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Research Article

Schmidt Hammer exposure-age dating of glacial landforms in the Cairngorm Mountains, Scotland

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ABSTRACT

This study investigates the response of glaciers in the Cairngorm Mountains, Scotland, during the Last Glacial–Interglacial Transition (LGIT). A Schmidt Hammer was used to document the deglacial history of the area using an established terrestrial cosmogenic nuclide dating (TCND) based age-calibration curve. Two glacial landforms delimiting the extent of former glaciers in Glen Avon and Coire t-Sneachda were confirmed to be of Loch Lomond (Younger Dryas) Stadial age, however, no significant difference in mean exposure-age between these sites was found. The use of the age-calibration curve indicated that parts of the study area were deglaciated before ~15 ka. Despite sources of uncertainty when using this approach, this study highlights the value of the Schmidt Hammer for effectively deriving preliminary exposure ages of glacial landforms in the Cairngorm Mountains. The careful generation of preliminary exposure-ages across other sites in the study area using this method is warranted, especially where the timing and sequence of deglaciation is less well understood.

Keywords: Deglaciation Dynamics; Geochronology; Schmidt Hammer; Glacier Change; Cairngorm Mountains; Younger Dryas.

[PRE-PRINT]

Introduction

The use of Schmidt Hammers in geomorphological research is longstanding (GOUDIE, 2006), with the instrument valued for its effectiveness as a relative dating tool in glacial environments (MCCARROLL, 1989; MCCARROLL & NESJE, 1993; HUBBARD & GLASSER, 2005). The technique has been used to assess the degree of surface weathering and test the rock strength of landforms (MCCARROLL, 1991; MCCARROLL and NESJE, 1993; EVANS, *et al*., 1999; SHAKESBY *et al*., 2006). The use of age calibration curves alongside the Schmidt Hammer allow for the conversion of the *R*-values produced by the device into age estimates (e.g., WINKLER, 2009). TOMKINS *et al*. (2018a) produced a Schmidt Hammer age-calibration curve constructed using 54 granite surfaces previously constrained using terrestrial cosmogenic nuclide dating (TCND) undertaken across the British Isles. The TCN dataset includes samples from local sites in the Cairngorm Mountains, from Glen Einich and Coire an Lochain as originally reported in EVEREST & KUBIK (2005) and KIRKBRIDE *et al*. (2014) respectively. The work of TOMKINS *et al*. (2018a) highlights that the use of age-calibration curves can elucidate the timing of deglaciation during the Lateglacial and Loch Lomond (Younger Dryas) Stadial by providing preliminary ages for glacial landforms in the British Isles. Since the publication of the initial (TOMKINS *et al*., 2016) and revised age-calibration curve (TOMKINS *et al*., 2018a; TOMKINS *et al*., 2022) Schmidt Hammer-derived deglaciation chronologies have been published for sites across the British Isles including the Wicklow Mountains (TOMKINS *et al*., 2018b), Lake District (HUGHES *et al*., 2019), Mourne Mountains (BARR *et al*., 2017; WILSON *et al*., 2019a), and various other sites across Ireland (WILSON *et al*., 2019a).

Across Scandinavia this technique has recently been used on resistant lithologies suitable for age-calibration curve development to assess blockfields (MARR *et al*., 2018), rock avalanches (WILSON *et al*., 2019b), snow avalanche boulder fans (MATTHEWS *et al*., 2020) and other periglacial landforms (MATTHEWS *et al*., 2018; MARR *et al*., 2019; WINKLER *et al*., 2020). Furthermore, a new age-calibration curve has been made available for the Pyrenees, allowing ice-extent from the Würmian maximum through to the Holocene to be delimited (TOMKINS *et al*. 2018c).

The value and potential of the Schmidt Hammer in geomorphological and geochronological studies of granitic landforms and landforms composed of rocks with similar resistance to weathering is therefore well evidenced. Schmidt Hammer derived deglacial chronologies advance understanding of glacier change, thus aid our ability to robustly forecast future glacier change and the loss of contemporary glaciers and ice-sheets (McCarroll, 2015). Whilst an age calibration curve has been established in the British Isles, including using data points from the Cairngorm Mountains (Tomkins *et al.*, 2018a), this technique has not been used to provide preliminary ages for deglaciation in the area. Therefore, the aim of this study is to report on the sequence and timing of deglaciation in the Northern Cairngorms, Scotland, using the established age-calibration curve available for the British Isles.

Study Site

The Cairngorm Mountains (57° 05′N, 3° 40′ W) are characterised by a large plateau area composed of granite. The granite pluton – intruded at ~425 Ma (Hall & Gillespie, 2017) – has been subsequently modified by Quaternary glaciations, with phases inferred from ~2.6 Ma onwards involving situations where the Cairngorms periodically hosted larger ice-masses and more topographically restricted mountain glaciers (Hall *et al.*, 2013). The term 'selective linear erosion' has been applied to describe the glacial modification of the Cairngorm massif (Rhea, 1998), with studies identifying the potential presence of wet-based conditions promoting erosion of pre-glacial valleys (Hall & Glasser, 2003) alongside the potential for glacial protection offered by cold-based ice on interfluves (Glasser, 1995). Periglacial conditions have promoted tor development, and at certain locations these tors have been modified by glacial erosion (Phillips *et al.*, 2006). The Cairngorm Mountains served as an ice-dispersal centre during Marine Isotope Stage 2 (the Last Glacial Maximum) (Ballantyne *et al.*, 2009). During deglaciation the decoupling of the 'local' Cairngorm ice-dome and Strath Spey lobe — a ~60 km outlet glacier flowing across the northern front of the massif (Brazier *et al.*, 1998; Sugden & Hall, 2020) — has been constrained, with recalibrated dates from Hall *et al.* (2016) providing evidence that deglaciation was punctuated by readvance of the Strath Spey glacier at 15.8 ± 0.8 ka (Ballantyne & Small, 2019). This readvance is suggested to be linked to an increase in palaeo-precipitation following the demise of marine-terminating sectors of the British-Irish Ice Sheet (HALL *et al.*, 2016). The pattern of ice-sheet deglaciation is also supported by modelling conducted by HUBBARD *et al.* (2008) where an independent ice-dispersal centre at ~15.7 ka over the Cairngorm Mountains has been hypothesised. However, debates currently center around: (i) the sequence and timing of deglaciation; and (ii) the extent and style of Loch Lomond (Younger Dryas) Stadial glaciation in the Cairngorm mountains (STANDELL, 2014).

