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Glaciation of the English Lake District during the Late-glacial: a new analysis using ^{10}Be and Schmidt hammer exposure dating

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Abstract

Recalibration of published ^{10}Be ages from the classic cirque moraines at Keskadale, Lake District, in combination with calibrated relative ages provided by Schmidt hammer exposure dating (SHED) in the nearby Ling Comb cirque, provide new insights into the extent and retreat history of glaciers during the Late-glacial interval (14.7–11.7 ka). Based on a globally-calibrated production rate, glacial surfaces at Keskadale return exposure ages of 12.3 ± 1.1 ka (lower moraine) and 12.5 ± 1.0 ka (upper cirque threshold), both within the Younger Dryas. A new ^{10}Be age of 8.6 ± 0.9 ka is reported from a boulder from the lower moraine crest which may reflect post-depositional exhumation, erosion or instability. Alternative locally-calibrated production rates from Scotland produce ^{10}Be ages that are up to ~8% older and push the oldest exposure ages to the Allerød-Younger Dryas boundary. At Ling Comb, ~4 km from Keskadale, granitic moraine boulders return calibrated relative ages which span the last glacial-interglacial transition, but these vary by ~6% depending on the choice of production rate. As post-depositional erosion of moraines can profoundly influence the distribution of boulder exposure ages, these data are interpreted as minimum limiting ages, with moraine deposition constrained conservatively to between 11.6 ± 1.3 ka and 12.3 ± 1.4 ka. While lithological and geomorphological processes, in combination with production rate uncertainty, complicate interpretation of these datasets, these data appear consistent with Younger Dryas glaciation of Lake District cirques.

Introduction

The Late-glacial interval is characterized by the oscillating climatic conditions associated with the successive Bølling-Older Dryas-Allerød-Younger Dryas chronozones during the Late Weichselian/Devensian Substage (Mangerud *et al.* 1974). This Late-glacial succession was originally defined by periods of biostratigraphical change reflected in palaeoecological records in Denmark (Iversen 1954), but this succession has been widely utilised in other regions; a trend which may reflect the widespread nature of temperature changes in the eastern Northern Atlantic region (Brooks *et al.* 2012). In Scandinavian records, the Late-glacial was originally correlated with the Late Weichselian Substage which was defined as the interval between the onset of the Bølling at 13,000 ^{14}C years BP and the onset of the Holocene at 10,000 ^{14}C years BP (Mangerud *et al.* 1974). More recent studies utilising high-resolution Greenland ice core stratigraphy have refined this interval to $14,692 \pm 186$ years to $11,703 \pm 99$ years (calendar years before AD 2000), encompassing Greenland Interstadial 1 and Greenland Stadial 1 (Lowe *et al.* 2008; Rasmussen *et al.* 2014). This ~3 ka interval is of particular importance from a palaeoclimatic and palaeoglaciological perspective as it is defined by frequent, abrupt and high magnitude shifts between

glacial and interglacial conditions (Severinghaus *et al.* 1998; Steffensen *et al.* 2008). However, there is still considerable uncertainty and debate regarding the response of proximal ice masses to these climatic shifts (Bromley *et al.* 2014; Lowe *et al.* 2019) and their potential drivers in the North Atlantic ocean-atmospheric system (Renssen *et al.* 2015). Resolving these debates will enable more robust analysis of the timing, rapidity and spatial uniformity of ice demise in the North Atlantic region following the Last Glacial Maximum (LGM; Clark *et al.* 2009; Hughes *et al.* 2016), with potential insights into the response of contemporary ice masses to anthropogenic forcing of climate.

Within this context, and despite over a century of research (Ward 1873; Marr 1916), uncertainty persists regarding the extent and retreat history of glaciers in the English Lake District during the Late-glacial period (Bickerdike *et al.* 2016). While this mountain range was an important centre for ice dispersal during the LGM (Clark *et al.* 2012) and sourced a component ice cap of the British Irish Ice Sheet (BIIS), there is a relative paucity of geochronological data to constrain the age and depositional history of post-LGM glacial landforms. However, on the basis of geomorphological and palynological records, it

has long been thought that glaciers occupied the cirques of the Lake District during the Younger Dryas Chronozone (12.9–11.7 ka; Manley 1959; Pennington *et al.* 1977; Sissons 1979; 1980), the last cold interval in the Late-glacial climatic sequence; a period which is broadly correlated with the Loch Lomond Stadial or Loch Lomond Readvance in Scotland (Simpson 1933; Lowe *et al.* 2019). This period of climatic deterioration, marked by a return to near-glacial conditions, is clearly identifiable in pollen stratigraphy (Donner 1957; Brooks and Birks 2000) but the glaciological response to this abrupt change is not fully understood. The presence of cirque moraines has been known for many years in the Lake District (e.g. Manley 1959) and the correlation of these with the Younger Dryas is also long-established (Pennington *et al.* 1977). The classic work of Sissons (1979; 1980) documented 64 key cirque sites occupied by glaciers during the Younger Dryas although later work has provided evidence for more extensive glaciers in some areas (e.g. McDougall 2001; 2013).

In Scotland, large ice fields and ice caps formed over the mountains during the Loch Lomond Stadial (Sissons 1974; Ballantyne 2002; Golledge 2007; Golledge *et al.* 2008) while glaciers are also thought to have been present in Wales at this time (Hughes 2002; 2009; Bendle and Glasser 2012). However, few radiometric ages exist from England and Wales testing the depositional history of cirque/cwm moraines, with only a small number of studies utilising cosmogenic exposure dating, with just a single paper from Wales (Phillips *et al.* 1994) and three papers from England (Ballantyne *et al.* 2009, Hughes *et al.* 2012, Wilson *et al.* 2013). In their review of Younger Dryas glaciation in the British Isles, Bickerdike *et al.* (2018, p. 1) noted that because of the scarcity of dating, it is difficult to “confidently identify the limits of LLS [Loch Lomond Stadial] glaciers and assess their synchronicity”. The best-dated sites using cosmogenic exposure dating are from Scotland where Loch Lomond Stadial moraines and related features, such as the ice-dammed lake shorelines at Glen Roy, were dated around a decade ago (Golledge *et al.* 2007; Fabel *et al.* 2010; Golledge 2010; Small *et al.* 2011). However, recent studies have challenged the timing of glaciation in Scotland as basal ^{14}C ages within moraine limits appear indicative of glacier retreat and final ice demise in Scotland during the early Younger Dryas (Bromley *et al.* 2014), although this scenario is disputed for both Rannoch Moor and Scotland in general by Small and Fabel (2016), Peacock and Rose (2017) and Lowe *et al.* (2019). A more recent study by Bromley *et al.* (2018) has reported ^{14}C ages from shelly tills from offshore sea loch sites that date to the Allerød. These maximum ages were interpreted as indicating ice advance and extensive glaciation during the Allerød by Bromley *et al.* (2018), with

restricted or marginal glaciation during the Younger Dryas. However, this position has been disputed by Lowe *et al.* (2019) who note that the age distribution of ^{14}C ages from reworked marine shells within glacial tills and other ice marginal sediments implies that ice advance post-dates the interval 14.5 to 12.6 cal ^{14}C ka BP; an interpretation which is consistent with extensive Loch Lomond Stadial glaciation.

