennan et al., 2006; Brooks et al., 2008), and (3) a maximum version with complete coverage of the landscape and margins that extended far onto the continental shelf (Sejrup et al., 2005; Greenwood and Clark, 2009; Clark et al., 2012a). All these reconstructions agree in showing central and northern Ireland being completely covered by the IIS; the main differences are in the extent of the western and southern margins and whether southwestern Ireland was the center of an independent ice cap (the Kerry-Cork Ice Cap, or KCIC) or was completely overridden by a contiguous IIS (Fig. 1).

Here we present new ^{10}Be surface exposure ages from cirque moraines in southwestern Ireland. The existence of cirque moraines indicates that they have not been covered by an ice sheet since their formation. Determining their age places a limiting minimum age on when an ice sheet could have last covered the mountains, thus helping to distinguish among the various reconstructions for this region (Fig. 1). In particular, these ages provide a unique and unequivocal constraint on ice-sheet thickness in this mountainous region, address the issue of existence of a separate KCIC and the possibility for ice extent offshore, and finally constrain the dimensions of the IIS.

2. Setting

The Macgillycuddy's Reeks (51°58′ – 52°03′N; 09°50′ – 09°34′W) are located on the Iveragh Peninsula in southwestern Ireland. This region exhibits classic alpine glacial topography, and includes the tallest peak in Ireland (Carrauntoohil at 1030 m). According to the minimal reconstructions, this mountain range is near the confluence of the northern-sourced IIS and the southern KCIC, whereas according to the maximum reconstruction, it was completely overridden by a southwest-flowing IIS, thus providing a strategic location for addressing the proposed reconstructions (Fig. 1).

The northern slopes of the Macgillycuddy's Reeks contain multiple cirque basins formed by local glaciation (Anderson et al., 1998). Harrison et al. (2010) reported ^{10}Be ages from two moraines deposited by a cirque and valley glacier in the Gaddagh valley ~4 km west of our study site (Fig. 2). Given the improved understanding of the ^{10}Be production rate, we have recalculated these ages using the same production rate as for our new ages (see Methods). Since the production rate is now lower, the ages are older, by up to 3 kyr, than those reported by Harrison et al. (2010), with ages on the outermost moraine being 19.4 ± 1.6 ka (GV1) and 25.9 ± 1.9 ka (GV2), and ages on the inner moraine being 16.8 ± 1.9 ka (GV4) and 17.1 ± 1.1 ka (GV3).

The southern slopes of the Macgillycuddy's Reeks are ice-scoured and suggest erosion from more contiguous southern-sourced ice (Warren, 1979). The minimal LGM reconstructions that suggest the existence of a KCIC propose an ice divide ~20 km south of the Reeks with northward flowing ice that reached ~700 m

