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Trimlines, blockfields and the vertical extent of the last ice sheet in southern Ireland

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Trimlines separating glacially abraded lower slopes from blockfield-covered summits on Irish mountains have traditionally been interpreted as representing the upper limit of the last ice sheet during the Last Glacial Maximum (LGM). Cosmogenic ^{10}Be exposure ages obtained for samples from glacially deposited perched boulders resting on blockfield debris on the summit area of Slievenamon (721 m a.s.l.) in southern Ireland demonstrate emplacement by the last Irish Ice Sheet (IIS), implying preservation of the blockfield under cold-based ice during the LGM, and supporting the view that trimlines throughout the British Isles represent former englacial thermal regime boundaries between a lower zone of warm-based sliding ice and an upper zone of cold-based ice. The youngest exposure age (22.6±1.1 or 21.0±0.9 ka, depending on the ^{10}Be production rate employed) is statistically indistinguishable from the mean age (23.4±1.2 or 21.8±0.9 ka) obtained for two samples from ice-abraded bedrock at high ground on Blackstairs Mountain, 51 km to the east, and with published cosmogenic ^{36}Cl ages. Collectively, these ages imply (i) early (24–21 ka) thinning of the last IIS and emergence of high ground in SE Ireland; (ii) relatively brief (1–3 ka) glacial occupation of southernmost Ireland during the LGM; (iii) decoupling of the Irish Sea Ice Stream and ice from the Irish midlands within a similar time frame; and (iv) that the southern fringe of Ireland was deglaciated before western and northern Ireland.

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During the global Last Glacial Maximum (LGM; *c.* 26.5–19.0 ka; Clark *et al*. 2009) the last Irish Ice Sheet (IIS) formed a major component of the last British–Irish Ice Sheet (BIIS). Research based primarily on offshore bathymetry, seismostratigraphy and offshore sediment cores, together with both onshore and offshore dating evidence, provides compelling evidence that during the LGM the IIS reached the Atlantic shelf edge in the west and northwest, extended southwards across the Celtic Sea shelf and was confluent with ice nourished in Scotland, NW England and Wales to form a major ice stream in the Irish Sea Basin (Sejrup *et al*. 2005; Scourse *et al*. 2009; Ballantyne 2010a; Dunlop *et al*. 2010; C.D. Clark *et al*. 2012; Ó Cofaigh *et al*. 2012a, b; Fig. 1). Constraining the vertical LGM dimensions of the last IIS has proved more problematic, however. Inverse models based on inferred ice-sheet extent or glacio-isostatic adjustment have produced widely different altitudinal outcomes (e.g. Boulton *et al*. 1991; Lambeck 1993, 1995; Brooks *et al*. 2008). Thermo-mechanically coupled (TMC) numerical models driven by proxy climatic parameters suggest a low-profile ice sheet with cold-based ice overlying mountain summits, periodically down-drawn by high-velocity ice streams (Boulton & Hagdorn 2006; Hubbard *et al*. 2009).

Critical to constraining the maximum altitude of the last IIS is the interpretation of trimlines that mark the upper altitudinal limit of glacially eroded terrain and the lower limit of autochthonous blockfields on mountain summits and plateaux. Such blockfields comprise a shallow (usually 0.4–1.0 m deep) mantle of coarse, bouldery regolith, sometimes interrupted by tors or angular shattered bedrock outcrops. Recent studies of blockfields on mountains in Scotland and Scandinavia have concluded that they formed through prolonged frost-wedging of jointed bedrock combined with granular disaggregation of clasts under severe periglacial conditions, with limited evidence of chemical alteration (Ballantyne 1998, 2010b; Goodfellow *et al*. 2009, 2014; Hopkinson & Ballantyne 2014). Most Irish blockfields and adjacent high-level rock outcrops exhibit no evidence of glacial erosion, although rare erratic boulders occur on or embedded within some blockfields, for example on the Mourne Mountains of NE Ireland (Vernon 1965) and on the quartzite mountains of northern Donegal (Ballantyne *et al*. 2007).

The trimlines that mark the lower limit of blockfields on Irish mountains were initially interpreted as indicating the maximum level of glacier ice, with blockfield-covered summits remaining above the last ice sheet as palaeonunataks (e.g. Wright 1927; Farrington 1947; Coudé 1977; Warren 1979; Rae *et al*. 2004). More recent studies have argued that they could equally represent a former englacial transition from erosive warm-based ice moving over low ground to cold-based ice that occupied former summits and plateaux (Ballantyne *et al*. 2006, 2007, 2008). In the latter case, it is assumed that cold-based ice was frozen to the underlying substrate and that the adhesive strength of the

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Fig. 1. Location of Slievenamon and Blackstairs Mountain and other locations mentioned in the text. The inset shows the lateral extent of the last Irish Ice Sheet as inferred by Sejrup *et al.* (2005).

rock–substrate interface exceeded basal shear stress (Kleman & Glasser 2007), permitting the survival of blockfields and frost-shattered bedrock outcrops throughout the last glacial cycle. This interpretation implies that trimlines define the minimum rather than maximum altitude of former ice cover during the LGM.