The northern Corries area hosts boulder-rich moraines and boulder limits indicative of restricted cirque-based glaciers (Figure 1 & 2). Here, boulder ridges have been inferred to delimit the Younger Dryas limit in Coire an t-Sneachda and Coire an Lochain (SISSONS, 1979; BENNETT & GLASSER, 1996). The boulder ridges contrast the larger hummocky moraine assemblages associated with active and oscillatory recession of Younger Dryas glaciers (LUKAS, 2005; BENN & LUKAS, 2006; BICKERDIKE *et al.*, 2018a), or more controversially, moraine formation by englacial thrusting at certain sites the British uplands (HAMBREY *et al.*, 1997; GRAHAM & MIDGLEY, 2000; GRAHAM *et al.*, 2007) and possibly select sites in the Cairngorm Mountains (BENNETT, 1996). SISSONS (1979) recognized likely sites of Younger Dryas glaciation in Coire an Lochain and Coire an t-Sneachda (Figure 1). Both glaciers had a predominantly northernly aspect and estimated equilibrium line altitudes (ELAs) of 1004 m and 1008 m respectively and a limited spatial extent (0.31 km^2 and 0.26 km^2 respectively) (SISSONS, 1979).

Whilst geochronological data on Coire an t-Sneachda are unavailable, terrestrial cosmogenic nuclide dating has been conducted at the adjacent Coire an Lochain highlighting the occupation by glacier-ice during the Younger Dryas (KIRKBRIDE *et al.*, 2014). In contrast to these north-facing corries, SISSONS (1979) suggested the Glen Avon Loch Lomond (Younger Dryas) Stadial glacier occupied an area of 1.15 km^2 with an ELA of 903 m. These reconstructions of spatially restricted glaciers contrast with the considerably larger, but topographically constrained glaciers reconstructed in Glen Gleusachan and Garbh Choire (BENNETT & GLASSER, 1991). More recently, studies across the British Isles have indicated that Younger Dryas glaciation in some locations involved plateau icefields feeding outlet glaciers (e.g., MCDOUGALL, 2001; MCDOUGALL, 2013;

BICKERDIKE *et al.*, 2018a), challenging earlier perspectives of topographically constrained 'alpine styles' of glaciation (e.g. SISSONS, 1980) and this has indeed been the subject of research in the Cairngorm Mountains (STANDELL, 2014). It should be noted that recent work by BICKERDIKE *et al.* (2018) provides a comprehensive review of the Younger Dryas event in the Cairngorm Mountains and East-Grampians, alongside other upland areas in the British Isles. Of particular note is the suggestion that relative aridity was experienced by some upland sites to the east of Scotland during the Younger Dryas (e.g., REA *et al.* 2020) associated with the West Highland Younger Dryas ice-cap and other ice-fields 'scavenging' precipitation from air-masses (GOLLEDGE *et al.* 2008; CHANDLER *et al.*, 2019).

Despite considerable research effort (e.g., EVEREST & KUBIK, 2006; PHILLIPS *et al.*, 2006; BALLANTYNE *et al.*, 2009; KIRKBRIDE *et al.*, 2014; STANDELL, 2014; HALL *et al.*, 2016) the precise sequence and timing of deglaciation at some sites is unclear. This is summarised by BICKERDIKE *et al.* (2018b: 1) who argue that "robust dates are relatively scarce, making it difficult to confidently identify the limits of LLS [Younger Dryas] glaciers and assess their synchroneity". Further work is therefore warranted to support modelling of the Younger Dryas event in this area by providing clear separation of younger moraines from older recessional sequences. Therefore, the principal aim of this contribution is to enhance understanding of the deglacial chronology of the Cairngorms using the Schmidt Hammer age-calibration curve established by TOMKINS *et al.* (2018a). This work is timely in that it follows independent validation highlighting the robustness of the Schmidt Hammer age-calibration curve for the British Isles (WILSON *et al.*, 2019a), reviews of the last Scottish ice-sheet (BALLANTYNE & SMALL, 2019) and Younger Dryas event in the British Isles (BICKERDIKE *et al.*, 2016; 2018a, b) and a recent study by Carter-Champion *et al.* (2022) investigating lake sediments from a site in the eastern Cairngorm Mountains.

Methods

This study was conducted on eight glacial landforms (hereafter 'site') in the Cairngorm Mountains, Scotland (Figure 1). At each site glacially-transported boulders and bedrock surfaces were measured using a