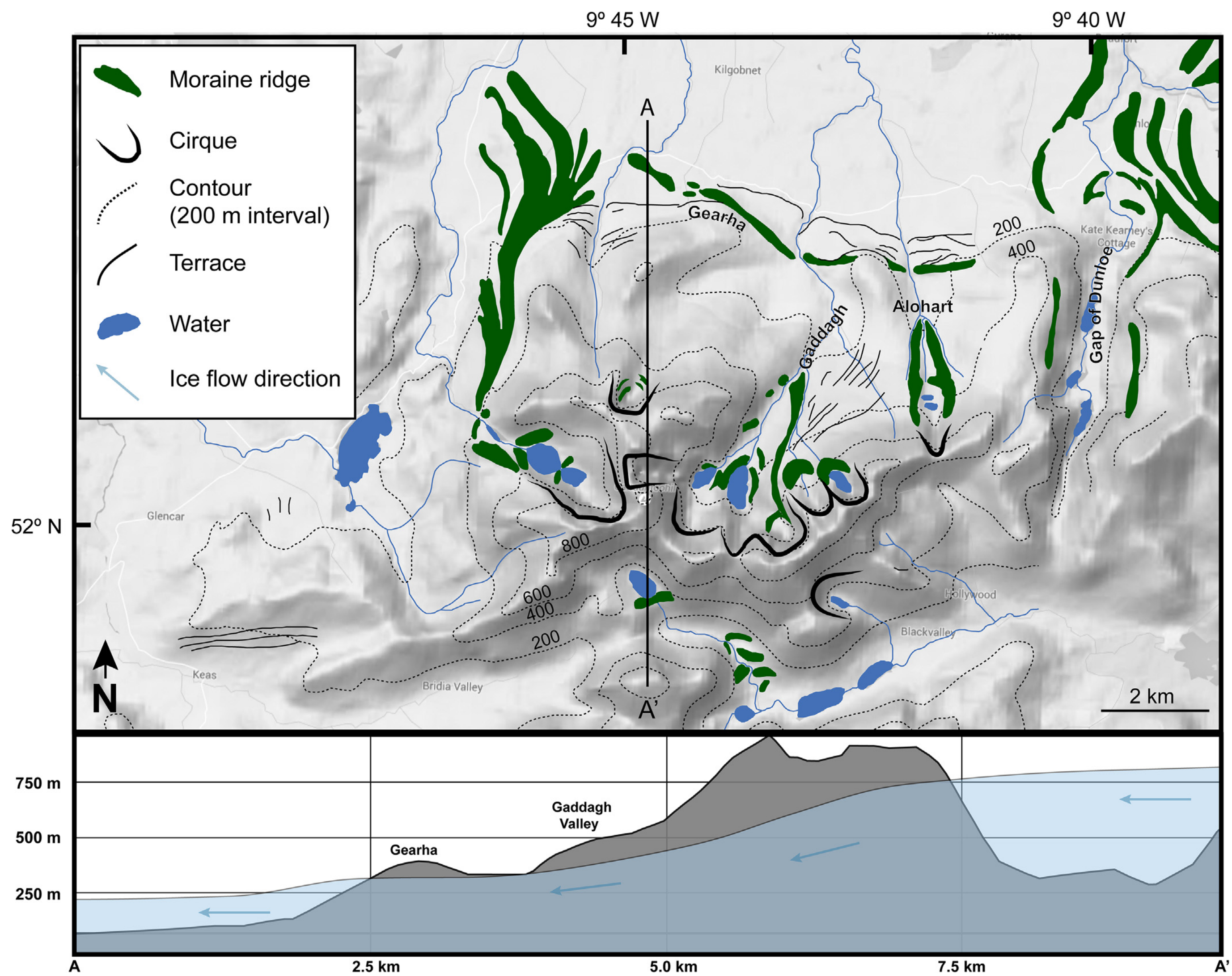

Fig. 2. Top panel) Map of the MacGillycuddy's Reeks redrawn from Warren (1979) highlighting the important locations and geomorphic features including moraines, terraces, and cirques. Bottom panel) Elevation profile of the MacGillycuddy's Reeks with the approximate Kerry-Cork Ice Cap surface build-up along the southern slopes and thinning as it diverts around the mountain range. Base map from Google Maps.

along the southern flanks of the Reeks before diverging around the mountains and converging on the northern side of the range, leaving the highest elevations ice-free as nunataks (Fig. 2) (Wright, 1927; Warren, 1979; Ballantyne et al., 2011). This minimal reconstruction does not include the possibility of contemporaneous cirque glaciation in the Reeks.

We dated moraines formed by a cirque glacier in the Alohart valley located on the eastern side of the Macgillycuddy's Reeks, ~2 km west of the Gap of Dunloe (Fig. 3B). Alohart is the lowest of the cirque basins in the Reeks (373 m cirque-floor elevation). A col located at the top of the cirque headwall reaches an elevation of 640 m. The cirque basin contains two distinct moraines (Fig. 4). The elongate outer moraine extends ~1750 m beyond the headwall and is characterized by lateral moraines with broad crests and steeply sloping sides and a terminal moraine with more gentle slopes. The arcuate inner moraine extends ~750 m beyond the headwall and also exhibits lateral moraines with steep proximal slopes and a terminal moraine with more gentle slopes. The crests of the lateral portions of the inner moraine are separated from the crests of the lateral portions of the outer moraine by a well-defined topographic low. The elevation difference from the base of the cirque headwall to the toe of the outer terminal moraine is ~250 m. Each moraine contains abundant, locally sourced quartzolithic sandstone boulders of the Devonian Old Red Sandstone. Warren (1979) proposed that the high-relief, steeply sloping Gearha moraine that crosses the valley ~2 km north of the Alohart moraines was deposited as a lateral moraine by the LGM KCIC where it encircled the northern portion of the Reeks.

3. Methods

We collected samples from 16 boulders from the two Alohart moraines for ^{10}Be cosmogenic surface exposure dating (Fig. 3). Each boulder was at least 0.5 m high above the ground surface, thus limiting the possibility of post-depositional exhumation, and located near or on the crest of the moraine, thus limiting the possibility of post-depositional movement. Sampled boulders had faceted surfaces indicating glacial erosion during transport. Quartz veins, when present, were low relief (<1 cm) suggesting little-to-no post-depositional erosion of the sampled surface. Our calculations do not account for possible erosion, but sensitivity tests suggest that a conservative erosion estimate of 1 mm ka^{-1} (Ballantyne and Stone, 2012) would increase our ages by <2%. Samples were from the upper 2 cm of each boulder's top surface. Samples were processed for ^{10}Be/^{9}Be measurements at the Oregon State University Cosmogenic Isotope Laboratory following the procedures of Licciardi (2000), and AMS measurements were made at the Purdue Rare Isotope Measurement (PRIME) Laboratory.

The ^{10}Be ages were calculated with the CRONUS-Earth online calculator (Balco et al., 2008) using the northeast North American (NENA) production rate (Balco et al., 2009) and the time-dependent scaling scheme of Lal (1991) and Stone (2000). We use the NENA production rate because it has greater latitudinal similarity with the our field site than the Arctic production rate (Young et al., 2013); calculated ages using the two rates have an average difference of <1.5% (Table S2). We also use the NENA production rate rather than recent production rates derived from Scotland (Ballantyne and Stone, 2012; Small and Fabel, 2015) because of greater confidence in the geologic constraints used to derive the NENA value. We note that although using the higher Scottish production rates reduces our ages by ~8%, they do not change our conclusions (see Supplementary Materials). Shielding factors for each sample were calculated using the CRONUS-geometric shielding calculator (Table 1). The moraine ages are reported using the arithmetic mean age of each sample set and the standard error of the distribution with the production rate uncertainty added in quadrature. Mean ages are interpreted as reflecting the end of moraine construction, and therefore the onset of deglaciation (Licciardi et al., 2009).