Bedrock outcrops above trimlines in Ireland have consistently yielded minimum cosmogenic ^{10}Be exposure ages (41.5±2.2 to 118.0±6.6 ka) that greatly exceed the age of the LGM (Ballantyne *et al.* 2006, 2008, 2011). These ages do not, however, discriminate between the two trimline interpretations outlined above, as pre-LGM apparent exposure ages may reflect either continuous exposure on former nunataks or prolonged exposure prior to burial by passive cold-based ice during the LGM (e.g. Fabel *et al.* 2002; Briner *et al.*

2003; Marquette *et al*. 2004; Staiger *et al*. 2005). Modelling of the former ice-surface profile based on the minimum LGM extent of glacier ice fed from the mountains of SW Ireland, however, implies that the LGM ice surface reached an altitude of at least 1200 m a.s.l. in this area, well above the maximum altitude (~700 m a.s.l.) of local trimlines and implying that summit blockfields were preserved under at least 200 m of cold-based glacier ice (Ballantyne *et al*. 2011). Moreover, post-LGM ^{10}Be exposure ages of 14.9±0.9 to 17.6±1.1 ka obtained by Fabel *et al*. (2012) for nine erratics resting on blockfields in NW Scotland demonstrate that the last ice sheet must have overtopped all summits in this area but preserved intact summit blockfields; five other blockfield erratics that they sampled yielded (minimum) pre-LGM ^{10}Be exposure ages of ≥25.0±1.5 to ≥176.7±11.6 ka, which were attributed to nuclide inheritance from a previous period of exposure. Fabel *et al*. (2012) suggested that their findings could be extended to all high-level trimlines and blockfields in the British Isles, including those on the mountains of Ireland.

Here we test the generality of this interpretation by reporting ^{10}Be exposure ages for glacially emplaced 'perched' boulders resting on sandstone blockfield debris on Slievenamon in southern Ireland, and comparing the results with exposure ages obtained for high-altitude ice-moulded bedrock on Blackstairs Mountain in SE Ireland.

Sampling sites

Slievenamon (longitude 52°26′N, latitude 7°34′W; Irish Grid Reference S 299308; altitude 721 m a.s.l.) is an isolated dome-shaped sandstone mountain located 34 km N of the south coast of Ireland (Fig. 1). Blackstairs Mountain (52°33′N, 6°48′W; Irish Grid Reference S 811448; 735 m a.s.l.), 51 km farther east, is the highest summit on an elongated ridge of granite. There is general consensus that the last ice movement across this area was to the S or SSE from the Irish midlands (e.g. Warren 1991, 1992; McCabe 1998, 2008; Smith & Knight 2011). Although earlier work attributed this ice movement to a 'Munsterian' glaciation that was tentatively assigned to Marine Isotope Stages (MIS) 8–6 (~302–132 ka; Bowen *et al*. 1986; McCabe 1987; Knight *et al*. 2004) or to extensive ice cover during MIS 3 (~58–31 ka; Bowen *et al*. 2002), stratigraphical and dating evidence from exposures on the south coast of Ireland has conclusively demonstrated southwards movement of inland ice across the present coastline during the LGM (Ó Cofaigh *et al*. 2012b), implying that the last ice sheet to occupy the Slievenamon–Blackstairs Mountain area was of LGM age.

Above ~650 m a.s.l. the summit of Slievenamon is occupied by a bouldery blockfield, in places comprising openwork clasts and elsewhere clasts embedded in a matrix of sandy fines, with a localized superficial cover of patchy peat (Fig. 2). Thicker peat obscures lower slopes, but occasional erratic conglomerate boulders, probably derived from an outcrop NW of the summit dome, occur up to at least 510 m a.s.l. in altitude. A striking feature of the blockfield above 650 m a.s.l. is the presence of large, perched boulders, some of which rest on other boulders (Fig. 3A, B), some of which are upturned (Fig. 3C) and some of which, at the summit, appear to rest on intact bedrock (Fig. 3D). These boulders are generally larger than the adjacent blockfield debris and their 'perched' attitudes demonstrate deposition from glacier ice rather than upheaving of boulders by frost action, and they cannot be of rockfall origin as cliffs are absent. The summit plateau of Blackstairs Mountain (680–735 m a.s.l.) is also occu-