Schmidt Hammer – a device originally designed to test intact concrete hardness in a non-destructive manner (GOUDIE, 2006; BUYUKSAGIS and GOKTAN, 2007). The Schmidt Hammer releases a spring-loaded mass against a rock surface, resulting in the recoil of the plunger mechanism. The plunger rebounds, yielding an *R*-value that reflects the surface hardness of the sample without damaging the surface (BASU & AYDIN, 2004). Rock surface compressive strength is related to the degree of weathering where *R*-values decline under longer exposure to weathering processes, therefore providing relative dates for rock surfaces exposed to atmospheric conditions (MATTHEWS & SHAKESBY, 1984; MCCARROLL, 1991). Study design and instrument error is known to play a significant role in determining *R*-values. Therefore, care is needed whilst operating the device to maximise the age-related signal and minimise non-age-related noise (BASU & AYDIN, 2004; SHAKESBY *et al*., 2006; DEMIRDAG *et al*., 2009). A recent overview of this approach can be found in DAVIES (2020). Schmidt Hammer surveys must be conducted with care as factors including surface roughness and moisture can influence the resulting *R*-values. A range of sampling methods have been employed by geomorphologists when using the Schmidt Hammer. For this work, the sampling procedure used the approach of TOMKINS *et al*. (2016; 2018a,b), using a mechanical N-type Schmidt hammer to enable comparison with the existing age-calibration curve for the British Isles. TOMKINS *et al*. (2018a) demonstrate that mean *R*-value can be used as a predictor for exposure-age using a linear regression model ($R^2 = .94$, $p < .01$). Prior to the field survey, the functioning of the hammer was checked against a standard Proceq testing anvil after SHAKESBY *et al*. (2006), then subsequently subjected to an in-the-field assessment. The data were collected using established sampling procedures (e.g., TOMKINS *et al*. 2018a, b), with sampling undertaken on boulders and bedrock, avoiding cracks, and normal to the target surface (HUBBARD & GLASSER, 2005). Conversion of *R*-values was initially achieved using the equation presented in Tomkins *et al*. (2018a), where *x* is the mean *R*-value for a surface and *y* is the exposure age:

$$y = -0.5678x + 37.692$$

This version of the age-calibration curve is underpinned by terrestrial cosmogenic nuclide dates calculated using the Loch Lomond Production Rate (LLPR) (FABEL *et al*., 2012; 4.02 ± 0.18 atoms $g^{-1} a^{-1}$) where 0 mm ka^{-1} erosion is assumed (TOMKINS *et al*., 2018a). An updated version of this age-calibration curve, now underpinned by 65 TCN dated surfaces, provided additional age estimates (see TOMKINS *et al*. 2022 for details) permitting the calculation of exposure-ages using the Loch Lomond production rate (LLPR; 3.99 ± 0.06 atoms g^{-1} a^{-1}; FABEL et al., 2012), the Glen Roy production rate (GRPR; 4.31 ± 0.21 atoms g^{-1} a^{-1}; SMALL AND FABEL, 2015), alongside the 'Balco v3' and 'CRONUS v2' globally calibrated ^{10}Be production rates (BALCO *et al*., 2008; MARRENO *et al*., 2016). Dates reported in the text are derived using the Tomkins *et al*. (2018a) version of the age-calibration curve and data derived using a rate of production rates, including values derived using an updated version of the age-calibration curve are presented in Table 1. Erosion rates of 1 mm ka^{-1} (e.g., Wilson *et al*., 2019c) or 0 mm ka^{-1} (e.g., Hughes *et al*., 2019) are assumed in some TCND studies in the British Isles and Tomkins *et al*. (2018a) highlight uncertainty in the local rate of postglacial surface erosion. André (2002) report low average postglacial surface erosion rates on abraded crystalline rocks of between 0.1 and 0.3 mm ka^{-1} highlighting that surface erosion may be more limited on the sampled surfaces reported in this study. Erosion rates of 1 mm ka^{-1} used to correct dated granite surfaces have been reported to result in TCN age estimates that are ~1% older than those calculated assuming no surface erosion (e.g., Ballantyne *et al*. 2013; Roberts *et al*., 2020). It is therefore important to note that the Schmidt Hammer approach used here produces minimum limiting ages for deglaciation in the study area (Tomkins *et al*., 2022).

To provide additional insight into the Last-glacial to Interglacial transition in the Cairngorm Mountains sampling was concentrated in the Glen More, Northern Corries and Loch Avon areas (Figure 1). This constrained the timing of glacier change at currently undated sites. The study included the sampling of: (i) ten exposed glacially abraded bedrock surfaces located on the Cairngorm plateau (PS; see geomorphological mapping by GLASSER, 1996); (ii) the boulder limit within Coire an t-Sneachda (CS; Sissons, 1979); (iii) the discrete debris accumulation on the east side of Coire an t-Sneachda (DDA; SISSONS, 1979; BRAZIER *et al*. 1996; JARMAN *et al*., 2013);

(iv) boulders within the limit of the Strath Spey glacier on the northern flank of the Granite massif (SP; HALL *et al*., 2016); (v) a degraded candidate moraine thought to pre-date the Younger Dryas in Coire an Lochain (CM; STANDELL, 2014); (vi) exposed glacially eroded bedrock near Strath Nethy (SN); and (vii) the moraines at the head (UA) and outlet of Loch Avon (LA). For the Loch Avon sites, the former is thought to demarcate either a topographically constrained smaller ice-mass originating from Hell's Lum Crag (SISSONS, 1979) or the terminus of outlet glaciers originating from a larger ice-mass and plateau icefield sourced from Coire Etchachan and the flanks of Beinn MacDuibh and other plateau surfaces above Hell's Lum Crag (STANDELL, 2014). The locations and imagery of the sampled sites can be seen in Figure 2. Each surface/boulder was subject to thirty impacts by the Schmidt Hammer device across a ~50 by 50 cm sample area. For the two bedrock sites reported here, a series of ~50 by 50 cm quadrats were used to obtain each sample.

Field checks were completed using a local calibration boulder located near Coire an t-Sneachda. Here, *R*-values obtained before ($\bar{x}$ = 38.43, SEM = 1.32) and after the field survey ($\bar{x}$ = 37.73, SEM = 0.95) were found to not significantly differ ($t_{(58)} = 4.431$, $p > .05$). Linear adjustment for instrument drift over the period of operation was therefore not applied. Values were adjusted to match existing data points collected by TOMKINS *et al*. (2018a). This was achieved using surfaces in Coire an Lochain following guidance from DORTCH *et al*. (2016). *R*-values for this boulder (LCO#3 in KIRKBRIDE *et al*., 2014) are available in TOMKINS *et al*. (2018a; supplementary materials) and appear on the published age-calibration curve. The correction factor (CF) was generated as follows:

$$CF = (Specified\ value) / (Average\ of\ 30\ readings)$$

Whilst DORTCH *et al*. (2016) and TOMKINS *et al*. (2018a) advocate the use of the University of Manchester's Doddington Sandstone boulder, in part to ensure the same surfaces are compared for the purpose of age calibration, here the LCO#3 boulder was located using a handheld Global Navigation Satellite System, with sample removal by previous workers evident on the boulder surface. The N-type hammer used in this study produced an *R*-value of 46.43 ± 1.52 (Mean ± Standard Error of the Mean, *n* = 30) for this boulder. Whilst a correction factor of 1.023 was applied to all Schmidt