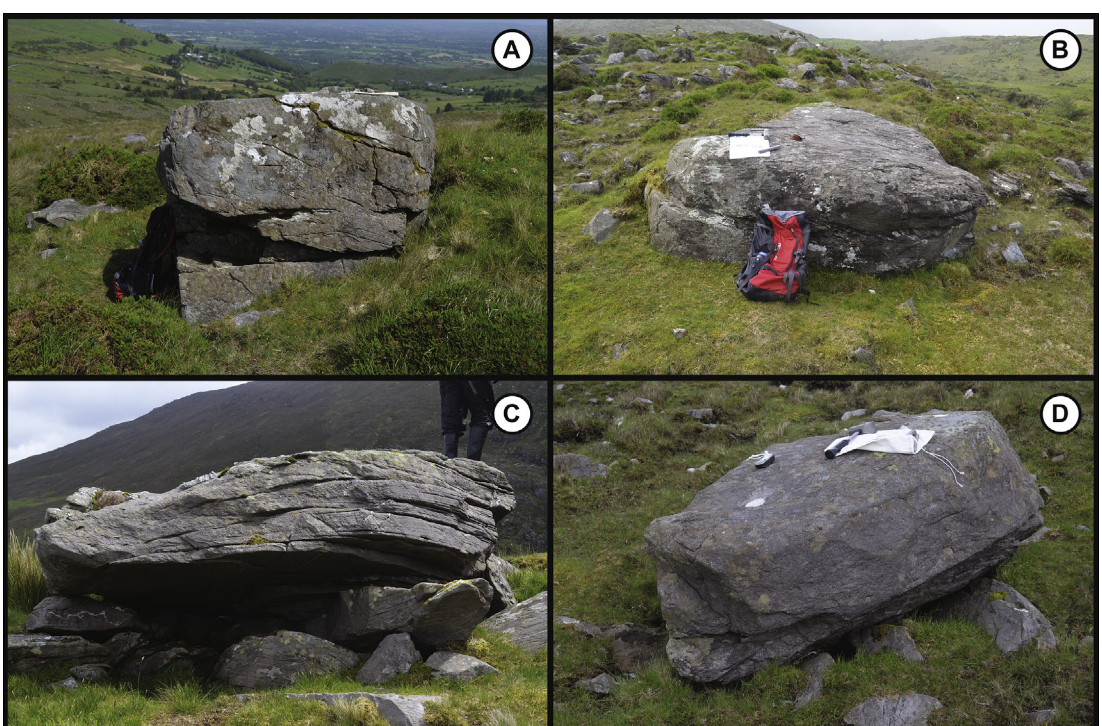

Fig. 3. Glacially deposited boulders along the crests of the inner (A and B) and outer (C and D) moraines in Alohart cirque basin that were sampled for surface exposure dating.

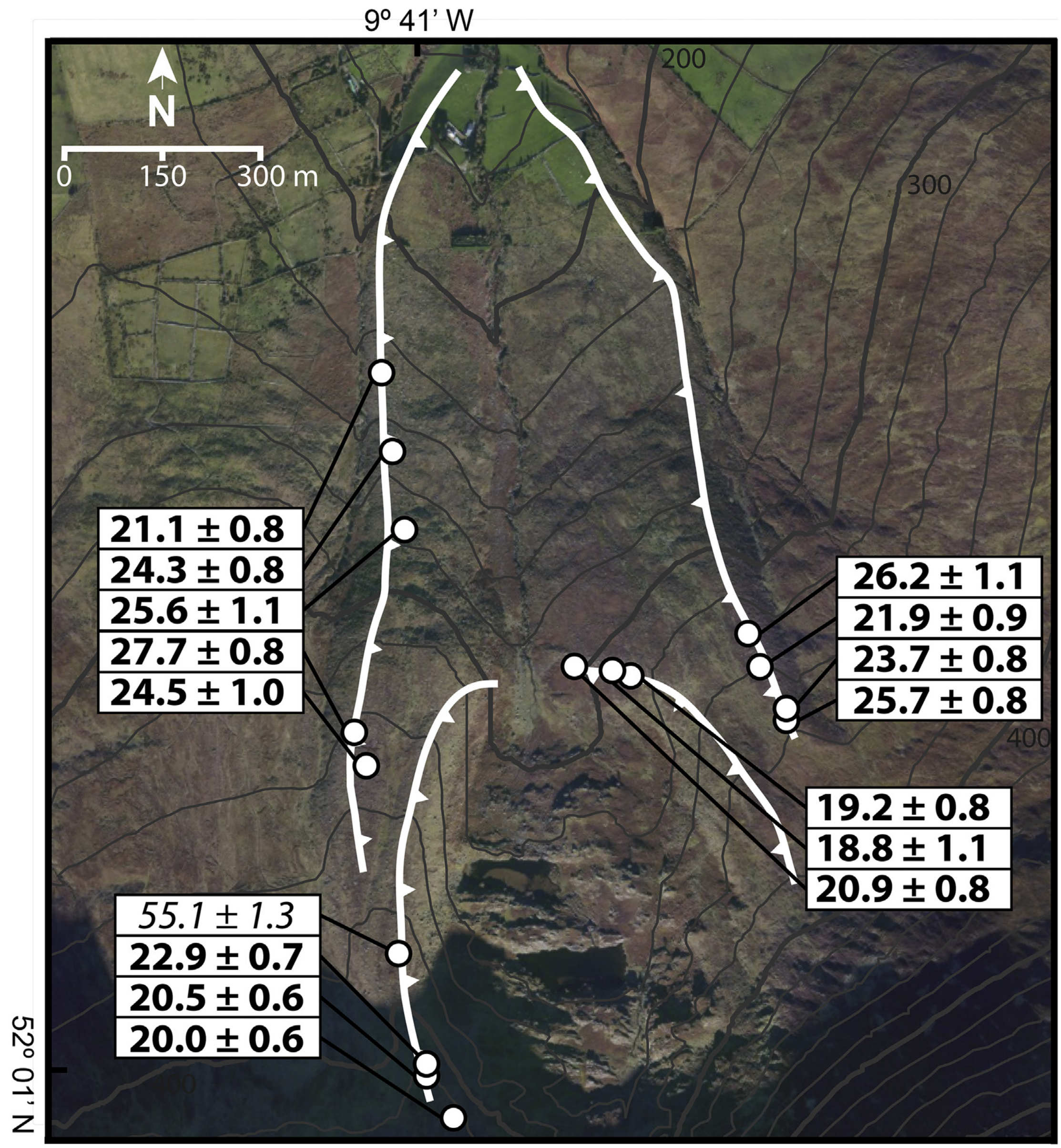

Fig. 4. Contour map of the Alohart cirque basin with location of dated samples indicated by a white circle and their respective ages shown in text boxes. Italicized age represents a statistical outlier that has been associated with cosmogenic nuclide inheritance. Moraine crests are indicated by the white lines with arrows indicating the proximal ice-contact surface. Base map from Apple Maps.