In the Lake District, Hughes *et al.* (2012) presented the first ^{10}Be exposure ages for this area, from a cirque at the head of Keskadale in the Derwent Fells. This preliminary study argued that the last glaciers at this site formed during the Younger Dryas Chronozone. However, recalibration of these data using new locally-calibrated production rates (e.g. Fabel *et al.* 2012, Small and Fabel 2015; Putnam *et al.* 2019) have pushed these ages older (Wilson 2014); a possibility raised by Bromley *et al.* (2018) in support of more extensive Allerød ice cover in Scotland. Elsewhere in the Lake District, the results of cosmogenic exposure dating have proved inconclusive in regards to the timing of glaciation, with potential bias introduced by nuclide inheritance (Wilson *et al.* 2013), minimal glacial erosion (Ballantyne *et al.* 2009) and post-depositional processes which influence moraine age distributions (Hallet and Putkonen 1994; Briner *et al.* 2005). In general, however, the depositional history of proposed Late-glacial landforms is poorly known. In this paper, we provide a reassessment of previously published preliminary exposure ages from the classic site of Keskadale and provide an additional age from the lower cirque moraine. In addition, Schmidt hammer exposure dating (SHED) is applied to cirque moraines formed in granitic lithologies at Ling Comb in the nearby Buttermere Fells to provide an independent assessment of cirque moraine age. The aim of this paper is to test the hypothesis that glaciers occupied these cirques during the Younger Dryas Chronozone.

Study area

This paper examines the cirque moraines at two sites, just ~4 km apart, at the head of Keskadale in the Derwent Fells and Ling Comb in the Buttermere Fells.

Keskadale is a headwater tributary of the Newlands Valley in the Derwent Fells in the NW Lake District (Figure 1). The valley is characterized by classic glacial features. The main valley of Keskadale is U-shaped with a well-developed NNW- to NNE-facing cirque at the head of the valley at Robinson Crag. The cirque consists of two basins, an upper cirque known as High Hole near Robinson Crag and a lower cirque on the northern edge of Buttermere Moss. The cirques are separated by a rock step which is the result of a change in rock type. The rock step and lower cirque are formed

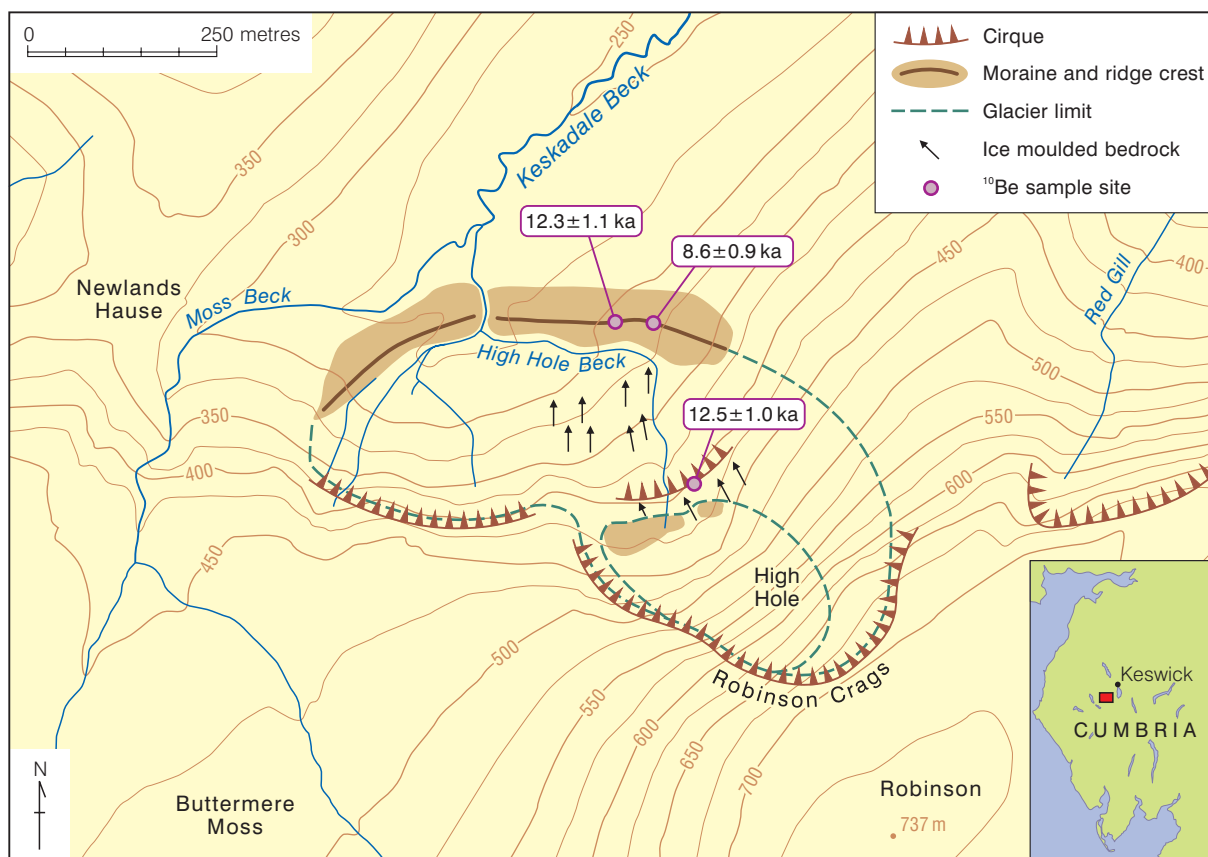


Figure 1: Geomorphological map of Keskadale showing the locations of ^{10}Be samples and their recalculated ages. Modified and updated from Hughes *et al.* (2012). Contains OS data © Crown copyright 2019.

in a band of quartz-rich greywacke sandstone at the axial plane of a major anticline fold. The upper cirque at High Hole is formed in mudstones with quartz-rich greywacke sandstone outcropping again towards the top of Robinson Craggs (EDINA Geology Digimap 2019).