Hammer exposure ages reported in this study, it should be noted that the uncertainty in the data reported by TOMKINS *et al*. (2018a; mean *R*-value = 47.52 ± 1.16; *n* = 30) and those derived by this study overlap. The application of this correction factor results in ages that are ~0.35 ka older than if uncorrected for age calibration using established procedures for Schmidt Hammer Dating in the British Isles (DORTCH *et al*., 2016; TOMKINS *et al*., 2018a). The resulting landform exposure-ages are reported alongside the standard deviation (σ) derived from the individual boulder/surface ages calculated from 30 impacts (between 7 and 16 individual ages per landform). To facilitate the interpretation of these data statistical analysis conducted in Minitab® was used to compare the boulder/surface exposure-ages derived from the eight sites. Separation of moraine chronologies was achieved using a one-way ANOVA (e.g., LICCIARDI *et al*., 2011; Corbett *et al*., 2011; Engel *et al*., 2011) and a Tukey procedure for pairwise comparisons and grouping following checks for normality (Kolmogorov-Smirnov) and variance (Bartlett's test).

Results

The *R*-value range for each site varied between 33 and 52 (Figure 3). The highest variability (52) was derived from the discrete debris accumulation found in Coire an t-Sneachda, and the minimum range (33) was derived from boulders found within the former limits of the Strath Spey glacier. Three samples had negatively skewed *R*-values, and five had slightly positively skewed distributions (Figure 3).

Following adjustment, the findings provided age constraint on previously undated granite surfaces derived from 2520 individual *R*-values. The statistical treatment of these data can obscure within landform variability, with individual surface ages (derived from 30 *R*-values from a single surface) obtained from a landform varying. Eight individual boulder ages (each derived from 30 *R*-values sampled from a single surface) obtained from the Strath Spey glacier margin yielded the highest consistency with Schmidt Hammer individual boulder ages having a range of 2.36 ka. Critically, three of the eight sites reported here had single boulder/surface

Schmidt Hammer ages (derived from 30 impacts) ranging by more than 4 ka. When *R*-values derived from the sampled surfaces were converted into landform ages (between 7 and 16 ages per landform), mean landform exposure-ages were found to span the last glacial to interglacial transition ranging from 16.70 ± 1.69 ka to 11.35 ± 1.16 (Table 1).

Landform ages derived from exposed bedrock on the Cairngorm plateau (in an area previously recognised to have undergone glacial abrasion) yielded an age indicating deglaciation before 15.55 ± 1.49 ka (n = 10). Boulder deposits found at sites in front of the inferred Loch Lomond (Younger Dryas) stadial glacial limits produced ages of, 15.62 ± 1.77 (n = 8) (DDA), 15.50 ± 0.90 (n = 8) (LA), and 14.50 ± 0.98 ka (n = 10) (CM). A bouldery moraine in Coire an t-Sneachda (CS) and the moraine assemblage located at the head of Loch Avon (UA) produced average ages of 11.35 ± 1.16 (n = 10) and 12.07 ± 1.04 ka (n = 16) respectively. These sites were previously hypothesised to be Loch Lomond (Younger Dryas) Stadial in age and produced values broadly coeval with the event. Boulder ages were, however, found to not differ between these sites ($p > .05$) but differed significantly to all other samples ($p < .05$), providing further evidence to support the Loch Lomond (Younger Dryas) origin of these landforms (Table 1).

Discussion

Late Devensian deglaciation of the Northern Cairngorms

Schmidt Hammer-derived ages obtained from the boulder and bedrock surfaces sampled in this study accord with the established view of deglaciation. Samples from exposed bedrock on the plateau (~1200 m above ordnance datum) in proximity to Stob Coire an t-Sneachda indicate that high-ground in this area was deglaciated before 15.84 ± 1.56 ka. Deglaciation of the Cairngorm plateau therefore appears to be broadly coeval with the recession of the Strath Spey glacier on the northern flank of the massif (Hall *et al*., 2016; Ballantyne & Small, 2019). Schmidt Hammer exposure ages place the timing of the deglaciation of the former margin of this ice-mass before 15.69 ± 0.66 ka. The Schmidt Hammer dates provide preliminary evidence for high-level valley side exposure before 16.70 ± 1.69, although further work is recommended to confirm this. Whilst there is some uncertainty in these dates due to the spread of the derived Schmidt Hammer exposure-ages obtained from this surface, the findings support the work of BALLANTYNE & SMALL (2019) who highlight the potential for the early deglaciation of high-ground in the massif, with reference to existing ^{10}Be dating of rock-slope failure deposits in Strath Nethy and erratic boulders found above 1100 m (BALLANTYNE and SMALL, 2019). The exposure of high-ground may have occurred contemporaneously with the readvance and subsequent recession of ice within the Moray-Firth Basin between 17.5 and 16.2 ka (Stage 9 in MERRITT *et al*., 2017) and mountain peaks in other ice-sheet sectors in Scotland are also thought to have been exposed at ~16 ka (Ballantyne and Small, 2019).

The underlying assumptions of the Schmidt Hammer approach used here introduces uncertainty regarding the reliability of any derived exposure-ages (DAVIES, 2020). However, the analysis demonstrates that *R*-values from these sites represent distinct statistical populations (Table 1). The grouping of the eight sites supports the hypothesis that deglaciation of high ground occurred in the east of the Cairngorm Mountains first and prior to removal of ice from other plateau areas. The statistical grouping does not permit the sequence of deglaciation to be distinguished from the readvance of the Strath Spey glacier in Glen More (Group B in Table 1). It should be noted that whilst these inferences are supported by a high number of impacts only a limited number of bedrock surfaces are sampled. This preliminary study therefore signifies that further targeting of these areas may produce further meaningful relative geochronological data. Additional work to confirm this sequence of deglaciation is certainly warranted and existing geomorphological mapping (e.g., GLASSER 1996; STANDELL, 2014) provides a basis for the targeted sampling of exposed glacially abraded bedrock across the Cairngorm Mountains.