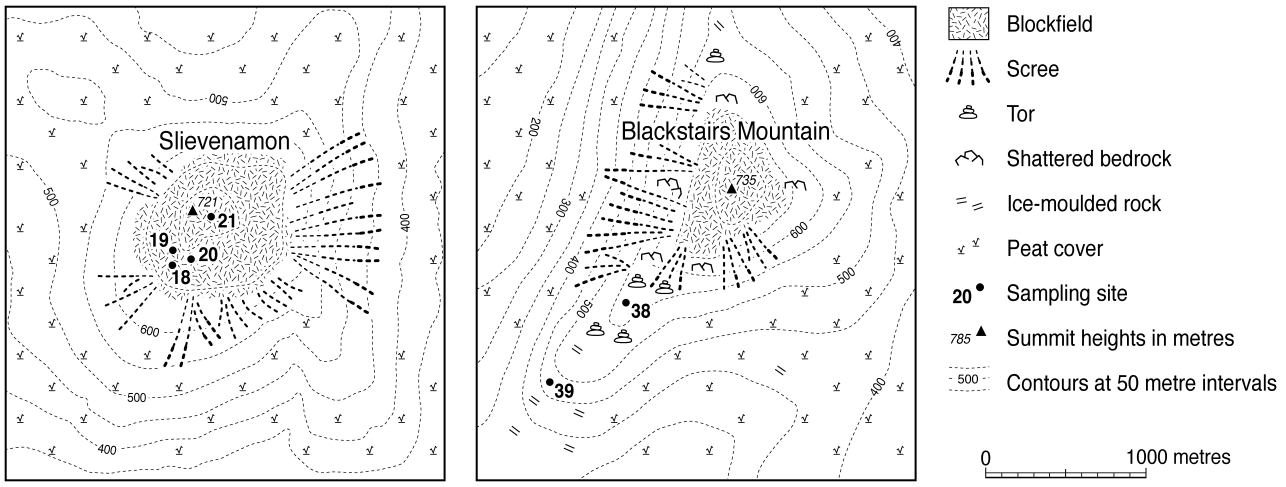

Fig. 2. Location of the sampling sites on Slievenamon and Blackstairs Mountain, showing the extent of summit blockfields and the location of tors, shattered bedrock outcrops and ice-moulded bedrock outcrops on Blackstairs Mountain.

Fig. 3. Sampled sandstone perched boulders on Slievenamon. A. Boulder from which sample IRE-SE-18 was obtained. B. Boulder from which sample IRE-SE-19 was obtained. C. Upturned boulder from which sample IRE-SE-20 was obtained. D. Boulder from which sample IRE-SE-20 was obtained. The spade is 0.9 m long; the walking pole is 1.2 m long. This figure is available in colour at http://www.boreas.dk.

pied by a blockfield, although conspicuous perched boulders are absent (Fig. 2). Moreover, boulders derived from schist outcrops at 585–690 m a.s.l. SW of the summit occur only a short distance down-slope from their parent outcrops, suggesting no or limited glacial entrainment of debris from the summit area. Subdued granite outcrops at 535–560 m a.s.l. are inferred to represent glacially modified 'tor plinths', similar to those described by Hall & Phillips (2006) in the Cairngorm Mountains of Scotland, and below 460 m a.s.l. ice-moulded granite slabs supporting perched boulders are present.

To establish whether or not the perched boulders on Slievenamon were emplaced by the last ice sheet (implying preservation of pre-existing blockfield debris under cold-based ice during the LGM) or an earlier ice sheet (suggesting that the summit of Slievenamon was a palaeonunatak during the LGM), we chiselled samples for cosmogenic ^{10}Be exposure dating from the near-horizontal upper surfaces of the four boulders illustrated in Fig. 3. Lack of suitable bedrock exposures on Slievenamon precluded sampling of bedrock surfaces to establish the timing of ice-sheet downwastage at this site, so we obtained two bedrock samples of vein quartz from Blackstairs Mountain to provide an indication of the timing of summit emergence in the area: one from a 'tor plinth' at 556 m a.s.l. and one from the plucked lee side of an ice-moulded outcrop at 460 m a.s.l. Sample locations and altitude were recorded using GPS and checked on 1:50000 contoured maps, and corrections for topographical shielding were calculated from the dip of sample surfaces (in all cases <15°) and skyline surveys (Table 1).

