

WEATHERING PITS AS INDICATORS OF THE RELATIVE AGE OF GRANITE SURFACES IN THE CAIRNGORM MOUNTAINS, SCOTLAND

BY

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ABSTRACT. Weathering pits 1–140 cm deep occur on granite surfaces in the Cairngorms associated with a range of landforms, including tors, glacially exposed slabs, large erratics and blockfields. Pit depth is positively correlated with cosmogenic exposure age, and both measures show consistent relationships on individual rock landforms. Rates of pit deepening are non-linear and a best fit is provided by the sigmoidal function $D = b_1 + \exp(b_2 + b_3/t)$. The deepest pits occur on unmodified tor summits, where ¹⁰Be exposure ages indicate that surfaces have been exposed to weathering for a minimum of 52–297 ka. Glacially exposed surfaces with pits 10–46 cm deep have given ¹⁰Be exposure durations of 21–79 ka, indicating exposure by glacial erosion before the last glacial cycle. The combination of cosmogenic exposure ages with weathering pit depths greatly extends the area over which inferences can be made regarding the ages of granite surfaces in the Cairngorms. Well-developed weathering pits on glacially exposed surfaces in other granite areas are potential indicators of glacial erosion before the Last Glacial Maximum.

Key words: weathering pit, cosmogenic exposure age, granite landform

Introduction

A lack of dating control is a major barrier to understanding the origins of rock landforms. Before the advent of exposure ages based on the accumulations of **cosmogenic radionuclides (CRNs)**, geomorphologists relied heavily on relative age criteria of uncertain and varied resolution to estimate the age of rock surfaces (Birkeland 1974). The great advantage of relative age criteria is that they are often widely distributed. In contrast, exposure ages based on the production and build-up of CRNs within terrestrial surfaces (Phillips 2001) have the

potential to closely constrain the timing of landform-shaping events that expose rock surfaces for the first time. Currently, however, CRN exposure age determinations are few and far between due to the time and expense involved in carrying out the analyses.

This paper explores how weathering pit depth can be combined with cosmogenic exposure ages to elucidate age relationships across a complex rock landscape. The study area lies in the Cairngorms Mountains, Scotland (Fig. 1a). It is a glaciated granite landscape, with generally thin (0–2 m) regolith, which displays a wide range of rock features including tors, blockfields, glacially exposed slabs and large erratic blocks. Horizontal surfaces commonly show weathering pits, with deeper pits absent from areas scoured by the last ice sheet (Hall and Glasser 2003). Cosmogenic exposure ages are available for a range of event surfaces created when flowing glacier ice removed blocks from tors or quarried other large blocks from slabs and cliffs (Phillips *et al.* 2006). As these event surfaces may carry weathering pits, it is possible to use exposure durations to calibrate the rate of pit deepening at these sites. This allows pit depths to be used as a proxy to constrain the age of landforms at other sites and so greatly extend the area over which inferences can be made about the age of key landforms.

The study area

The Cairngorm Mountains is an area of exceptional geomorphological significance (Brazier *et al.* 1996; Gordon 1993) (Fig. 1b). It displays a wide range of characteristic granite landforms, including tors, domes and basins (Hall 1996). It is a classic landscape of selective linear glacial erosion (Sugden 1968), with sharp contrasts between the deep

valleys and corries and the relatively unmodified plateaux. It carries also a wealth of periglacial features, both relict and active, that are typical of mid- and high-latitude granite mountains (Ballantyne 1996).

The glacial history of the Cairngorm Mountains is summarized elsewhere (Phillips *et al.* 2006). As a major centre for ice dispersion across northeast Scotland, the mountains have experienced long periods of ice cover during the Pleistocene. An ice cover model equivalent to $\delta^{18}\text{O}$ values of -37‰ or less in the GRIP Summit record provides the best fit with available evidence for the glacial history of the Cairngorms. Prolonged periods of ice cover are consistent with results from two nuclide CRNs for tor summits which indicate burial for at least half of the last 800 ka. The model suggests that the Cairngorm summits remained covered by at least thin ice for 96% of the total duration of 4–2 Marine Oxygen Isotope Stages (OIS). The last period of prolonged ice-free conditions was in the warmer phases of OIS 5 and was *c.* 19 ka in total duration. It also implies that ice-free conditions on the Cairngorm plateau, and hence weathering pit development, must be largely restricted to the periods of relative warmth represented by interglacials and the temperature maxima of interstadials.