Potential moraine 'fragments' at the western end of Loch Avon also provide evidence for the persistence of topographically constrained ice within Glen Avon prior to 15.50 ± 0.90 ka. Field mapping of the glacial geomorphology of this area has identified a series of subtle morainic features (STANDELL, 2014; Figure 2). To date, the timing of glacial recession into Loch Avon has not been explored, and these data provide strong evidence for the persistence of ice in select valleys between ~16 and 15 ka, analogous with emerging findings from other ice-dispersal centres that developed during the demise of the British-Irish Ice Sheet (WILSON *et al*., 2018).

Finally, prominent boulders (*n* = 8) perched on the landform running along the eastern valley axis of Coire an t-Sneachda yielded a mean age of 15.62 ± 1.77 ka. This landform has previously been interpreted as a protalus rampart (SISSONS, 1979), ice marginal moraine (BRAZIER *et al*., 1996), landslide deposit or fluvially modified bedrock-controlled ridge (BALLANTYNE, 1996), and more recently discussed as a potential 'ice-debris landform' (JARMAN *et al*., 2013). Highly variable *R*-values are indicative of the exhumation of some boulders possibly during the Loch Lomond (Younger Dryas) Stadial. A rock-slope failure origin occurring coincidently with the deglaciation of the Cairngorm ice dispersal centre seems plausible (JARMAN *et al*., 2013), and rock-slope failures of this age have been successfully identified elsewhere in the British Isles (BALLANTYNE *et al*., 2013; 2014). Regardless of the mode of emplacement for this landform, the age constraint provided here fits the wider field of evidence for the removal of ice from the Cairngorm Mountains from ~16 to 15 ka (STANDELL, 2014) and accords with existing theory around the demise of this sector of the British-Irish Ice Sheet (HUBBARD *et al*., 2009). The spread of individual surface ages may indicate previous may indicate previous exposure of boulders and boulder exhumation at this site, however excluding the oldest (18.85 ka) and youngest (12.54 ka) boulders from this data only reduces the mean exposure age by >1% (with a standard deviation of 0.63 ka).

Younger Dryas glacial landsystems and recession

Ten granite boulders within the cirque glacial landsystem in Coire an t-Sneachda, and sixteen boulders perched on and embedded within various moraines at the head of Loch Avon constrain a renewed phase of glacier activity linked to the Loch Lomond (Younger Dryas) Stadial. In this study ages of 11.35 ± 1.16 ka (CS) and 12.07 ± 1.04 ka (UA) were calculated from individual boulder ages (*n* = 10 and *n* = 16 respectively). Boulder limits provide convincing geomorphologic evidence that permit the reconstruction of the former dimensions of these glaciers, confirming the maximum extent of these glaciers as suggested by other work (SISSONS, 1979). The ages post-dating the close of this event perhaps hint at: (i) the late deglaciation of certain sites driven by topo-climatic controls (e.g., COLEMAN *et al*., 2009; TOMKINS *et al*., 2018b; BOSTON & LUKAS, 2019); (ii) the possibility of boulder exhumation associated with moraine degradation (HEYMAN *et al*., 2011; CRUMP *et al*., 2017) of Loch Lomond (Younger Dryas) Stadial sites and/or the spalling of boulder surfaces (e.g., BARR *et al*., 2017); or (iii) the persistence of ice towards the close of the Younger Dryas (LOWE *et al*., 2019). Care when lumping and/or splitting moraine chronologies has been advocated (KIRKBRIDE and WINKLER, 2012) and this is especially warranted considering the sources of uncertainty when using this particular geochronological approach. Notably, the mean Schmidt Hammer dates derived from these Loch Lomond (Younger Dryas) sites were not found to differ significantly ($p > .05$), as reflected in the variability of the individual surface ages within each landform sample.

Successful identification of the Loch Lomond (Younger Dryas) Stadial maximum extent at two sites highlights the potential of the technique to further validate existing palaeoglacier reconstructions as summarised in BICKERDIKE *et al*. (2018a). Two scenarios have been proposed for the Cairngorm Moutains: (i) a 'valley-style' reconstruction involving ice sources from the eastern flank of Beinn Macduibh (5.92 km^2); and (ii) a 'plateau-style' reconstruction involving extensive ice-coverage across the Cairngorm plateau (8.38 km^2) (STANDELL, 2014). Critically, both these reconstructions have considerably larger ice-coverage in the Avon area than the 1.15 km^2 topographically constrained Loch Lomond (Younger Dryas) glacier envisaged by SISSONS (1979; Figure 1) and involve contributions from source areas from the north-eastern flanks of Beinn Macduibh. Targeted sampling is likely to reduce ambiguity over the lateral extent of Loch Lomond (Younger Dryas) stadial glaciers and confirm whether ice sourced in Etchachan nourished the Loch Avon glacier.

Wider outlook on Schmidt Hammer Dating in the British Isles

The approach has successfully generated preliminary ages for the Cairngorm Mountains study area and differentiated phases of deglaciation, demonstrating the usefulness of the Schmidt Hammer age-calibration curve detailed in Tomkins *et al*. (2018a; 2022) for deriving exposure ages in the British Isles (WILSON *et al*., 2019a). However, the Schmidt Hammer approach used in this study has been found to not be applicable to all areas across the British Isles (e.g., BARR *et al*., 2017). Uncertainty, as highlighted by the scatter of the derived *R*-values, is driven by instrument error and study design. Uncertainty is further compounded by the impact of inheritance (prior exposure) and post-depositional disturbance resulting in the exhumation of boulders (Matthews and Winkler, 2022). The paraglacial alteration of moraines is well documented in contemporary glacial environments (BALLANTYNE & BENN, 1994; SCHOMAKER, 2008; EVANS, 2009; KIRKBRIDE & WINKLER, 2012; CRUMP *et al*., 2017; TONKIN *et al*. 2017). The study highlights the value of applying this approach to sites that typically would not be optimal (i.e., sites inferred to have undergone moraine degradation) for terrestrial cosmogenic nuclide sample collection (HEYMAN *et al*., 2011).