Sample preparation and exposure age calibration

Sample thicknesses were measured and samples crushed and sieved. Pure quartz was obtained from

Table 1. Sample location and ^{10}Be analytical data. ^{10}Be concentrations are normalized to a ^{10}Be/^{9}Be value of 2.851×10^{-12} for the ICN 01-5-4 standard, as specified by Nishiizumi *et al.* (2007). This is equivalent to the 07KNSTD normalization of the CRONUS calculator (Balco *et al.* 2008). AMS ^{10}Be analyses were conducted at the Lawrence Livermore Center for Accelerator Mass Spectrometry (LLNL-CAMS). Errors (±1σ) include laboratory procedural uncertainties and individual AMS measurement errors, but do not include additional contributions for laboratory standard reproducibility or interlaboratory comparison errors.

Sample	Irish Grid Reference	Latitude (°N)	Longitude (°W)	Altitude (m a.s.l.)	Thickness (mm)	Density (g cm^{-3})	Shielding correction	^{10}Be (10^5 atoms g^{-1})
Slievenamon perched boulder samples								
IRE-SE-18	S 296304	52.425	7.566	673	30	2.65	0.999	1.665±0.032
IRE-SE-19	S 296304	52.425	7.566	675	25	2.65	0.999	2.186±0.049
IRE-SE-20	S 297304	52.425	7.564	683	27	2.65	1.000	2.264±0.044
IRE-SE-21	S 299308	52.428	7.561	720	35	2.65	1.000	2.854±0.054
Blackstairs Mountains bedrock samples								
IRE-SE-38	S 808445	54.456	6.809	556	34	2.65	0.999	1.544±0.061
IRE-SE-39	S 799436	54.588	6.822	452	39	2.65	0.947	1.336±0.032

samples by floatation in dense liquids and selective dissolution of other minerals with dilute HF (Kohl & Nishiizumi 1992). Beryllium-10 was separated from samples weighing 10–20 g in the presence of ~250 µg ^{9}Be carrier, using conventional methods (Ditchburn & Whitehead 1994; see also Stone 2005). Details of the isotopic analyses are given in Table 2. Blank corrections amounted to <1% in all cases.

Exposure ages were calculated using the Lm scaling of the CRONUS-Earth online calculator (Balco *et al.* 2008); other scaling schemes produce ages up to 1.9% older. In the calculation of ^{10}Be exposure ages we employed two local production rates (LPRs) derived from sites in Scotland, the LL LPR and NWH11.6 LPR, with reference ^{10}Be production rates (Lm scaling) of 3.92±0.18 and 4.20±0.14 atoms g^{-1} a^{-1}, respectively (Ballantyne & Stone 2012; Fabel *et al.* 2012). These two LPRs effectively bracket the range of possible ^{10}Be exposure ages; the NWH11.6 LPR produces ^{10}Be exposure ages ~6.6% lower than the LL LPR. We assumed a surface erosion rate (ε) of 1 mm ka^{-1} for all exposure-age samples (Ballantyne 2010a); assumption of ε = 0 reduces reported ^{10}Be ages by 1.8–3.0% and assumption of ε = 2 mm ka^{-1} increases ^{10}Be ages by a similar amount. Cited uncertainties (±1σ) associated with cosmogenic isotope exposure dates are total (external) uncertainties. Below we report individual ^{10}Be ages calculated using LL LPR first, followed by ages calculated using NWH11.6 LPR in parentheses.

Results

Blackstairs Mountain

The two Blackstairs Mountain bedrock samples yielded very similar exposure ages (Table 2) with an

Table 2. ^{10}Be exposure ages. Scaling from CRONUS online calculator (Balco *et al.* 2008): wrapper script version 2.2; main calculator version 2.1; constants version 2.2.1; muons version 1.1. Internal uncertainties (±1σ) reflect analytical uncertainties on ^{10}Be measurements only. External uncertainties (±1σ) incorporate in addition uncertainties in the calibration and scaling procedure.

Sample	LL LPR			NWH11.6 LPR		
	Exposure age (ka)	Internal uncertainty (ka)	External uncertainty (ka)	Exposure age (ka)	Internal uncertainty (ka)	External uncertainty (ka)
Slievenamon perched boulder samples						
IRE-SE-18	22.58	0.44	1.14	21.10	0.41	0.85
IRE-SE-19	29.67	0.68	1.55	27.72	0.64	1.18
IRE-SE-20	30.56	0.62	1.56	28.54	0.57	1.17
IRE-SE-21	37.79	0.75	1.93	35.28	0.70	1.45
Blackstairs Mountains bedrock samples						
IRE-SE-38	23.29	0.95	1.44	21.77	0.89	1.17
IRE-SE-39	23.40	0.58	1.23	21.87	0.54	0.95
Uncertainty-weighted mean	23.37	0.50	1.19	21.84	0.46	0.90
Wicklow Mountains bedrock samples (recalibrated from data in Ballantyne *et al.* 2006)						
Djouce summit (725 m a.s.l.)	21.97	0.49	1.13	20.53	0.45	0.86
Scarr summit (600 m a.s.l.)	21.21	0.54	1.12	19.82	0.51	0.86
Kanturk summit (523 m a.s.l.)	20.96	0.57	1.13	19.59	0.54	0.88
Uncertainty-weighted mean	21.44	0.31	1.04	20.04	0.29	0.76