Ling Comb is a N- to NNE-facing cirque draining into the glacial lake of Crummock Water, of which the latter is just over 1 km away and 300–500 m lower in altitude. The cirque is formed in granite of the Ennerdale Intrusion (EDINA Geology Digimap 2019), which is an Ordovician laccolith intruded into the Skiddaw Group and the lower part of the Borrowdale Volcanic Group (Hughes *et al.* 1996). The Ennerdale Intrusion is also commonly referred to as the Ennerdale Granophyre (e.g. Lee 1986).

Methods

^{10}Be exposure dating

Samples were taken for ^{10}Be dating and published in Hughes *et al.* (2012). These are now recalculated in this new paper. A third sample, previously unpublished, is also included in this new paper. The details of these samples are provided in Table 1.

In Hughes *et al.* (2012) two exposure ages were obtained from a cirque at the head of Keskadale (Figures 1 and 2). One sample was from a boulder on the lower moraine (PHSITE 2) and another was from bedrock at the lip of a higher inset cirque called High Hole (PHSITE 6). The ages were calculated using the same ^{10}Be standard NIST_27900.

Table 1: ^{10}Be sample data.

Sample	Elevation (m)	Latitude ($^{\circ}\text{N}$)	Longitude ($^{\circ}\text{W}$)	Sample thickness (cm)	Sample density (g cm^{-3})	Shielding correction	^{10}Be concentration (Atoms g^{-1})	Uncertainty in ^{10}Be concentration (Atoms g^{-1})	Name of ^{10}Be standard
PHSITE2	310	54.5472	-3.2399	2	2.65	0.9630	73,240	3,497	NIST_30600
PHSITE3	315	54.5474	-3.2389	5	2.65	0.9630	45,266	3,174	NIST_27900
PHSITE6	420	54.5452	-3.2383	2	2.62	0.9275	74,060	2,614	NIST_27900

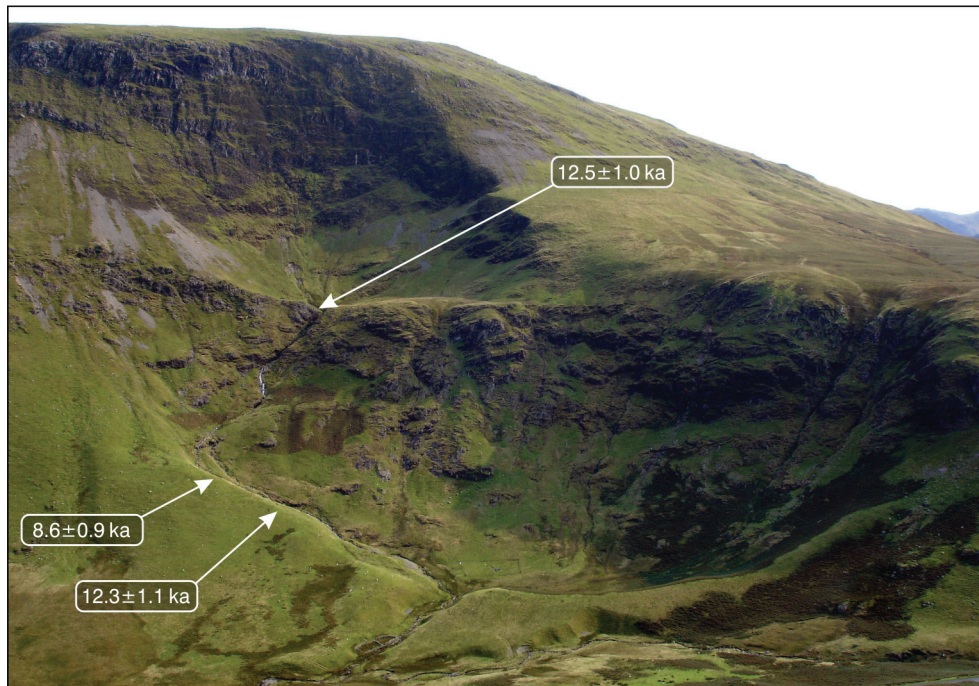


Figure 2: Photograph of Keskadale showing the upper and lower cirque basins. Photograph by Philip Hughes.

However, PHSITE 2 was measured on the AMS at SUERC in March 2010 whereas PHSITE 6 was measured nearly 18 months later in August/September 2011. It has since become apparent during a wider analysis of exposure ages reported over the period 2009–2016 (Hughes *et al.* 2018) that the ^{10}Be standards changed between these times from NIST_30600 (for PHSITE 2) to NIST_27900 (for PHSITE 6). The exposure age for PHSITE 2 was therefore calculated using the incorrect ^{10}Be standard in Hughes *et al.* (2012). However, the exposure age for PHSITE 6 was calculated using the correct ^{10}Be standard. This is important because it means that the age for PHSITE 2 appears to be too old in the original paper (Hughes *et al.* 2012) and in subsequent recalculations (e.g. Wilson 2014; Bickerdike *et al.* 2018; Bromley *et al.* 2018).

A new sample was dated using ^{10}Be after the Hughes *et al.* (2012) paper was submitted. This sample (PHSITE 3) was obtained from a small boulder (0.5 x 0.5 x 0.3 m, LWH) on the lower moraine at Keskadale, approximately ~50 m from PHSITE 2. The sample was taken from a quartz vein on the top surface of the boulder, with age calculation completed with respect to the NIST_27900 standard. The sample was crushed and sieved at the University of Manchester and the 125–250 and 250–500 μm fractions were sent to the NERC Cosmogenic Isotope Analysis Facility. The sample was then prepared for ^{10}Be analysis following procedures outlined in Glasser *et al.* (2011). Correction factors for shielding were calculated using the Cronus Geometric Shielding

calculator (http://hess.ess.washington.edu/math/general/skyline_input.php).