When combined with geomorphological observations the Schmidt Hammer as a tool can provide insight into glaciological processes, paraglacial landform evolution, and periglacial activity. This is illustrated in this study by the 'candidate moraine' (CM) – a heavily degraded morainic landform found in proximity to Coire an Lochain which was hypothesized – on the basis of moraine morphology – to be influenced by post-depositional processes (STANDELL, 2014). The geochronological work undertaken in this study hints at a prolonged period of geomorphological activity following the recession of ice. A mean-landform age post-dating deglaciation of other sites provides evidence for the post-depositional disturbance of this landform resulting in a degraded moraine morphology, potentially followed by subsequent periglacial disturbance during the Loch Lomond (Younger Dryas) Stadial. The implication of this is that other landforms pre-dating the Loch Lomond (Younger Dryas) Stadial may have been subject to reworking, producing ages post-dating the actual time of deposition, including certain sites reported in this study. Finally, this study highlights that the extensive use of this approach in the Cairngorm Mountains could help elucidate the sequence of glacier recession and provide insight into the associated paraglacial and periglacial degradation of landforms in the British Isles.

Conclusions

1. Schmidt Hammer exposure-ages document deglaciation spanning the last glacial to interglacial transition, with progressive deglaciation of the Cairngorm Mountains occurring between 16.70 ± 1.69 ka and 15.50 ± 0.90 ka.

2. The evidence presented here reflects the persistence of local ice across the Cairngorm Mountains before ~15 ka, with plateau surfaces possibly exposed before 15.55 ± 1.49 ka. This response may be temporally coincident with other wasting sectors of the British-Irish Ice Sheet.

3. Loch Lomond (Younger Dryas) Stadial deglaciation appears to constrain two previously undated sites, confirming the extent of a restricted cirque-based glacier in Coire an t-Sneachda and a larger glacier draining into Glen Avon. Abandonment of Younger Dryas maximum extents at these sites occurred before 12.07 ± 1.04 ka and 11.35 ± 1.16 ka.

4. One site post-dates the other sites potentially due to post-depositional disturbance such as paraglacial degradation or subsequent periglacial disturbance during the Loch Lomond (Younger Dryas) Stadial. The usefulness of this technique for investigating the para- and periglacial disturbance of ice-marginal landforms and other para- and periglacial phenomena is therefore highlighted by this study.

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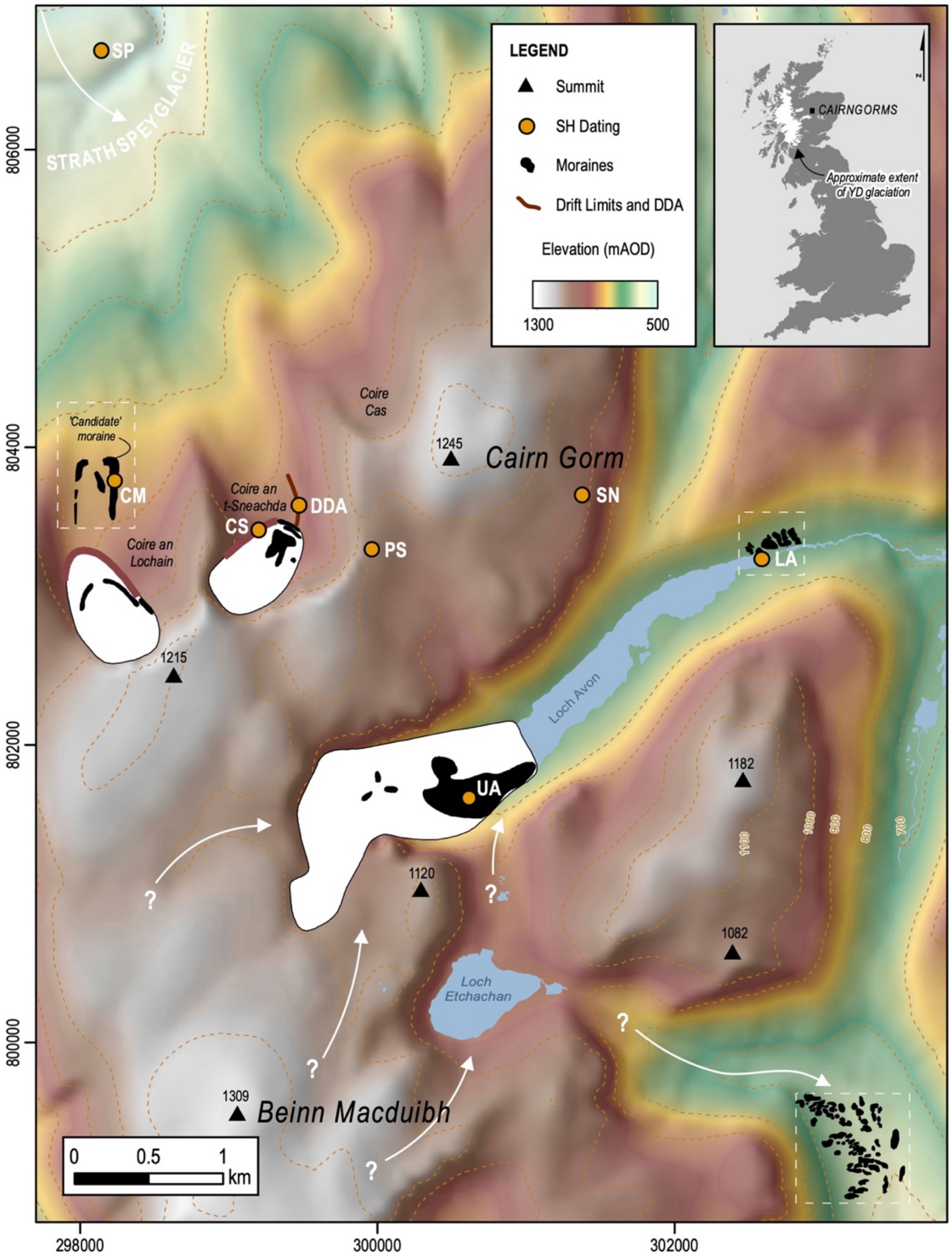