uncertainty-weighted mean age of 23.4±1.2 ka (21.8±0.9 ka). This deglaciation age is consistent with radiocarbon and OSL dates constraining the timing of advance of ice from the Irish midlands across the south coast of Ireland after ~24 ka (Hughes *et al*. 2011; Ó Cofaigh *et al*. 2012b) and the reconstruction of BIIS retreat chronology by C. D. Clark *et al*. (2012), which depicts deglaciation of most of southern Ireland prior to ~19 ka. It is also broadly in accord with Bayesian modelling that incorporates all published radiocarbon, OSL and cosmogenic isotope ages relating to the advance and retreat of the Irish Sea Ice Stream (Chiverrell *et al*. 2013). This model suggests that the last BIIS reached its maximum southern extent on the Celtic Shelf south of Ireland and impinged on the Scilly Isles (McCarroll *et al*. 2010) sometime between 24.3 and 23.1 ka, then retreated rapidly, with the ice margin reaching a position in the Irish Sea Basin east of Blackstairs Mountain at 23.4–22.4 ka. The overlap between the Blackstairs Mountain exposure ages reported here and the retrodictions of the Bayesian model suggests that the former are reasonably representative of the timing of ice thinning to expose high ground at this site. Assuming that the retreating margin of the 'inland' ice was aligned roughly parallel to the present south coast of Ireland, as implied by the retreat pattern depicted in C. D. Clark *et al*. (2012), it is likely that the higher parts of Slievenamon had also emerged above the thinning ice sheet by 23–22 ka.

We note, however, that bedrock samples from three high-altitude sites in the Wicklow Mountains, ~70 km NNE of Blackstairs Mountain, produced recalibrated ^{10}Be exposure ages ~2 ka younger than those obtained for the latter (Table 2). This may indicate that the Blackstairs ages are compromised by nuclide inheritance owing to insufficient rock removal by glacial erosion. However, whereas Blackstairs Mountain was over-run by extraneous ice from the N or NW, during the LGM the Wicklows nourished an independent ice dome that fed into the 'inland' ice to the west and the Irish Sea Ice Stream to the east (Warren 1993; Ballantyne *et al*. 2006; Smith & Knight 2011). It is therefore possible that the younger ages obtained for the Wicklow summits (Table 2) reflect persistence of a residual icecap on the higher parts of these mountains long after Blackstairs Mountain emerged from the downwasting IIS.

Perched boulders on Slievenamon

Like the blockfield erratics in NW Scotland exposure-dated by Fabel *et al*. (2012), the four perched boulders on the Slievenamon blockfield produced a wide range of ^{10}Be exposure ages, from 22.6±1.1 ka (21.1±0.9 ka) to 37.8±1.9 ka (35.3±1.5 ka). Although the four exposure ages increase with the altitude of the sampling sites (Tables 1, 2), we attach no significance to this in view of the limited altitudinal range of the sampled boulders (673–720 m a.s.l.) and the fact that two samples (IRE-SE-18 and IRE-SE-19) produced very different exposure ages but differ in altitude by only 2 m. Tested using the two-sample difference of means test based on internal uncertainties, all of these four ages differ from each other at $p<0.0001$, except for the middle two, which are statistically indistinguishable (Table 2). All are significantly older ($p<0.0001$) than the ages obtained for deglaciation of Blackstairs Mountain, except for sample IRE-SE-18, which produced an exposure age of 22.6±1.1 ka (21.1±0.9 ka) that is statistically indistinguishable from both the Blackstairs Mountain ages, lending support to the assumption that Slievenamon emerged from the downwasting ice sheet at roughly the same time as Blackstairs Mountain. It is also notable that all four of the exposure ages obtained from the high-altitude perched boulders on Slievenamon are significantly younger (at $p<0.01$) than all but one of 10 apparent exposure ages obtained from above-trimline bedrock outcrops on various Irish mountains (Fig. 4).