For all samples, exposure ages were calculated using the online calculators formerly known as the CRONUS-Earth online calculators, hereafter referred to as Cronus V3 (<http://hess.ess.washington.edu/math/>; Wrapper script 3.0.2, Main calculator 3.0.2, constants 3.0.4, muons 1A; Balco *et al.* 2008). Four different production rate calibration datasets were used to calculate the ages. These include:

- (i) the default global production rate used in Cronus V3 (Borchers *et al.* 2015),
- (ii) the Glen Roy production rate (GR PR; Small and Fabel, 2015), which is derived from tephra within a floating varve chronology (MacLeod *et al.* 2015),
- (iii) the Loch Lomond production rate (LL PR; Fabel *et al.* 2012), which is based on ^{10}Be concentrations from erratic boulders on the terminal moraine of the Younger Dryas Loch Lomond glacier advance, the timing of which is independently constrained by ^{14}C ages derived from a varve chronology (MacLeod *et al.* 2011),
- (iv) the Rannoch Moor production rate (RM PR; Putnam *et al.* 2019), which is based on ^{10}Be concentrations from boulders deposited on a glacial moraine belt on Rannoch Moor, bracketed by proximal ^{14}C ages (Bromley *et al.* 2014) and ^{14}C ages from outlet glaciers of the West Highland ice field (Bromley *et al.* 2018).

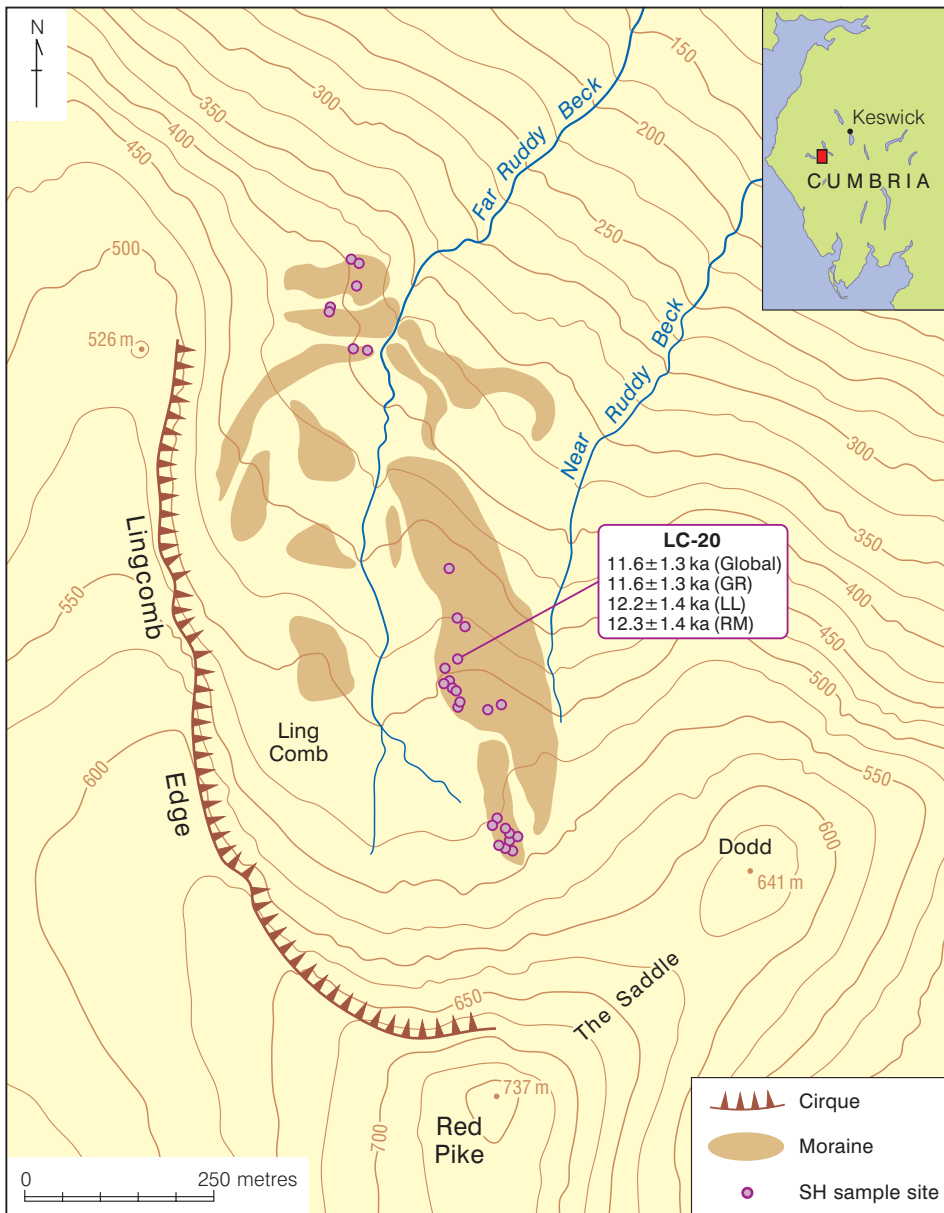


Figure 3: Geomorphological map of Ling Comb on Red Pike above Buttermere. SHED sample locations are indicated, including the boulder which returned the oldest calibrated relative exposure age (LC-20) showing the various ages associated with different production rates (Table 3). Contains OS data © Crown copyright 2019.

Using the Lm scaling, these local calibrations return production rates of 3.953 ± 0.151 (RM PR), 3.963 ± 0.094 (LL PR) and 4.205 ± 0.041 atoms $\text{g}^{-1} \text{yr}^{-1}$ (GR PR). Ages are reported using the time-dependent Lm (Lal 1991; Nishiizumi *et al.* 1989) and LSDn scaling schemes (Lifton *et al.* 2014; denoted Sa in Borchers *et al.* 2015 and Marrero *et al.* 2016). While scaling scheme choice has only a marginal effect on the resulting ages (~ 0.1 ka), erosion rate variability is likely more significant. Further discussion is focused on ages calculated assuming 0 mm ka^{-1} erosion and using the Lm scaling scheme as this generates a minimum age for each sample; an approach which is consistent with the utilisation of moraine ages as minimum limiting ages (Briner *et al.* 2005).