4. Results

Nine ^{10}Be ages from the outer moraine range from 21.1 ± 0.8 ka to 27.7 ± 0.8 ka (Fig. 5A). Based on Chauvenet's criterion, there are no statistical outliers. The mean age and uncertainty of the outer moraine is 24.5 ± 1.4 ka. Six of the seven ages from the inner moraine range from 18.8 ± 1.1 ka to 22.9 ± 0.7 ka (Fig. 5B). One sample from this moraine is 55.1 ± 1.4 ka and is an outlier based on Chauvenet's criterion, likely due to inheritance. The mean age and uncertainty of the six remaining samples is 20.4 ± 1.2 ka. A lack of moraines up-ice from the inner moraine suggests that this age represents the final deglaciation of the Alohart cirque basin. The spread in the distribution of our ages from each moraine (Fig. 5) is comparable to that found in other dating studies of glacier moraines (Putnam et al., 2013; Rood et al., 2011), and indicates that the various sources of geologic uncertainty (exhumation, erosion, and inheritance) that cannot be identified when sampling are insignificant. On the other hand, differences resulting from large inheritance are not expected to be systematic and will introduce a large spread in the age distribution with significant differences between ages (Bentley et al., 2010). Our one sample from the inner moraine that is ~30 kyr older than the other moraine ages is a typical example of an outlier due to inheritance.

5. Discussion

Our new ^{10}Be ages indicate that a cirque glacier occupied the Alohart drainage and deposited moraines at 24.5 ± 1.4 ka and 20.4 ± 1.2 ka. The two ages on the inner moraine from the Gaddagh valley 4 km to the west (Harrison et al., 2010) (Fig. 2) extend this interval of cirque glaciation in the Reeks to ~17 ka. The two ages from the outer moraine from the Gaddagh valley are similar to our two age populations from Alohart. We do not know the context for the two boulders, but we speculate they may be recording the same

Table 1
Moraine surface-exposure sample details and ^{10}Be data and ages.[a]

Laboratory no.	Sample ID	Latitude (DD)	Longitude (DD)	Elevation (m a.s.l.)	Boulder dimensions			Sample thickness (cm)	Shielding correction	Quartz weight (g)	Carrier added (g)	$^{10}Be/^{9}Be$ (10^{-14})[b]	[^{10}Be] (10^4 atoms g^{-1})	AMS standard	^{10}Be age and internal uncertainty (ka)	Moraine mean age[c] (ka)
					Length (cm)	Height (cm)	Width (cm)									
Inner moraine																20.4 ± 1.2
201400635	ALH-13-1	52.0126	−9.6784	428	380	70	300	2	0.989	31.8834	0.8050	20.35 ± 0.58	12.21 ± 0.39	07KNSTD	20.5 ± 0.6	
201500443	ALH-13-2	52.0126	−9.67835	428	330	100	320	2	0.989	40.0130	0.8660	26.49 ± 0.69	13.63 ± 0.40	07KNSTD	22.9 ± 0.7	
201500444	ALH-13-3	52.0120	−9.67765	421	380	90	200	2	0.988	42.1550	0.8570	24.46 ± 0.67	11.82 ± 0.36	07KNSTD	20.0 ± 0.6	
201400636	ALH-13-4[d]	52.0137	−9.6790	390	180	80	270	2	0.995	30.2205	0.7461	53.75 ± 1.18	31.66 ± 0.77	07KNSTD	*55.1 ± 1.4*	
201400641	ALH-13-16	52.0183	−9.6754	297	260	80	220	2	0.993	24.6938	0.7755	14.85 ± 0.53	11.06 ± 0.44	07KNSTD	20.9 ± 0.8	
201500450	ALH-13-17	52.0182	−9.67463	305	240	140	170	2	0.995	30.1160	0.8460	15.12 ± 0.81	10.05 ± 0.60	07KNSTD	18.8 ± 1.1	
201401891	ALH-13-18	52.0182	−9.6745	306	350	70	250	2	0.995	30.3895	0.8661	15.12 ± 0.60	10.28 ± 0.46	07KNSTD	19.2 ± 0.8	
Outer moraine																24.5 ± 1.4
201400637	ALH-13-5	52.0177	−9.6702	354	160	45	290	2	0.995	40.9901	0.8039	30.72 ± 0.84	14.35 ± 0.44	07KNSTD	25.7 ± 0.8	
201500445	ALH-13-6	52.0177	−9.67018	354	280	110	240	2	0.997	39.1360	0.8660	25.22 ± 0.72	13.26 ± 0.42	07KNSTD	23.7 ± 0.8	
201400638	ALH-13-7	52.0188	−9.6715	332	400	50	200	2	0.997	30.0000	0.7813	23.20 ± 0.88	14.37 ± 0.61	07KNSTD	26.2 ± 1.1	
201500446	ALH-13-9	52.0183	−9.67077	340	100	50	130	2	0.998	21.5180	0.8530	12.95 ± 0.50	12.12 ± 0.52	07KNSTD	21.9 ± 0.9	
201500447	ALH-13-10	52.0213	−9.67930	261	260	100	260	2	0.997	42.3610	0.8510	26.18 ± 0.81	12.50 ± 0.43	07KNSTD	24.3 ± 0.8	
201500448	ALH-13-11	52.0197	−9.67880	294	250	100	200	2	0.996	21.5780	0.8540	14.47 ± 0.56	13.54 ± 0.60	07KNSTD	25.6 ± 1.1	
201400639	ALH-13-12	52.0170	−9.6801	344	150	100	120	2	0.997	39.7781	0.7963	32.25 ± 0.82	15.38 ± 0.44	07KNSTD	27.7 ± 0.8	
201500449	ALH-13-13	52.0166	−9.67990	359	300	130	220	2	0.995	28.3340	0.8330	19.73 ± 0.72	13.76 ± 0.56	07KNSTD	24.5 ± 1.0	
201400640	ALH-13-15	52.0220	−9.6794	236	240	80	180	2	0.998	34.3785	0.7593	20.17 ± 0.73	10.59 ± 0.43	07KNSTD	21.1 ± 0.8	