Discussion

Although the exposure ages obtained for all four perched boulders on Slievenamon either straddle or exceed the timing of the global LGM (Fig. 4) and three exceed the timing (24.3–23.1 ka) of the maximum southern extension of the BIIS suggested by Bayesian modelling (Chiverrell *et al*. 2013), consideration of the wider evidence for the chronology of the build-up of the ice sheet implies that at least three of the boulders and probably all four must have been emplaced by the last IIS and not by an earlier thicker ice sheet. Flowline evidence based on subglacial bedform alignment suggests that initial expansion of the last IIS was associated with advance of ice from west-central Scotland that extended up to 200 km into the Irish Midlands (Greenwood & Clark 2009). As multiple radiocarbon dates from sites in the Scottish lowlands indicate ice-free conditions prior to ~32 ka (Bos *et al*. 2004; Brown *et al*. 2007), this scenario implies very limited ice cover in Ireland prior to that date. Similarly, organic-rich silts sandwiched between two tills at Derryvree in County Fermanagh (Fig. 1) produced a radiocarbon age of 30.5±1.2 ^{14}C ka (36.9–31.7 cal. ^{14}C ka; Colhoun *et al*. 1972) and organic detritus from lacustrine deposits under till at Greenagho, also in County Fermanagh, produced a radiocarbon age of 32.5±0.3 ^{14}C ka (37.2–35.7 cal. ^{14}C ka; Dardis *et al*. 1985). These ages indicate ice-free conditions in north-central Ireland until at least ~34 ka, prior to the build-up and expansion of the IIS. Additionally, a wide range of radiocarbon ages (43.9±0.5 to 26.4±0.1 cal. ^{14}C ka) obtained for reworked marine shells at Glenulra, in western Ireland (McCabe *et al*. 2007), imply open water and hence ice-free con-

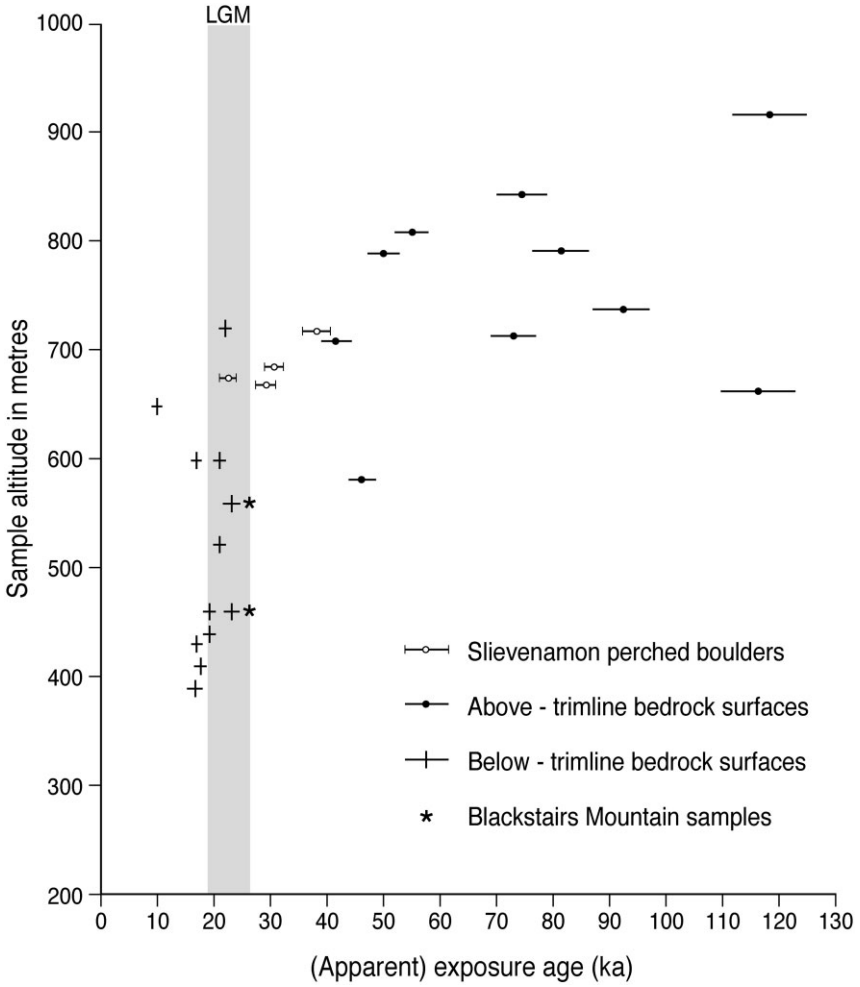

Fig. 4. Ages of the perched boulders on Slievenamon depicted on an age-altitude plot that also shows above- and below-trimline bedrock ages obtained on various Irish mountains for sites above 400 m a.s.l. (data from Ballantyne *et al.* 2006, 2008, 2011, 2013). All ages were calculated or recalculated using the LL LPR assuming a sampling surface erosion rate of 1 mm ka^{-1}. Horizontal bars indicate total (external) uncertainty at ±1σ. The perched boulder ages are significantly (p<0.01) younger than all but one of the (apparent) above-trimline bedrock exposure ages. The duration of the global LGM (26.5–19.0 ka) is depicted by the shaded zone.