Schmidt hammer exposure dating

To investigate the glacial history of the Ling Comb cirque (Figure 3), glacially-deposited moraine boulders were

sampled using the Schmidt hammer (SH). In total, 30 boulders were investigated and 30 R-values were generated for each boulder ($R_{\text{total}} = 900$). This value exceeds the recommendation of Niedzielski *et al.* (2009) of 20 R-values for granite surfaces (minimum sample size in terms of mean at $\alpha = 0.05$). All surfaces were of sufficient size (Sumner and Nel 2002) and were free of surface discontinuities (Williams and Robinson 1983) and lichen (Matthews and Owen 2008). R-values were recorded perpendicular to the tested surface to reduce the risk of frictional sliding of the plunger tip (Viles *et al.* 2011), with single impacts separated by at least a plunger width (Aydin 2009), and no outliers were removed following Niedzielski *et al.* (2009). Reported R-values are the arithmetic mean of 30 R-values and the standard error of the mean (SEM). To account for SH drift with use (Tomkins *et al.* 2018a), instrument calibration was based on the University of Manchester calibration boulder

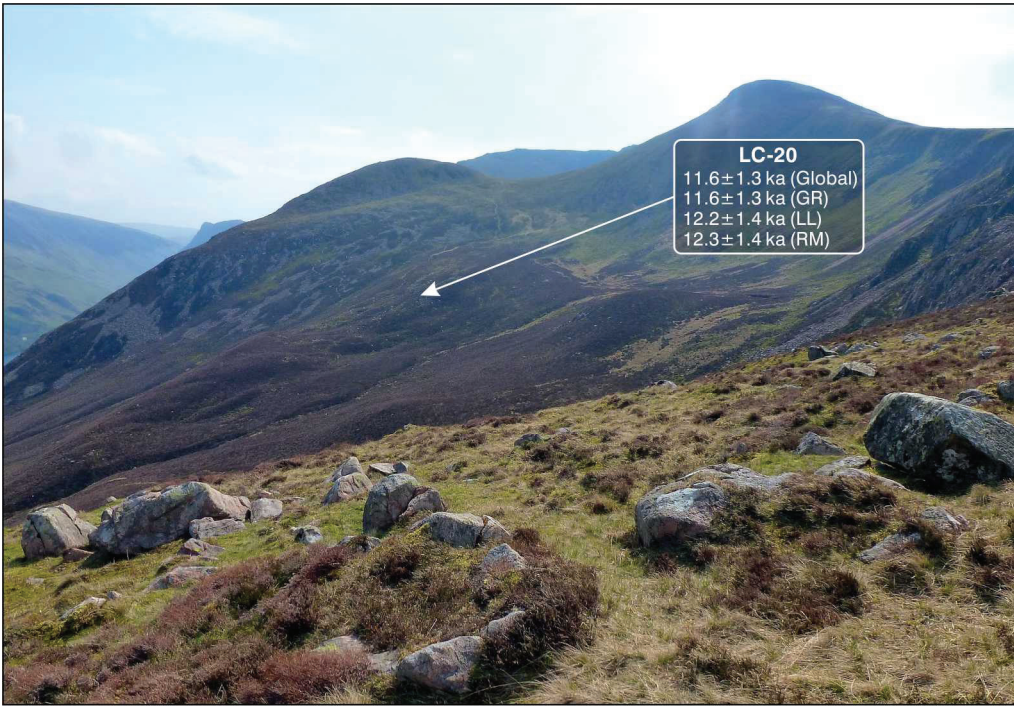


Figure 4: Photograph of Ling Comb showing the uppermost and intermediate moraines with Red Pike the peak at the head of the cirque. The location of the boulder which returned the oldest calibrated relative exposure age (LC-20) is indicated, showing the various ages associated with different production rates (Table 3). Photograph by Matt Tomkins.

(Dortch *et al.* 2016) and performed using SHED-Earth, an online calculator developed to enable wider and more consistent application of SHED (<http://shed.earth>). SH exposure ages and 1σ uncertainties were calculated based on the arithmetic mean for each surface ($n = 30$) and the ^{10}Be -SH calibration curve presented Tomkins *et al.* (2018a). This calibration curve is based on 54 ^{10}Be dated granite surfaces from sites across Scotland, NW England and Ireland

and has been used to investigate the timing and pattern of glacial retreat in the Wicklow Mountains, Ireland (Tomkins *et al.* 2018b), and the Mourne Mountains, Northern Ireland (Barr *et al.* 2017). Since the publication of these data, this calibration curve has been updated with an additional 11 ^{10}Be dated granite surfaces from the Wicklow Mountains (Barth *et al.* 2018) and the northern Cairngorms (Hall *et al.* 2016). However, the addition of these data has only a

Table 2: ^{10}Be exposure ages calculated using the online calculators formerly known as the CRONUS-Earth online calculators (<http://hess.ess.washington.edu/math/>; Wrapper script 3.0.2, Main calculator 3.0.2, constants 3.0.4, muons 1A; Balco *et al.* 2008), using the default global production rate of Borchers *et al.* (2015)¹, the Small and Fabel (2015) Glen Roy production rate (GR PR)², the Fabel *et al.* (2012) Loch Lomond production rate (LL PR)³ and the Putnam *et al.* (2019) Rannoch Moor production rate (RM PR)⁴. The ages are calculated using the Lm and LSDn/Sa scaling frameworks and assuming 0 mm ka⁻¹ erosion.

Geomorphological context	Sample name	Production rate calibration dataset	Lm scaling			LSDn/Sa scaling		
			Age (yr)	Internal error (yr)	External error (yr)	Age (yr)	Internal error (yr)	External error (yr)
Moraine boulder (lower crest)	PHSITE2	Global ¹	12,326	590	1,099	12,270	588	934
		Glen Roy ²	12,328	591	603	12,432	596	608
		Loch Lomond ³	13,079	627	698	13,212	633	702
		Rannoch Moor ⁴	13,361	633	729	13,296	637	731
Moraine boulder (lower crest)	PHSITE3	Global ¹	8,561	602	881	8,502	597	781
		Glen Roy ²	8,568	602	608	8,637	607	613
		Loch Lomond ³	9,104	640	675	9,233	649	683
		Rannoch Moor ⁴	9,197	646	694	9,290	653	699
Upper cirque bedrock lip	PHSITE6	Global ¹	12,468	441	1,037	12,425	440	857
		Glen Roy ²	12,483	441	458	12,603	445	461
		Loch Lomond ³	13,229	468	563	13,386	474	565
		Rannoch Moor ⁴	13,361	473	598	13,469	477	600

marginal impact on the slope of the associated calibration curve, and resulting surface exposure ages vary by ≤ 0.09 ka, significantly smaller than measurement uncertainty (± 1.4 ka). The Tomkins *et al.* (2018a) ^{10}Be -SH calibration curve has recently been independently tested by Wilson *et al.* (2019) who found a close correspondence (within 2σ) between cosmogenic exposure ages and calibrated relative exposure ages generated using SHED at 7 sites in Ireland and Scotland.