[a] Age calculations use standard atmosphere, density of 2.65 g cm^{-3}, and zero erosion.
[b] 1-sigma AMS uncertainty.
[c] Moraine mean age and uncertainty is calculated as the straight mean and standard error with the production rate uncertainty added in quadrature.
[d] Age excluded using Chauvenet's criterion.

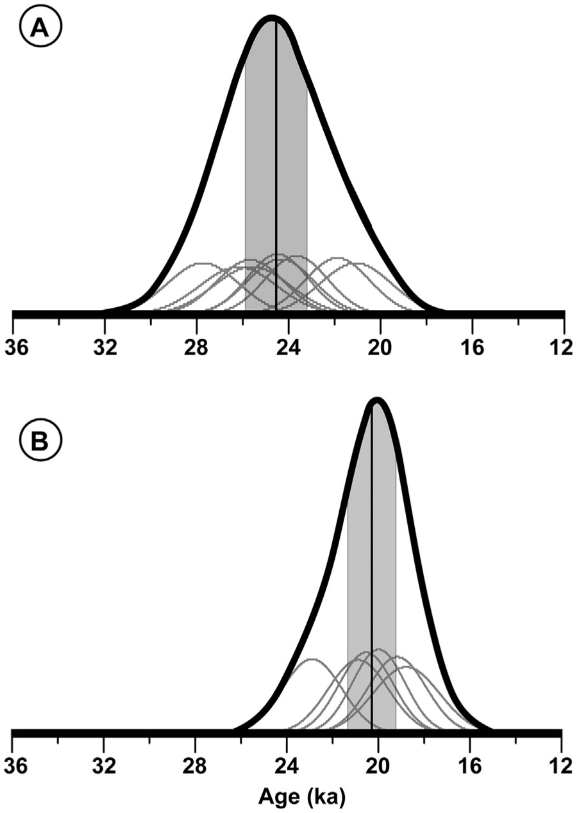

Fig. 5. A) Probability distribution of the nine samples located on the outer moraine. B) Probability distribution of the six samples located on the inner moraine. Vertical line represents the reported arithmetic mean. Gray bar represents the combined analytical and production rate uncertainty.

two events as at Alohart. We were unable to find any additional suitable boulders for sampling from the associated outer Gaddagh Valley moraine.

Trimlines and ice-flow features in the mountainous region of southwestern Ireland have long been used to argue for a KCIC (Wright, 1927; Farrington, 1954; Warren, 1979; Rae et al., 2004). Ballantyne et al. (2011) considered two alternative hypotheses for the trimlines: that they represent a former ice surface, or that they record an englacial transition from erosive warm-based ice below to non-erosive cold-based ice above. Ballantyne et al. (2011) favored the second englacial interpretation and reconstructed the ice surface with an elevation of 500 m north of the Macgillycuddy's Reeks, therefore requiring that the Alohart cirque was overridden by the KCIC. Our data, however, clearly demonstrate that the KCIC did not override the Alohart cirque within the last 24.5 ± 1.4 ka, suggesting that if their reconstruction is for a KCIC for that time or later, its elevations north of the Macgillycuddy's Reeks are too high. An alternative hypothesis, discussed further below, is that their reconstruction predates 24.5 ± 1.4 ka, with cirque glaciation developing after the KCIC had thinned and retreated from the Alohart drainage.

Although they favored an englacial origin for the trimlines, Ballantyne et al. (2011) also reconstructed a regional ice surface based on the alternative interpretation that trimlines record the former ice surface. Fig. 6 shows their reconstruction but modified to include the constraints from our Alohart cirque ages, assuming that their ice-surface reconstruction is contemporaneous with or younger than the 24.5 ± 1.4 ka age from Alohart. These data support the hypothesis by Warren (1979) that the southern-sourced KCIC was diverted around the Macgillycuddy's Reeks, leaving the mountains ice free and forming piedmont lobes in the lowlands to the north.

Because our results demonstrate that the northern flanks of the Macgillycuddy's Reeks above an elevation of ~200 m were not covered by the IIS nor the KCIC since at least 24.5 ± 1.4 ka, those maximum reconstructions showing a contiguous IIS covering southwestern Ireland at 23 ka (Clark et al., 2012a) or 24 ka (Greenwood and Clark, 2009) (Fig. 1D) are too large. Instead, our results are consistent with the minimal ice-sheet reconstructions for Ireland showing a separate KCIC since 24.5 ± 1.4 ka (Fig. 1), albeit with less ice than previously inferred. Our results are also consistent with an intermediate reconstruction (BIM-1 model of Shennan et al., 2006) that shows a thin KCIC (ice thickness <125 m) over the Macgillycuddy's Reeks at 24 ka, but suggests that another, intermediate reconstruction with ice thicknesses >375 m over the Alohart site at 24 ka and 21 ka (Brooks et al., 2008) is too thick (Fig. 1C).