ditions in adjacent Donegal Bay (Fig. 1) during much of the ~20 ka prior to the westwards expansion of the last IIS. Finally, radiocarbon ages on reworked marine shells and OSL ages obtained for glacifluvial and glaciolacustrine deposits under a till of 'inland' provenance demonstrate that southwards-moving ice from the Irish midlands did not cross the south coast until after ~24 ka (Ó Cofaigh *et al.* 2012b). Collectively, the above dating evidence implies that the bulk of the last IIS expanded from initially ice-free conditions at ~34 ka to reach the south coast after ~24 ka. The exposure ages of two of the perched boulders on Slievenamon (29.7±1.6 ka (27.7±1.2 ka) and 30.6±1.6 ka (28.5±1.2 ka)) fall within this long period of ice-sheet build-up and expansion, implying that even though these ages may be compromised by exposure prior to entrainment, the boulders can only have been deposited by the last IIS and not by an earlier ice sheet. This conclusion is confirmed by the age of 22.6±1.1 ka (21.1±0.9 ka) for sample IRE-SE-18, which not only post-dates the inferred maximum southern extension of the last BIIS, but also is statistically indistinguishable from the Blackstairs Mountain deglacial ages, suggesting that the summit of Slievenamon emerged from the thinning ice sheet at roughly 23–22 ka.

Wider implications

Interpretation of trimlines

The presence of boulders deposited by the last IIS on blockfield debris on Slievenamon demonstrates that ice must have overtopped the summit of that mountain during the LGM, and hence had a surface altitude >721 m a.s.l. at this locality. More importantly, our findings provide the first independent evidence to support the suggestion of Fabel *et al.* (2012) that *all* blockfields in the British Isles inside the limits of the last BIIS represent preservation of blockfield debris under passive cold-based ice rather than palaeonunataks that remained above the last ice sheet, particularly as the two studies were carried out at sites 600 km apart. If this is the case, all associated trimlines represent a former englacial transition within a thick ice sheet,

from erosive warm-based ice at lower altitudes to 'passive' cold-based ice that formerly covered and preserved pre-existing blockfields on high ground.

This conclusion is consistent with evidence of glacial modification of tors that surmount blockfields on the high plateau of the Cairngorm Mountains in NE Scotland (Hall & Phillips 2006), post-LGM ^{10}Be exposure ages obtained on some tors in the same area (Phillips *et al.* 2006), modelling of ice thickness over blockfield-mantled mountains in SW Ireland (Ballantyne *et al.* 2011) and retrodiction of former ice-sheet thickness by TMC modelling (Hubbard *et al.* 2009). More generally, it accords with evidence for emergence of glacially unmodified blockfields from under the retreating margins of cold-based plateau icecaps (Rea *et al.* 1996) and a substantial body of evidence demonstrating that plateau blockfields in Scandinavia, Svalbard and North America survived, apparently intact, under a 'protective' cover of cold-based glacier ice during the LGM (e.g. Kleman & Stroeven 1997; Fabel *et al.* 2002; Hättestrand & Stroeven 2002; Briner *et al.* 2003; Marquette *et al.* 2004; Staiger *et al.* 2005; Fjellanger *et al.* 2006; Phillips *et al.* 2006; Kleman & Glasser 2007; Linge *et al.* 2007; Hormes *et al.* 2011). Indeed, although trimlines certainly represent the former upper altitudinal limit of LGM icefields or valley glaciers elsewhere (Ballantyne 2013), the research reported here contributes to a growing body of evidence that trimlines representing the altitudinal transition between 'erosive' and 'passive' ice cover within a former thick ice sheet are the norm rather than the exception.

Implications for blockfield evolution

Blockfields on mountains in the British Isles have traditionally been attributed to formation by frost weathering under severe periglacial (permafrost) conditions on nunataks that remained above the level of the last ice sheet (e.g. Ballantyne & Harris 1994; Ballantyne 1998; Ballantyne *et al.* 1998). Preservation of plateau and summit blockfields under cold-based ice within a thick LGM ice sheet implies a much longer history of blockfield evolution, with blockfields developing under periglacial conditions prior to and after successive periods of burial under cold-based ice within thick ice sheets. However, rates of plateau and summit lowering since the early Pleistocene implied by cosmogenic exposure ages obtained on emergent tors in the Cairngorm Mountains of Scotland (Phillips *et al.* 2006) suggest that the blockfield debris now present on mountains may be no greater than late Pleistocene (<135 ka) in age (Hopkinson & Ballantyne 2014).