Results

^{10}Be exposure ages – Keskadale

The geomorphology of the headwall of Keskadale was described in Hughes *et al.* (2012) and is illustrated in Figure 1. The ^{10}Be ages are shown in Table 2 calculated using different scaling schemes and production rates. Using the Lm scaling, the ^{10}Be ages for the lower moraine are 12.3 ± 1.1 and 8.6 ± 0.9 ka based upon a globally-calibrated production rate, but these ages are shifted $\sim 8\%$ older to 13.4 ± 0.7 ka and 9.2 ± 0.7 ka respectively when utilising the lowest locally-calibration production rate (RM PR; Putnam *et al.* 2019). The higher cirque threshold bedrock sample returned exposure ages which range between 12.5 ± 1.0 ka and 13.4 ± 0.6 ka. The youngest age from sample PHSITE3 is considered an outlier.

Geomorphology and SHED ages – Ling Comb

The glacial geomorphology of the Ling Comb cirque is illustrated in Figure 3. Ling Comb contains a series of moraines between 390 and 550 m but these are not as stratigraphically distinct as at Keskadale and instead are more diffuse. The moraine distributions are shown in Figure 4.

For all sampled boulders, surface R-values vary between 45.17 ± 0.70 (LC-20) and 49.05 ± 0.61 (LC-04) (Table 3). The distribution of R-values is platykurtic (Kurtosis = -0.957) while the resulting distribution of calibrated surface exposure ages is positively skewed (Skewness = 0.414). Calibrated surface exposure ages, interpolated based on the ^{10}Be -SH calibration curve in Tomkins *et al.* (2018a), range from 9.48 ± 1.34 ka to 11.58 ± 1.33 ka (Global PR) or 10.08 ± 1.39 ka to 12.31 ± 1.38 ka (RM PR). Variation in age due to choice of production rate is $\sim 6\%$. These data are interpreted to reflect the cumulative exposure of rock surfaces to subaerial weathering (André 2002; Tomkins *et al.* 2018c), with an assumption of contemporaneous exposure and deglaciation. However, boulder exposure may occur long after glacial retreat, as moraines stabilise and erode through time (Hallet and Putkonen 1994; Putkonen and Swanson 2003; Applegate *et al.* 2010). This process can lead to temporary rock surface shielding under a cover of

glacial till and higher SH R-values. In these environments, calibrated surface exposure ages will post-date retreat and instead may primarily reflect the timing of boulder exhumation and moraine stabilisation (Hallet and Putkonen 1994). This pattern of deglaciation, moraine deposition and subsequent stabilisation is consistent with the positively-skewed distribution of boulder R-values. Given the growing consensus that moraine ages are more likely influenced by post-glacial instability than prior exposure (Heyman *et al.* 2011; Murari *et al.* 2014), the most cautious approach is to interpret SHED data as minimum limiting ages (Briner *et al.* 2005). As a result, the greatest boulder age (LC-20) is hypothesized to most closely match the true age of a moraine, although only under an assumption of no prior exposure (Putkonen and Swanson 2003). While further work is necessary to investigate the depth dependence of SH R-values, evidence from large scale ^{10}Be -SH datasets from the British Isles (Tomkins *et al.* 2018a) and the Pyrenees (Tomkins *et al.* 2018c) indicates that SHED is insensitive to nuclide inheritance, as inherited ^{10}Be surfaces return SH R-values that are indistinguishable (i.e. within measurement uncertainty) from proximal inheritance free surfaces (see Tomkins *et al.* 2018b; Samples CAC 25-28). Based on this reasoning, the timing of deglaciation is constrained conservatively to between 11.6 ± 1.3 ka and 12.3 ± 1.4 ka, depending on choice of production rate. While the temporal precision of this approach precludes precise moraine age determination, these data appear consistent with Younger Dryas or early Holocene deglaciation of the Ling Comb cirque.

Discussion

Deglaciation of Keskadale

Recalibration of ^{10}Be ages from Keskadale with corrected ^{10}Be standards indicates that both the lower moraine and the higher cirque threshold yield identical exposure ages (i.e. within measurement uncertainty) of 12.3 ± 1.1 and 12.5 ± 1.0 ka. An additional boulder on the lower moraine returned an exposure age of 8.6 ± 0.9 ka, which likely reflects post-depositional exhumation, surface erosion or boulder instability.

In turn, the oldest exposure ages from Keskadale, calculated using a globally-calibrated production rate, suggest that the last glacier that occupied this cirque retreated during the Younger Dryas. However, the external errors associated with these ages do not preclude the possibility that these surfaces were exposed earlier, within or prior to the Younger Dryas. Furthermore, if locally-calibrated and lower production rates from Scotland are applied (~ 3.95

atoms $\text{g}^{-1} \text{yr}^{-1}$; Fabel *et al.* 2012; Putnam *et al.* 2019) then the exposure ages are older by $\sim 8\%$ (Table 2); a change which is sufficient to support glacier retreat at prior to the Allerød/Younger Dryas boundary (~ 12.9 ka). Uncertainty introduced by production rate variation is compounded by the possibility of nuclide inheritance, particularly for bedrock sample PHSITE 6. Ultimately, the small sample size of ^{10}Be ages, in combination with production and erosion rate uncertainty as well as geomorphological processes (e.g.

nuclide inheritance, boulder exhumation), prevents reliable sub-millennial estimation of moraine age.

Despite this, undated moraines are present inside of the higher cirque threshold (Fig. 1) and due to their stratigraphic position, must relate to a later glacial stage. However, how long a glacier occupied this site at High Hole after the retreat of the larger cirque glacier is unknown. In addition, it is unclear as to whether these upper moraines represent a re-advance or a standstill. The moraines within

Table 3. Calibrated relative surface exposure ages derived from Schmidt hammer exposure dating (SHED). Reported ages (sorted in age descending order) are calculated using the mean of 30 R-values from individual glacial boulders and interpolated based on a ^{10}Be -SH calibration curve made available at <http://shed.earth>. To ensure consistency with the results of ^{10}Be , the ^{10}Be ages which underpin this calibration curve ($n = 65$) were calculated using the Lm scaling, assuming 0 mm ka^{-1} erosion and using a range of production rates. These include the default global production rate used in the Cronus-Earth 3.0 calculator (Borchers *et al.* 2015), in addition to local production rates from Glen Roy (GR PR; Small and Fabel, 2015), Loch Lomond (LL PR; Fabel *et al.*, 2012) and Rannoch Moor (RM PR; Putnam *et al.*, 2019). SEM = Standard Error of the Mean.