The formation of weathering pits

Weathering pits are a common feature of granite terrain in many parts of the world. Pits form on exposed and near-horizontal surfaces and have not been observed under soil cover (Hedges 1969) or beneath long-lying snow banks (Dahl 1966). The pits originate in slight depressions where water gathers after rainfall or snowmelt. Whereas the surrounding surfaces soon dry out, the depression is kept moist or supports a shallow pool for long periods. The presence of water provides a locus for more rapid weathering and the depression is widened and deepened (Goudie and Migoñ 1997). As pits grow, they may coalesce with their neighbours or reach horizontal and vertical joint boundaries and so drain.

Many Cairngorm weathering pits are active today. Most pits retain water for long periods (Fig. 2a) but a few have a partial cover of lichen or moss on the pit floor (Fig. 2b) and appear to be generally dry. The pit floor frequently retains a thin residue of granular gravel (Fig. 2b). This residue is composed of pebbles, granules and sand grains that include granite fragments, orthoclase phenocrysts and

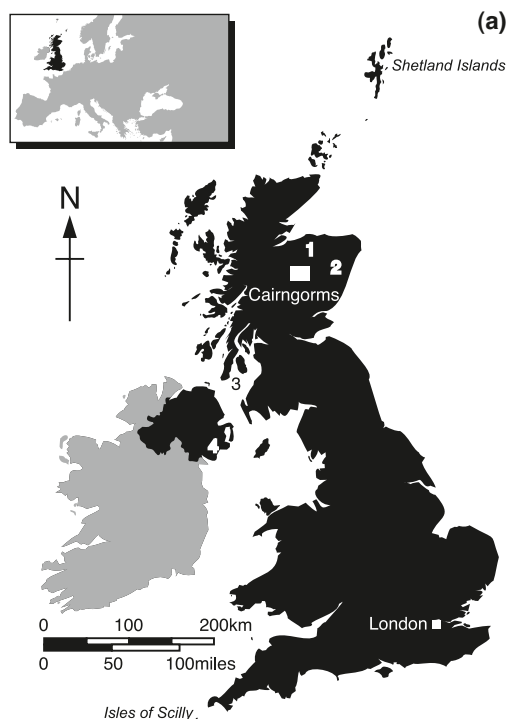


Fig. 1(a) Cairngorms location map: 1, Ben Rinnes; 2, Bennachie; 3, Arran; 4, Mourne Mountains. (b) Location map and tor groups. Group names and National Grid References are given in Table 1

quartz grains. Variable amounts of organic material may also be present. The granite surface of the sides and base of the pools is rough, with projecting, sometimes loose, mineral crystals.

Form of weathering pits in the Cairngorms

Dimensions of 375 pits from a range of landforms on the Cairngorm plateau were measured using a pair of metre rules. The pits were treated as elliptical cylinders, with the A and B axes as the maximum and minimum widths of the circumference and the C axis as the depth to the pit floor. The pits tend to be circular or ovoid in plan (mean $a/b = 1.22 \pm 0.31$). Shallow pits or pans are often broad and irregular in outline but protuberances are largely removed from pits >10 cm deep. Pit deepening appears to keep pace with pit widening through time, although there is a wide range of forms (Fig. 3). Many pits have spillways (Fig. 2a) and some pits are slightly undercut, with a broad base to the pit beneath a relatively constricted rim.