One of the critical records for constraining the timing of the maximum Irish and British ice-sheet extent on the western continental shelf comes from the Barra Fan, where the first occurrence of glacimarine turbidites at ~27 ka is interpreted as marking the arrival of the ice-sheet margin to its LGM limit (Kroon et al., 2000; Wilson et al., 2002). Turbidite sedimentation ended ~23 ka, suggesting onset of retreat of the LGM margin at that time. On the Irish Sea coast, a calibrated ^{14}C age on reworked shells from till on the Ards Peninsula suggests ice advance across the site sometime after 28.6 ka (Hill and Prior, 1968), whereas a limiting calibrated ^{14}C age from a marine core suggests deglaciation of the Irish Sea by ~23.3 ka (Kershaw, 1986). Agreement of these age constraints from the western and eastern IIS margins thus suggests that the LGM IIS was ~27-23 ka (Clark et al., 2012b).

We cannot exclude reconstructions in which a larger KCIC or the IIS covered the Reeks before 24.5 ± 1.4 ka, generally corresponding to the end of the LGM IIS. As discussed above, the KCIC reconstruction by Ballantyne et al. (2011) may predate cirque glaciation. Alternatively, Greenwood and Clark et al. (2009) reconstructed an IIS that covered southwestern Ireland at 28 ka. In either case, if the Alohart site was ice covered, our age for the outer moraine (24.5 ± 1.4 ka) requires substantial thinning and retreat of any ice cover by that time, and is thus consistent with the end of the LGM IIS being at ~23 ka (Clark et al., 2012b).

6. Conclusions

We present new ^{10}Be ages that identify deposition of two moraines by a cirque glacier in the Alohart drainage of the Macgillycuddy's Reeks, southwestern Ireland, at 24.5 ± 1.4 ka and 20.4 ± 1.2 ka. Two ages from a moraine 4 km to the west extend the interval of cirque glaciation within the Macgillycuddy's Reeks to ~17 ka (Harrison et al., 2010). The ages on the oldest Alohart moraine demonstrate that the Macgillycuddy's Reeks have not been covered by either the IIS or KCIC since at least 24.5 ± 1.4 ka. Reconstructions of an extensive IIS covering southwestern Ireland and extending onto the adjacent continental shelf at 23 or 24 ka are thus too large, whereas reconstructions of a KCIC covering the Macgillycuddy's Reeks need to be reduced, unless that reconstruction relates to an earlier phase of the LGM. Our results are consistent with reconstructions of a separate KCIC that was diverted around the Macgillycuddy's Reeks to form piedmont lobes in the lowlands to the north. Complete coverage of the Reeks during an early phase of the LGM by either the IIS or the KCIC remains a possibility, although substantial thinning and ice-margin retreat would be required by the time the oldest moraine was deposited in the Alohart cirque basin 24.5 ± 1.4 ka.