Sample name	Latitude (°)	Longitude (°)	Elevation (m)	Mean SH	± SEM	Global PR	± 1σ	GR PR	± 1σ	LL PR	± 1σ	RM PR	± 1σ
LC-20	54.53257	-3.29951	490	45.17	0.70	11.58	1.33	11.59	1.33	12.18	1.37	12.31	1.38
LC-30	54.53728	-3.30195	394	45.91	0.69	11.19	1.33	11.19	1.33	11.76	1.37	11.88	1.38
LC-18	54.53230	-3.29966	496	46.07	0.54	11.10	1.33	11.11	1.33	11.67	1.37	11.79	1.38
LC-13	54.53201	-3.29947	507	46.17	0.52	11.04	1.33	11.05	1.33	11.61	1.37	11.73	1.38
LC-15	54.53219	-3.29953	501	46.37	0.65	10.93	1.33	10.94	1.33	11.49	1.37	11.62	1.38
LC-29	54.53723	-3.30180	391	46.62	0.71	10.80	1.33	10.81	1.33	11.35	1.37	11.47	1.38
LC-26	54.53665	-3.30238	408	46.63	0.61	10.80	1.33	10.80	1.33	11.35	1.37	11.47	1.38
LC-14	54.53206	-3.29944	507	46.75	0.72	10.73	1.33	10.73	1.33	11.28	1.37	11.40	1.38
LC-07	54.53037	-3.29853	535	46.85	0.69	10.68	1.33	10.68	1.33	11.23	1.37	11.34	1.38
LC-01	54.53032	-3.29826	542	47.13	0.70	10.52	1.33	10.53	1.33	11.07	1.37	11.18	1.38
LC-28	54.53696	-3.30183	395	47.30	0.63	10.43	1.33	10.44	1.33	10.97	1.37	11.08	1.39
LC-17	54.53228	-3.29975	496	47.45	0.60	10.35	1.33	10.36	1.33	10.88	1.37	11.00	1.39
LC-25	54.53622	-3.30187	395	47.51	0.63	10.32	1.33	10.33	1.33	10.85	1.38	10.96	1.39
LC-21	54.53296	-3.29937	473	47.63	0.60	10.25	1.33	10.26	1.33	10.78	1.38	10.90	1.39
LC-24	54.53621	-3.30156	396	47.72	0.59	10.20	1.33	10.21	1.33	10.73	1.38	10.84	1.39
LC-09	54.53061	-3.29869	525	47.79	0.70	10.17	1.33	10.17	1.33	10.69	1.38	10.80	1.39
LC-23	54.53364	-3.29973	462	47.93	0.61	10.09	1.33	10.09	1.33	10.61	1.38	10.72	1.39
LC-10	54.53070	-3.29860	526	48.01	0.62	10.05	1.33	10.05	1.33	10.57	1.38	10.68	1.39
LC-12	54.53197	-3.29885	508	48.21	0.54	9.94	1.33	9.94	1.33	10.45	1.38	10.56	1.39
LC-22	54.53306	-3.29954	471	48.28	0.61	9.90	1.33	9.91	1.33	10.41	1.38	10.52	1.39
LC-05	54.53052	-3.29833	531	48.47	0.77	9.80	1.33	9.80	1.33	10.30	1.38	10.41	1.39
LC-02	54.53044	-3.29833	536	48.48	0.72	9.79	1.33	9.80	1.33	10.30	1.38	10.41	1.39
LC-27	54.53670	-3.30236	403	48.61	0.57	9.72	1.33	9.73	1.33	10.22	1.38	10.33	1.39
LC-19	54.53246	-3.29977	491	48.72	0.57	9.66	1.34	9.67	1.33	10.16	1.38	10.27	1.39
LC-11	54.53205	-3.29857	505	48.79	0.57	9.62	1.34	9.63	1.33	10.12	1.38	10.22	1.39
LC-03	54.53049	-3.29822	535	48.93	0.62	9.55	1.34	9.55	1.33	10.04	1.38	10.14	1.39
LC-08	54.53035	-3.29841	537	48.97	0.70	9.53	1.34	9.53	1.33	10.02	1.38	10.13	1.39
LC-06	54.53056	-3.29839	533	49.03	0.60	9.50	1.34	9.50	1.33	9.99	1.38	10.09	1.39
LC-16	54.53221	-3.29960	500	49.03	0.71	9.50	1.34	9.50	1.33	9.99	1.38	10.09	1.39
LC-04	54.53049	-3.29818	536	49.05	0.61	9.48	1.34	9.49	1.33	9.97	1.38	10.08	1.39

High Hole are small and subdued (1–2 m high) suggesting limited erosion of the upper basin. In addition, the distance of the sediment ridges and mounds from the headwall is ~100 m (Fig. 1) and it is likely that this feature was marginal between a niche glacier and a snowpatch (cf. Ballantyne and Benn 1994). At its largest, the High Hole ice/snow feature could have covered an area of just 6–7 hectares (0.06–0.07 km²), although this is still larger than some small glaciers that exist today in southern Europe (e.g. Hughes 2007).

Wider context

It is forty years since Sissons (1980) identified 64 sites occupied by Younger Dryas glaciers in the English Lake District. The most significant challenge to Sisson's ideas has been the reinterpretation of the geomorphological evidence at some sites as evidence of large plateau icefields rather than smaller discrete glaciers (e.g. McDougall 2001; 2013; Brown *et al.* 2013). Nevertheless, the established view is that the last glaciers of the Lake District re-advanced during the Younger Dryas. However, there is very little geochronological evidence that directly tests this assumption.