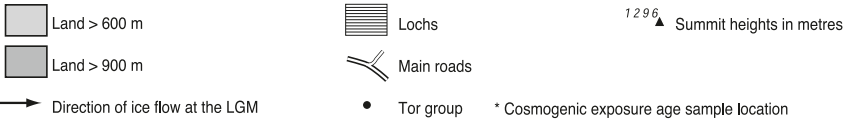
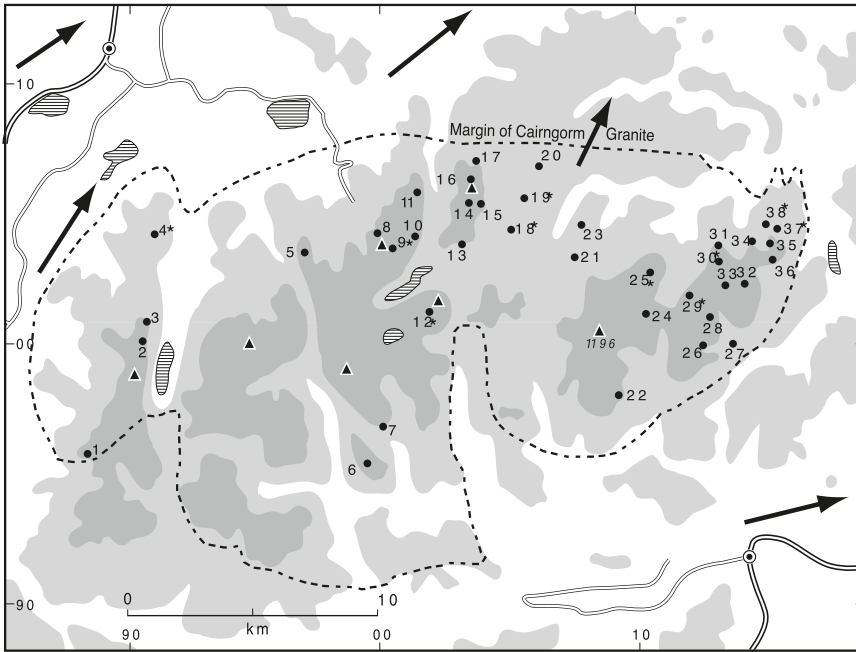
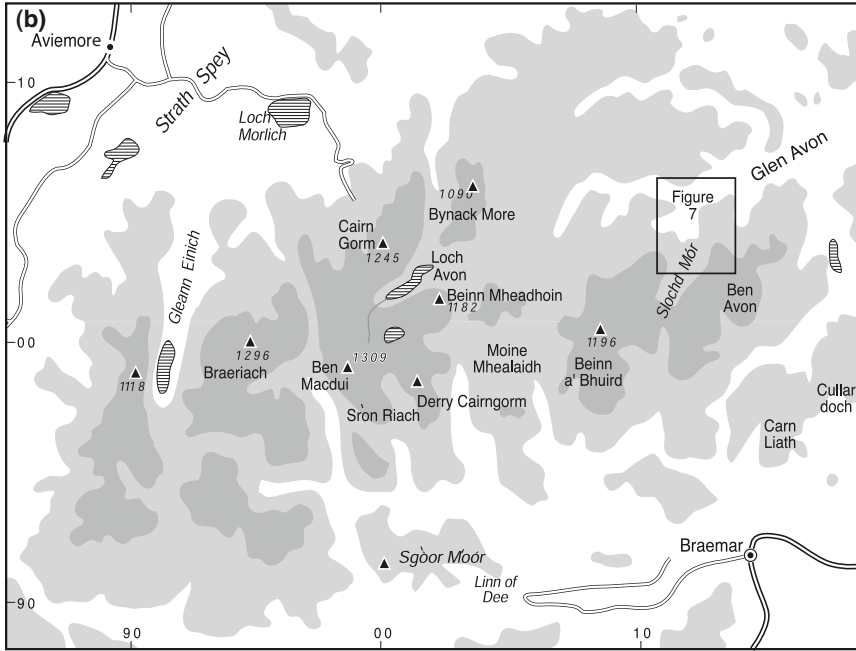