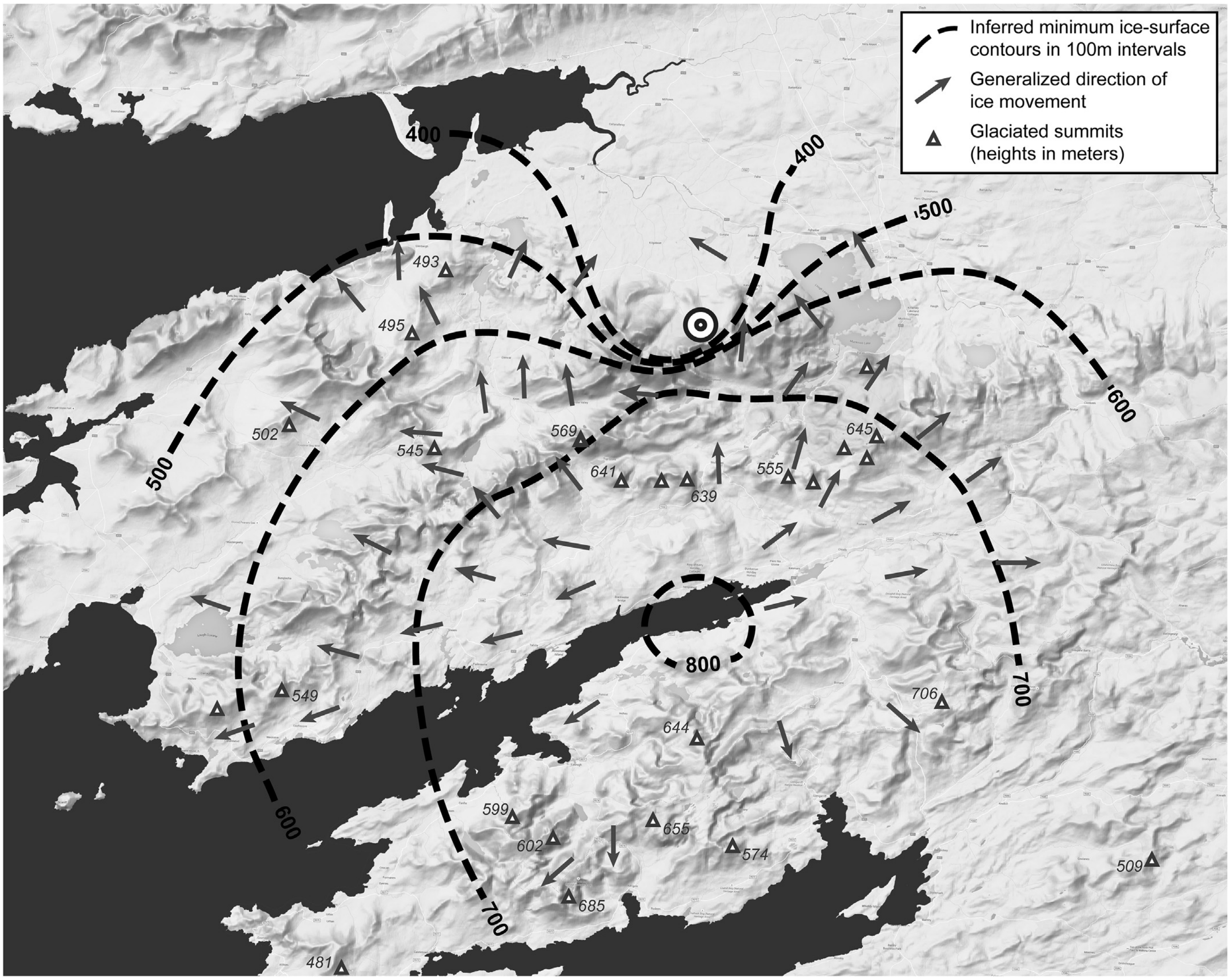

Fig. 6. Map of the proposed contours of minimum ice surface altitude for the Kerry-Cork Ice Cap redrawn from Ballantyne et al. (2011) and modified to account for our ages from Alohart cirque basin. Arrows indicate generalized directions of ice movement. Triangles mark glaciated summits with their respective elevations in meters. Circle marks the location of the Alohart valley. Base map from Google Maps.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2016.04.006.

References

Anderson, E., Harrison, S., Passmore, D.G., Mighall, T.M., 1998. Geomorphic evidence of younger Dryas glaciation in the MacGillycuddy's Reeks, southwest Ireland. J. Quat. Sci. 13, 75–90.

Bentley, M.J., Fogwill, C.J., Le Brocq, A.M., Hubbard, A.L., Sugden, D.E., Dunai, T.J., Freeman, S.P.H.T., 2010. Deglacial history of the West Antarctic Ice Sheet in the Weddell Sea embayment: constraints on past ice volume change. Geology 38, 411–414.

Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J., 2008. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. Quat. Geochronol. 3 (3), 174–195. http://dx.doi.org/10.1016/j.quageo.2007.12.001.

Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., Schaefer, J.M., 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. Quat. Geochronol. 4 (2), 93–107. http://dx.doi.org/10.1016/j.quageo.2008.09.001.

Ballantyne, C.K., McCarroll, D., Stone, J.O., 2011. Periglacial trimlines and the extent of the Kerry-Cork Ice Cap, SW Ireland. Quat. Sci. Rev. 30 (27–28), 3834–3845. http://dx.doi.org/10.1016/j.quascirev.2011.10.006.

Ballantyne, C.K., Stone, J.O., 2012. Did large ice caps persist on low ground in north-west Scotland during the Lateglacial Interstade? J. Quat. Sci. 27, 297–306.

Bowen, D.Q., Rose, J., McCabe, A.M., 1986. Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales. Quat. Sci. Rev. 5, 299–340. http://dx.doi.org/10.1016/0277-3791(86)90194-0.

Braconnot, P., Harrison, S.P., Kageyama, M., Bartlein, P.J., Masson-Delmotte, V., Abe-Ouchi, A., Otto-Bliesner, B., Zhao, Y., 2012. Evaluation of climate models using palaeoclimatic data. Nat. Clim. Change 2 (6), 417–424. http://dx.doi.org/10.1038/nclimate1456.

Brooks, A.J., Bradley, S.L., Edwards, R.J., Milne, G.A., Horton, B., Shennan, I., 2008. Postglacial relative sea-level observations from Ireland and their role in glacial rebound modeling. J. Quat. Sci. 23 (2), 175–192.

Carlson, A.E., Clark, P.U., 2012. Ice sheet sources of sea level rise and freshwater discharge during the last deglaciation. Rev. Geophys. 50 (4), 4007–4072. http://dx.doi.org/10.1029/2011RG000371.

Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Jordan, C., Sejrup, H.P., 2012a. Pattern and timing of retreat of the last British-Irish ice sheet. Quat. Sci. Rev. 44 (C), 112–146. http://dx.doi.org/10.1016/j.quascirev.2010.07.019.

Clark, J., McCabe, A.M., Bowen, D.Q., Clark, P.U., 2012b. Response of the Irish Ice Sheet to abrupt climate change during the last deglaciation. Quat. Sci. Rev. 35 (C), 100–115. http://dx.doi.org/10.1016/j.quascirev.2012.01.001.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., 2009. The last glacial maximum. Science 325, 710–714. http://dx.doi.org/10.1126/science.1172873.

Farrington, A., 1954. A note on the correlation of Kerry-Cork glaciations with those of the rest of Ireland. Ir. Geogr. 3, 47–53.

Greenwood, S.L., Clark, C.D., 2009. Reconstructing the last Irish Ice Sheet 2: a geomorphologically-driven model of ice sheet growth, retreat and dynamics. Quat. Sci. Rev. 28 (27–28), 3101–3123. http://dx.doi.org/10.1016/j.quascirev.2009.09.014.

Harrison, S., Glasser, N., Anderson, E., Ivy-Ochs, S., Kubik, P.W., 2010. Late Pleistocene mountain glacier response to North Atlantic climate change in southwest Ireland. Quat. Sci. Rev. 29 (27–28), 3948–3955. http://dx.doi.org/10.1016/j.quascirev.2010.09.015.

Hill, A.R., Prior, D.B., 1968. Directions of ice movement in north-east Ireland. Proc. R. Ir. Acad. 66B, 71–84.