Figure 1. The Cairngorm Plateau and associated palaeoglaciers. The glacier margins and associated landforms are after SISSONS (1979) (as digitised by BICKERDIKE *et al.*, 2016; 2018a). The 'candidate moraine' in Coire an Lochain, moraine detail (dashed boxes) and plateau source areas (white arrows) are derived from the geomorphological mapping presented by STANDELL (2014) and the discrete debris accumulation mapped can be found in JARMAN *et al.* (2013). The Strath Spey glacier is approximately represented after Figure 1 in Hall *et al.* (2016). Crown copyright and database rights [2021] Ordnance Survey (100025252).

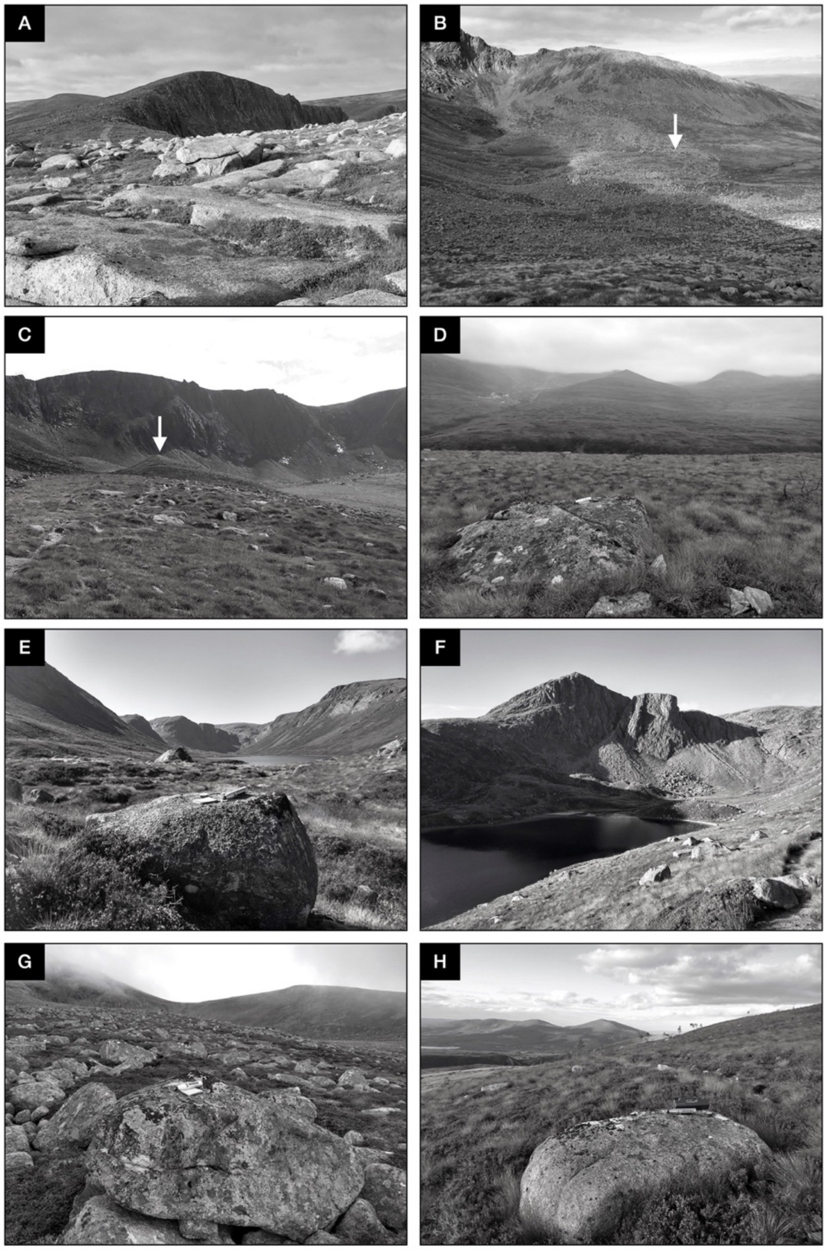

Figure 2. Sampled sites reported in this study. (A) Bedrock surfaces above Coire an t-Sneachda (PS). (B) The boulder-limit in Coire an t-Sneachda (CS). (C) Boulders perched on the discrete debris accumulation (DDA) in Coire an t-Sneachda. (D) Boulders near Glen More inferred to have originated from the Strath Spey glacier (SP). (E) Boulders at the outlet of Loch Avon (LA). (F) Younger Dryas deposits at the head of Loch Avon (UA). (G) A degraded morainic landform in proximity to Coire an Lochain (CM). (H) The local age calibration boulder used to assess instrument degradation over the duration of the survey.