Fig. 1. Continued

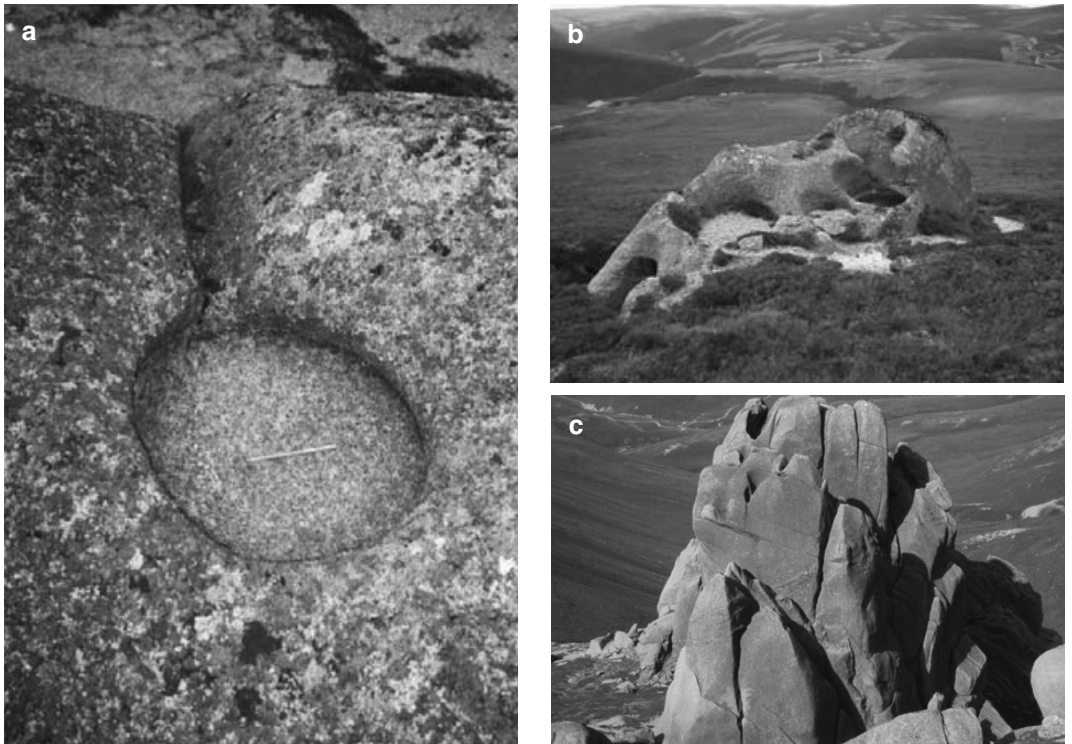


Fig. 2. Weathering pits: (a) Pit with water and spillway; (b) pits with vegetation and gravel, An Cnoith, (c) edge pits on the summit of the tower tor at Clach bun Rudhtair (Group 31)