Hillenbrand, C.D., Bentley, M.J., Stolldorf, T.D., Hein, A.S., Kuhn, G., Graham, A.G.C., Fogwill, C.J., Kristoffersen, Y., Smith, J.A., Anderson, J.B., Larter, R.D., Melles, M., Hodgson, D.A., Mulvaney, R., Sugden, D.E., 2014. Reconstruction of changes in the Weddell Sea sector of the Antarctic Ice Sheet since the Last Glacial Maximum. Quat. Sci. Rev. 100 (C), 111–136. http://dx.doi.org/10.1016/j.quascirev.2013.07.020.

Hostetler, S.W., Bartlein, P.J., Clark, P.U., Small, E.E., 2000. Simulated influences of Lake Agassiz on the climate of central North America 11,000 years ago. Nature 405 (6784), 334–337. http://dx.doi.org/10.1038/35012581.

Kershaw, P.J., 1986. Radiocarbon dating of Irish Sea sediments. Estuar. Coast. Shelf Sci. 23, 296–303.

Kroon, D., Shimmield, G., Austin, W.E.N., Derrick, S., Knutz, P., Shimmield, T., 2000. Century- to millennial-scale sedimentological–geochemical records of glacial–Holocene sediment variations from the Barra Fan (NE Atlantic). J. Geol. Soc. 157 (3), 643–653. http://dx.doi.org/10.1144/jgs.157.3.643.

Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. Earth Planet. Sci. Lett. http://dx.doi.org/10.1016/0012-821X(91)90220-C.

Lambeck, K., 1996. Glaciation and sea-level change for Ireland and the Irish Sea since Late Devensian/Midlandian time. J. Geol. Soc. 153, 853–872.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. Proc. Natl. Acad. Sci. 111 (43), 15296–15303. http://dx.doi.org/10.1073/pnas.1411762111.

Licciardi, J.M., 2000. Alpine Glacier and Pluvial Lake Records of Late Pleistocene Climate Variability in the Western United States. Ph.D. thesis. Oregon State University.

Licciardi, J.M., Schaefer, J.M., Taggart, J.R., Lund, D.C., 2009. Holocene glacier fluctuations in the Peruvian Andes indicate northern climate linkages. Science 325 (5948), 1677–1679. http://dx.doi.org/10.1126/science.1175010.

McCabe, A.M., 1987. Quaternary deposits and glacial stratigraphy in Ireland. Quat. Sci. Rev. 6 (3), 259–299.

Peltier, W.R., Argus, D.F., Drummond, R., 2015. Space geodesy constrains ice age terminal deglaciation: the global ICE-6G_C (VM5a) model. J. Geophys. Res. Solid Earth 120, 450–487. http://dx.doi.org/10.1002/(ISSN)2169-9356.

Putnam, A.E., Schaefer, J.M., Denton, G.H., Barrell, D.J.A., Birkel, S.D., Andersen, B.G., Kaplan, M.R., Finkel, R.C., Schwartz, R., Doughty, A.M., 2013. The Last Glacial Maximum at 44°S documented by a 10Be moraine chronology at Lake Ohau, Southern Alps of New Zealand. Quat. Sci. Rev. 62, 114–141.

Rae, A.C., Harrison, S., Mighall, T., Dawson, A.G., 2004. Periglacial trimlines and nunataks of the Last Glacial Maximum: the Gap of Dunloe, southwest Ireland. J. Quat. Sci. 19, 87–97.

Rood, D.H., Burbank, D.W., Finkel, R.C., 2011. Chronology of glaciations in the Sierra Nevada, California, from ^{10}Be surface exposure dating. Quat. Sci. Rev. 30, 646–661.

Sejrup, H.P., Hjelstuen, B.O., Torbjørn Dahlgren, K.I., Haflidason, H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M.S., Vorren, T.O., 2005. Pleistocene glacial history of the NW European continental margin. Mar. Pet. Geol. 22 (9–10), 1111–1129. http://dx.doi.org/10.1016/j.marpetgeo.2004.09.007.

Shennan, I., Bradley, S., Milne, G., Brooks, A., Bassett, S., Hamilton, S., 2006. Relative sea-level changes, glacial isostatic modelling and ice-sheet reconstructions from the British Isles since the Last Glacial Maximum. J. Quat. Sci. 21 (6), 585–599. http://dx.doi.org/10.1002/jqs.1049.

Small, D., Fabel, D., 2015. A Lateglacial ^{10}Be production rate from glacial lake shorelines in Scotland. J. Quat. Sci. 30, 509–513.

Stone, J.O., 2000. Air pressure and cosmogenic isotope production. J. Geophys. Res. Solid Earth 105 (B10), 23753–23759. http://dx.doi.org/10.1029/2000JB900181.

Warren, W.P., 1979. Moraines on the northern slopes and foothills of the Macgillycuddy's Reeks, south-west Ireland. In: Schluchter, Ch (Ed.), Moraines and Varves. Balkema, Rotterdam, pp. 223–226.

Weber, M.E., Clark, P.U., Ricken, W., Mitrovica, J.X., Hostetler, S.W., Kuhn, G., 2011. Interhemispheric ice-sheet synchronicity during the Last Glacial Maximum. Science 334 (6060), 1265–1269. http://dx.doi.org/10.1126/science.1209299.

Wilson, L.J., Austin, W., Jansen, E., 2002. The last British Ice Sheet: growth, maximum extent and deglaciation. Polar Res. 21 (2), 243–250.

Wright, W.B., 1927. The Geology of Killarney and Kenmare. Geological Survey of Ireland, Dublin.

Young, N.E., Schaefer, J.M., Briner, J.P., Goehring, B.M., 2013. A ^{10}Be production-rate calibration for the Arctic. J. Quat. Sci. 28 (5), 515–526. http://dx.doi.org/10.1002/jqs.2642.