The first cosmogenic exposure ages for the Lake District were reported by Ballantyne *et al.* (2009). In this paper, ³⁶Cl ages were reported from two boulder samples from a small cirque west of Scafell Pike that had previously been identified as a Younger Dryas site by Sissons (1979; 1980). However, in Ballantyne *et al.* (2009), only one ³⁶Cl age fell within the Younger Dryas (12.5 ± 0.8 ka) and the other age was significantly older (35.1 ± 2.3 ka) (these ages have not been recalibrated and will be subject to change depending on choice of production rate). More consistent results were obtained by Hughes *et al.* (2012) who dated a moraine boulder and the cirque threshold at Keskadale, which is the focus of this new paper. These preliminary ages supported a Younger Dryas origin and, in combination with geomorphological and sedimentary analysis, appeared to support two clear phases of glaciation during the early and late Younger Dryas. However, re-analysis of these data raises questions about the ages. Wilson *et al.* (2013) attempted to provide a more comprehensive analysis of the extent and retreat history of Younger Dryas glaciers based on ¹⁰Be and ³⁶Cl ages from glacial boulders at the margins of and within the limits of former valley glaciers. However, the results proved far from conclusive as many ³⁶Cl ages were older than the Younger Dryas and many predated the LGM. These anomalous ages were interpreted to reflect bias introduced by nuclide inheritance, in part due to the resistance of Borrowdale Volcanic Group lithologies to glacial erosion, and also potentially production of ³⁶Cl deep below

rock surfaces (see discussion in Wilson *et al.* 2013). Similarly, one ¹⁰Be sample from Watendlath (WAT-02), located outside of the Sissons (1979; 1980) proposed Younger Dryas limit, but within the limit proposed by McDougall (2001), returns an exposure age (Lm, 0 mm ka⁻¹ erosion) which ranges between 14.6 ± 1.3 ka and 15.5 ± 0.9 ka depending on production rate. This predates the Younger Dryas but is much closer than most ³⁶Cl samples to the hypothesized age of glaciation. The most recent paper utilising cosmogenic exposure dating on Lake District moraines is that by Wilson *et al.* (2018) where ¹⁰Be analyses were used to constrain the timing of moraine deposition in the Duddon valley to 15.0–16.0 ka using a globally-calibrated production rate, or 15.9–17.0 ka using a locally-calibrated production rate (Lm, 0 mm ka⁻¹ erosion, Putnam *et al.* 2019). However, no cosmogenic exposure ages have been published from hypothesized Younger Dryas ice limits in the Lake District since Wilson *et al.* (2013) and the timing of the last phases of local glaciation remains unclear.

Understanding the extent, magnitude and rapidity of ice demise during the Late-glacial interval is all the more pressing given the debate in Scotland regarding the relative size of Allerød and Younger Dryas glaciers (e.g. Ballantyne and Stone 2012; Bromley *et al.* 2014, 2016, 2018; Small and Fabel 2016; Peacock and Rose 2017; Lowe *et al.* 2019). This, in combination with inconclusive evidence from the Lake District, means that there are now doubts about the age of the moraines ascribed to the Younger Dryas by authors such as Sissons (1979; 1980). Furthermore, moraines beyond those ascribed to the Younger Dryas by Sissons (1980) have been associated with outlet glaciers of larger configurations of Younger Dryas icefields (e.g. McDougall 2001). Many such moraines exist, such as the Rosthwaite moraine (Wilson 1977). The timing of this outer glacial limit versus the inner glacial limit, both of which have previously been hypothesized to correlate with the Younger Dryas glaciation, now needs testing further.

This paper contributes to this debate by applying SHED to moraines ascribed to the Younger Dryas by Sissons (1980) at Ling Comb in the Buttermere Fells. The bedrock lithology of this area is formed in granite of the Ennerdale Intrusion so is likely suitable for SHED (Tomkins *et al.* 2016). However, given that this lithology has not previously been tested, we cannot exclude the possibility that enhanced or suppressed weathering of these rock surfaces, in part due to lithological variation (e.g. surface texture, mineralogical contact), may have introduced bias to the associated calibrated relative exposure ages. While further analysis using ¹⁰Be will be required to assess this, the available data support the hypothesis that ice occupied this cirque during the Younger

Dryas. Deglaciation is constrained conservatively to between 11.6 ± 1.3 ka and 12.3 ± 1.4 ka; a broad range which reflects uncertainty introduced by lithology (e.g. potential variation in weathering rate), degradation of the moraine surfaces (Hallet and Putkonen 1994) and variation between global and locally-calibrated production rates. However, as with the ^{10}Be chronology from Keskadale, these data do not refute an earlier age for deglaciation, and is inconclusive with regards to the extent of ice during the preceding Allerød.

Future work requires hypothesised Younger Dryas moraines to be dated using a larger sample size of ^{10}Be analyses. This may be preferable over ^{36}Cl for this region given the problems encountered by Wilson *et al.* (2013). Alternatively, SHED offers a rapid and cost-effective method to test the age of cirque moraines in the Lake District, but further work is necessary to assess the significance of lithological variability in rock surface weathering rate. However, if the results of this study are representative of the wider Lake District, then it is likely that both ^{10}Be exposure dating and SHED will prove inconclusive for separating out Allerød *versus* Younger Dryas moraines and for constraining the timing of glacial events during the abrupt climatic shifts which characterise the Late-glacial. One possibility for further work that may improve geochronological precision for deciphering glacier fluctuations at sub-millennial and centennial scales in the Late-glacial may be to utilize high-resolution ^{14}C and sedimentological analyses from proglacial lakes beyond but proximal to moraine limits. This approach has been used effectively at Lake Kråkenes in Norway to investigate rapid changes in Younger Dryas glacier behavior (Bakke *et al.* 2009). A similar approach, focused on sites with suitable moraine and lake records, may enable more precise

separation of glacial stages and a more robust understanding of the glaciological response to climate during the Late-glacial.

Conclusions

Recalibration and refinement of ^{10}Be ages from Keskadale, in combination with calibrated relative exposure ages from moraine boulders in Ling Comb, appear consistent with the presence of Younger Dryas ice in the cirques of the English Lake District. However, the exposure age data (both ^{10}Be and SHED) are sensitive to the choice of production rate; a situation which precludes sub-millennial estimation of moraine age. Moreover, this uncertainty is compounded by post-depositional modification of moraines (e.g. boulder exhumation, erosion, toppling), nuclide inheritance and lithological variation in rock surface weathering rate. These issues are hampered by a small sample size for ^{10}Be , with ages of 12.3 ± 1.1 and 8.6 ± 0.9 ka from the lower cirque moraine and an age of 12.5 ± 1.0 ka from the higher cirque threshold. Local production rates from Scotland increase these ages by up to $\sim 8\%$ and shift the oldest exposure ages to the Allerød/Younger Dryas boundary. Despite this uncertainty, undated moraines higher in the Keskadale cirque may represent later Younger Dryas glacier advance or stabilisation. Moreover, at Ling Comb below Red Pike, ~ 4 km from Keskadale, SHED ages from granitic boulder surfaces support a Younger Dryas age for a series of cirque moraines at this site. Overall, the ^{10}Be and SHED data are consistent with final cirque deglaciation during the Younger Dryas or early Holocene, although further research is necessary to improve geochronological precision for understanding glacier fluctuations during the Late-glacial.

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