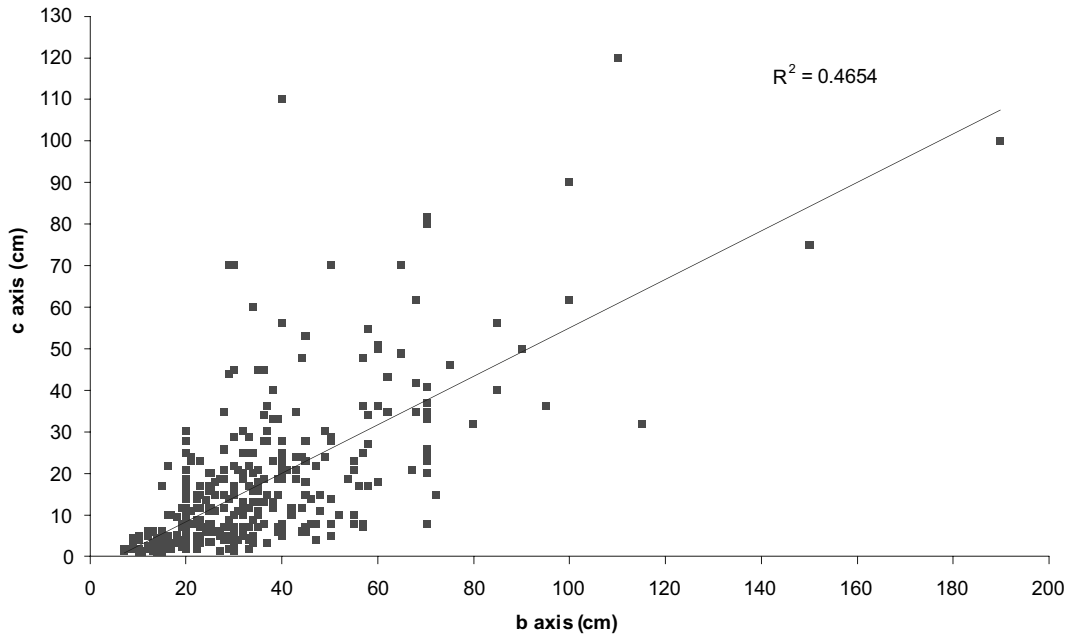


Fig. 3. Weathering pit geometry

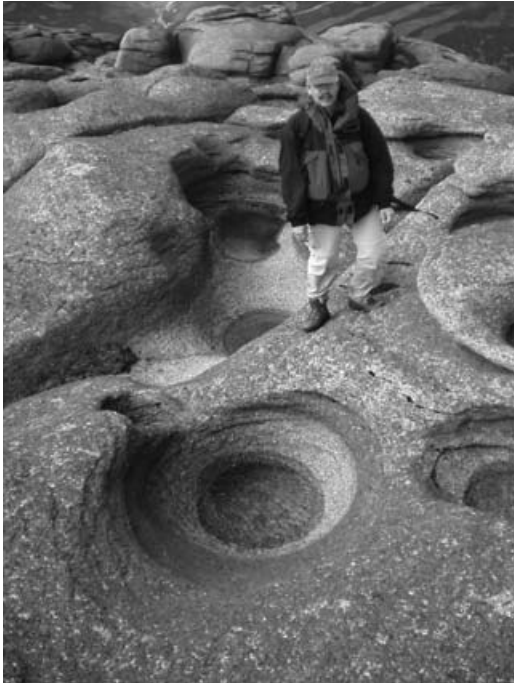


Fig. 4. Clach Bhàn, the surface of the northern part of the tor with pits 18–140 cm deep

Pit depths form a continuum that ranges from 1 to 140 cm. Pits of various dimensions may occur side by side on the near-horizontal surfaces of tor blocks (Fig. 4) and glaciated slabs. This indicates that pit formation and enlargement is a continuous process operating on exposed surfaces. Grooves or rills are more characteristic of tilted slabs. Tor surfaces locally display deep pits on inclined surfaces and edges. Edge pits may form cascading systems (Fig. 2c), indicating that overflow from an upper pit or rill may initiate pits and rills lower down a block edge. A number of edge pits exceed 100 cm in depth and the largest is 226 cm deep. Edge pits may form relatively rapidly and so are excluded from further consideration here.

Weathering pits and landforms

Pit depth must link in some way with the total duration of periods of exposure to weathering. The wide range of pit depths in the Cairngorms implies significant differences in the timing of the initial exposure of surfaces in which the pits are set. Hori-

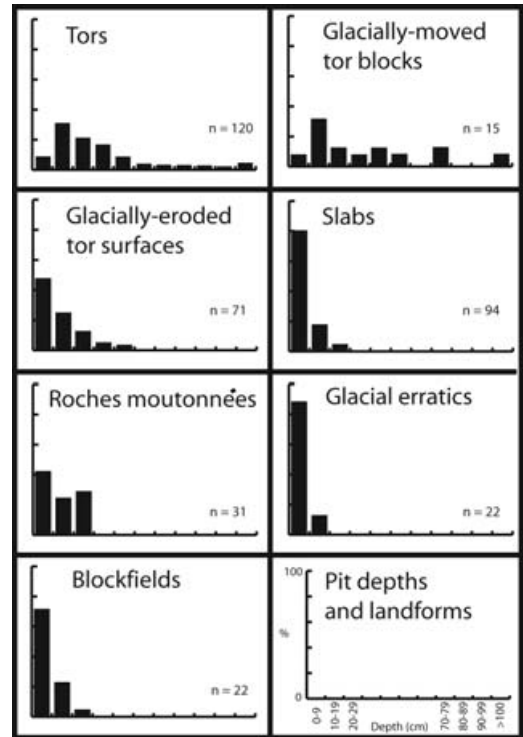


Fig. 5. Pit depths on the surfaces of different granite landforms in the Cairngorms