Implications for deglacial chronology

The two deglacial exposure ages obtained from Blackstairs Mountain (mean age 23.7±1.2 ka (21.8±0.9 ka)) and the youngest exposure age obtained for perched boulders on Slievenamon (22.6±1.1 ka (21.1±0.9 ka)) imply ice-sheet thinning and emergence of high ground at roughly 24–22 ka (LL LPR) or 23–21 ka (NWH11.6 LPR). Within dating uncertainty, these ages are consistent with a single ^{36}Cl deglacial exposure age of 23.6±2.8 ka reported for a site at Hatton Farm (245 m a.s.l.), 18 km NE from Blackstairs Mountain, and with a ^{36}Cl exposure age of 22.3±2.0 ka obtained on the Mottee Stone, a large erratic boulder at 250 m a.s.l. on the SE footslopes of the Wicklow Hills, 55 km NW of Blackstairs Mountain (Bowen *et al.* 2002), Collectively, these dates suggest that emergence of high ground from under the downwasting ice sheet was succeeded by deglaciation of low ground in SE Ireland within a similar time frame. Given that ice moving south from the Irish Midlands crossed the south coast of Ireland after ~24 ka, as implied by radiocarbon and OSL ages obtained from deposits underlying 'inland' till at coastal locations (Ó Cofaigh *et al.* 2012b), the above ages suggest that glacial occupation of the southern and southeastern fringes of Ireland during the LGM was comparatively brief, perhaps no longer than several centuries and probably not longer than three millennia. As noted earlier, Bayesian modelling of the retreat of the Irish Sea Ice Stream suggests that the ice margin in the Irish Sea Basin lay east of Blackstairs Mountain at 23.4–22.4 ka (Chiverrell *et al.* 2013). Although the wide uncertainties in the exposure ages listed above preclude definitive conclusions, the available dating evidence suggests decoupling of the Irish Sea Ice Stream from 'inland' ice moving southwards or southeastwards from the Irish Midlands at a very early stage in deglaciation, only 1–3 ka after the BIIS reached its maximum southernmost extent at 24.3–23.1 ka (Chiverrell *et al.* 2013). Finally, we note that the deglaciation ages listed above are older than all radiocarbon and cosmogenic isotope deglaciation ages reported for the western or northern coastal fringes of Ireland (Bowen *et al.* 2002; McCabe & Clark 2003; McCabe *et al.* 2007; Ballantyne *et al.* 2007, 2008, 2013; J. Clark *et al.* 2009a, b, 2012), even when reported ^{10}Be ages are recalculated using the LPRs employed here; this implies that southern and southeastern Ireland were the first parts of the present Irish land surface to experience deglaciation.

Conclusions

- Four glacially deposited perched boulders resting on a blockfield on the summit area of Slievenamon (721 m a.s.l.) in southern Ireland produced cosmogenic ^{10}Be exposure ages ranging from 37.8±1.9 to 22.6±1.1 ka or 35.3±1.5 to 21.1±0.9 ka, depending on the ^{10}Be production rate employed in the age calculation. The exposure ages of three of these boulders demonstrate that the summit of Slievenamon was over-ridden by the last Irish Ice Sheet.

- The above finding supports the suggestion of Fabel *et al.* (2012) that all blockfields on mountains in the British Isles within the limits of the last ice sheet were preserved under passive cold-based ice during the LGM, implying that trimlines separating blockfields from glacially abraded rock on lower ground represent a former englacial boundary between warm-based sliding ice on low ground and cold-based ice occupying summits and plateaux.
- Preservation of blockfields under cold-based ice within the last British–Irish Ice sheet implies that they have evolved over much longer time scales than previously believed, potentially spanning much of the Pleistocene, although evidence for slow surface lowering elsewhere suggests that the present blockfield debris mantle may represent frost weathering under severe periglacial conditions during the later Pleistocene.
- The exposure age of the youngest perched boulder on Slievenamon (22.6±1.1 ka (21.1±0.9 ka) is consistent with two almost identical deglacial ages with a mean of 23.4±1.2 ka (21.8±0.9 ka) obtained for samples from high-level bedrock sites on Blackstairs Mountain, 51 km farther east, and with ^{36}Cl exposure ages of 23.6±2.8 and 22.3±2.0 ka reported by Bowen *et al.* (2002). Collectively, these ages imply: (i) early deglaciation of southernmost Ireland and emergence of high ground through thinning and retreat of 'inland' ice from the Irish midlands within 1–3 ka after the last British–Irish Ice Sheet reached its southernmost extent, and (ii) decoupling of 'inland' ice from the Irish Sea Ice Stream in this area within a similar time frame.

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