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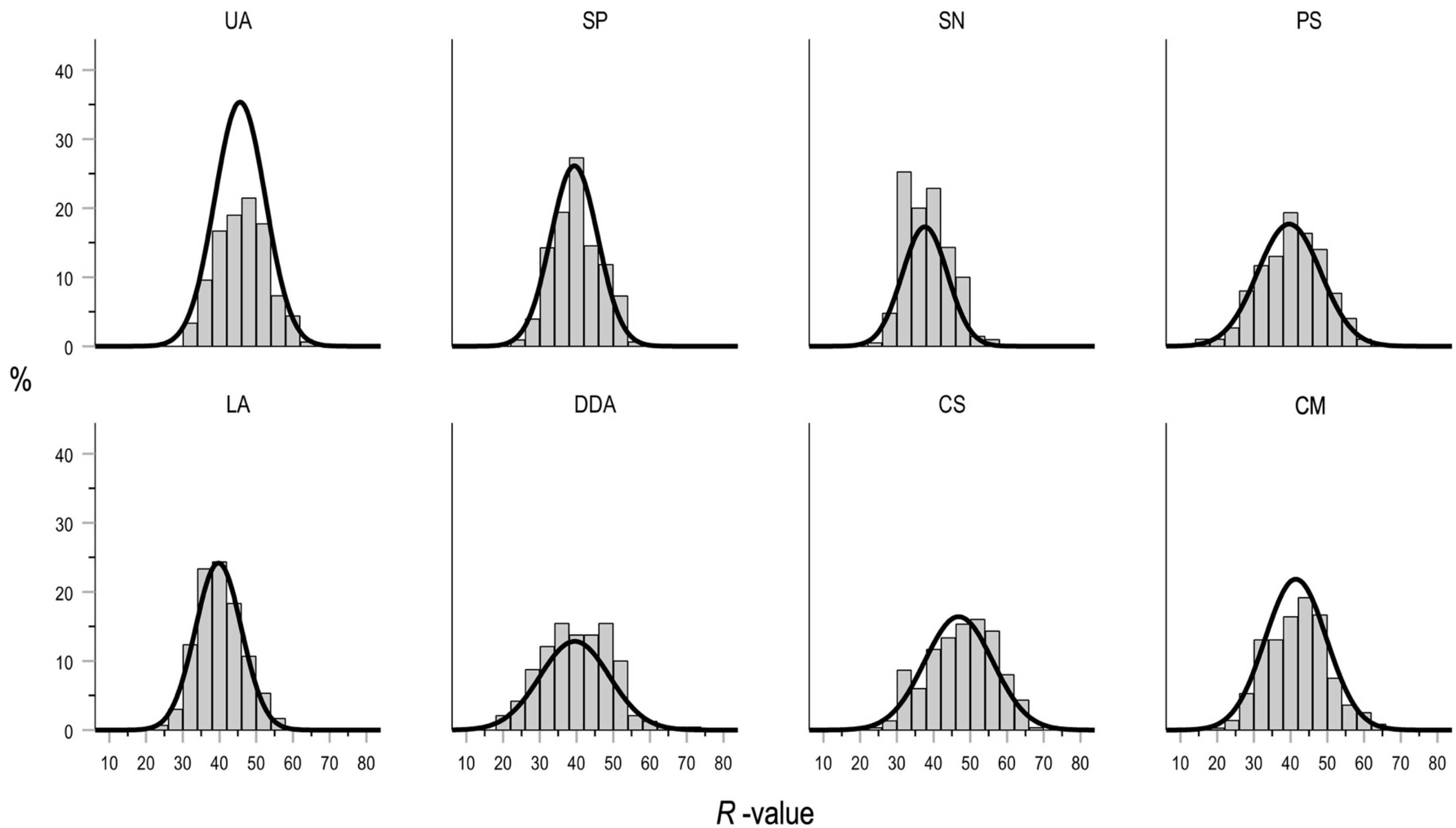

Figure 3. The frequency distributions of all *R*-values (i.e., not split by boulder/surface) derived from sites in the northern Cairngorm mountains. These data are displayed with a class-interval of four units and with normal distributions fitted.

[PRE-PRINT]

Table 1. **Summary statistical data for the Schmidt Hammer exposure-ages and associated *R*-values reported in this study.**

Site	*Type*	R_{total}	*No. of surfaces ages*	*Mean R-value ± 95%CI (all R-values)*	*Mean surface exposure-age ± 1σ*					*Pairwise comparisons*[c]	
					Tomkins et al. (2018)[a]	*LLPR*[b]	*CRONUS*[b]	*Balco*[b]	*GRPR*[b]		
CS	Boulders	300	10	46.84 ± 1.05	11.35 ± 1.16	11.44 ± 1.22	11.28 ± 1.21	10.74 ± 1.15	10.81± 1.15	A		
UA	Boulders	480	16	45.60 ± 0.62	12.07 ± 1.04	12.20 ± 1.09	12.03 ± 1.08	11.45 ± 1.03	11.52 ± 1.03	A		
CM	Boulders	360	12	41.43 ± 0.86	14.50 ± 0.98	14.73 ± 1.02	14.55 ± 1.02	13.84 ± 0.96	13.92 ± 0.96		B	
LA	Boulders	300	10	39.71 ± 0.71	15.50 ± 0.90	15.78 ± 0.95	15.60 ± 0.94	14.82 ± 0.89	14.91± 0.89		B	
PS	Bedrock	300	10	39.61 ± 0.97	15.55 ± 1.49	15.84 ± 1.56	15.65 ± 1.55	14.88 ± 1.47	14.96 ± 1.47		B	
DDA	Boulders	240	8	39.50 ± 1.20	15.62 ± 1.77	15.91 ± 1.85	15.72 ± 1.85	14.94 ± 1.74	15.02 ± 1.75		B	
SP	Boulders	330	11	39.38 ± 0.69	15.69 ± 0.66	15.98 ± 0.69	15.79 ± 0.69	15.01 ± 0.65	15.09 ± 0.65		B	C
SN	Bedrock	210	7	37.63 ± 0.83	16.70 ± 1.69	17.04 ± 1.77	16.85 ± 1.76	16.01 ± 1.66	16.09 ± 1.67			C

[a] Schmidt Hammer exposure-ages derived via the age-calibration calculation provided in Tomkins *et al.* (2018a) and as used in Wilson *et al*. (2019a).

[b] Schmidt Hammer exposure-ages derived using the updated age-calibration curve via the online calculator (see Tomkins *et al*., 2022).

[c] Grouping is derived using Tukey pairwise comparisons at 95% confidence. Where mean landform exposure-ages share a group, no statistical difference was found.