zontal surfaces suited to the development of weathering pits occur on a range of Cairngorm landforms and so it is important to view the weathering pits in the context of specific landforms and surfaces (Fig. 5).

Glacial slabs and roches moutonnées

Near-horizontal granite slabs occur frequently in valleys and corries in the Cairngorms. The slabs are defined by widely spaced vertical joints and have been exposed by glacial entrainment of tabular blocks along near-horizontal sheet joints. A key observation is that, despite methodical searching, no weathering pits deeper than 5 cm have been observed on horizontal granite surfaces on the floors of glacial valleys and corries.

Ice-moulded surfaces also occur away from valley and corrie floors. These surfaces are characterized by a lack of regolith, exposure of large areas of jointed granite including slabs and lee-side cliffs, and by perched erratic blocks. Some of these surfaces lack deeper weathering pits. In contrast, large



Fig. 6. Sgòr Mòr summit. Weathering pits 23 and 11 cm deep set into ice-moulded slabs and roches moutonnées

roches moutonnées above Loch Avon carry weathering pits up to 26 cm deep (Hall and Glasser 2003) and other ice-moulded surfaces have weathering pits >10 cm deep (Fig. 6).

Large glacial erratics

Large granite blocks occur in many of the valleys and corries of the Cairngorm as part of moraines or as the products of rockfall and cliff collapse. No pits deeper than a few centimetres have been observed on these blocks. Large granite erratics can be identified on the Cairngorm plateau by contrasts between the massive blocks, up to 6 m in A-axis length, and the block size of the regolith on which they rest, by contrasts in joint orientation between the bedrock and the block and by their situation as isolated blocks in zones of predominantly sandy regolith. The most frequent blocks occur as boulder trains transported by ice from out of the main valleys and corries, with good examples north of Bynack More and southeast of the corries of Beinn a' Bhuid. These blocks occasionally display horizontal surfaces suitable for the development of weathering pits. Examples have been observed on the metamorphic terrain NE of Ben Avon of large granite erratics with weathering pits 10–11 cm deep but other blocks either show no pits or have pits <10 cm deep. A notable exception is the ridge of Dà Dhruim Lom (Fig. 7a) where weathering pits 9–31 cm deep are found on the sides of some blocks (Fig. 7b). The side pits must have developed on the upper, horizontal surfaces of the blocks prior to at least one phase of glacial transport.

Elsewhere in the Cairngorms, pit depths on the sides of glacially transported tor blocks reach 70

cm. No pits >10 cm deep have been observed on the upper surfaces of these transported blocks, although these surfaces are not usually horizontal.

Tors

A detailed model of the stages of glacial modification of Cairngorm tors is presented elsewhere (Hall and Phillips 2006). On Ben Avon (Groups 27–29, 31 and 33; see Table 1 for details of tor groups) large tors retain a delicate superstructure and have been largely unaffected by the movement of glacier ice (Stage 1). Elsewhere tors show glacial modification that ranges from the removal of individual blocks and loose superstructure (Stage 2), through the loss of a large part of the original upstanding rock mass (Stage 3) to the reduction of the former tor to a stump or root (Stages 4 and 5).

The deepest pits in the Cairngorms are mainly those associated with tors that show little or no glacial modification. The development of weathering pits is an important process in the lowering and variegation of tor surfaces. On tor summits, pits on the surfaces and edges of blocks may exceed 100 cm in depth and diameter (Fig. 5). On some larger tors, such as Clach na Gnùis (Group 30) and Ben Avon summit (Group 29), there is an association between pit depth and height above the surrounding surface. Pitting is deepest and densest on the higher surfaces, with pits 50–160 cm deep. Lower lying parts of tors may also carry pits but usually pit depths are <50 cm. In the zone around the base of the tors, close to the contact with the surface of the surrounding regolith, pits are generally shallow or absent.

In contrast, some large tors in Groups 15 and 33 show pits up to 100 cm deep just 1–3 m above the tor base. Toppled tor blocks may also show deep pits, up to a maximum of 48 cm. Although the blocks are tilted from their original position, the vertical alignment of the pits on the top surface shows that pit development postdates toppling.

Glacially modified tors display two types of surface. Residual surfaces occur widely, especially on the lee side of the tors, and display the rounded and fretted edges and open joints typical of unmodified tor surfaces. Residual surfaces carry pits up to 60 cm deep. Other surfaces have formed by the glacial removal of blocks from the tor summit or, if the entire tor form has been demolished, a plinth or base (Hall and Phillips 2006). These glacially exposed surfaces carry weathering pits 2–45 cm deep (Fig. 8). One notable exception is provided by Clach Bhàn (Group 37), a tor with a subdued form that

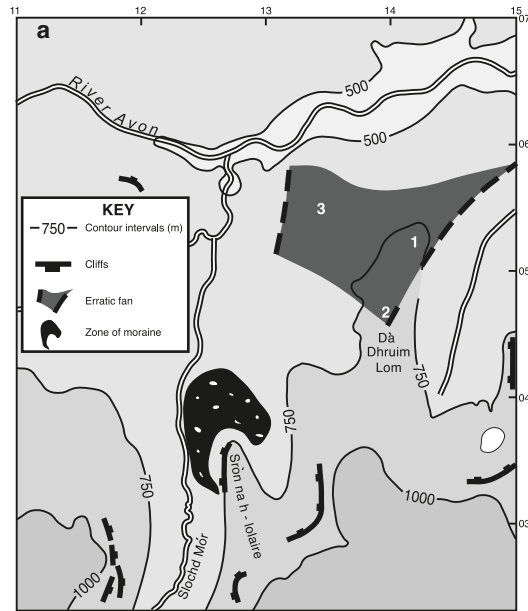


Fig. 7. Dà Dhruim Lom: (a) map of erratic fan showing locations of sites 1–3. (b) Weathering pit 20 cm deep on the side of a glacially transported block on Dà Dhruim Lom at Site 3

points to loss of superstructure due to block entrainment by glacier ice but which carries a superb sequence of weathering pits of which the deepest is 140 cm (Fig. 4). Roches moutonnées and whalebacks representing tor roots occur at low levels in

Glen Avon but show only shallow weathering pits. In contrast, whaleback forms, also representing ice-moulded tor roots, are found on the lower slopes of the Sròn Riach and show arrays of pits up to 28 cm deep. Fine examples of glacially stripped

Table 1. Tor groups

Number	Name	General location
1	Meall Dubhag	NN 880951
2	Sgòran Dubh Mor	NH 904003
3	Sgòran Dubh Beag	NH 907009
4*	Creag Dhubh	NH 905040
5	Lurcher's Crag	NH 970043
6	Carn a' Mhaim	NH 995952
7	Sròn Riach	NN 999978
8	Sròn an Aonaich	NJ 002056
9*	Cairn Gorm	NJ 008041
10	Ciste Mhearad	NJ 016044
11*	Tor 1028	NJ 016060
12*	Barns of Beinn Mheadhoin	NJ 025017
13	Á Choinneach	NJ 037039
14	Little Barns of Bynack	NJ 043058
15	Barns of Bynack	NJ 045058
16	Bynack More	NJ 035069
17	Coire Odhar	NJ 041075
18*	Creag Mhór	NJ 058048
19*	Dagrum	NJ 062055
20	Coire Riabhach Bheag	NJ 071063
21	Cnap Leum an Easaich	NJ 082033
22	Á Chioch	NO 097986
23	Carn an t-Sionnaich	NJ 078046
24	Cnap a Chléirich	NJ 108010
25	Stob an t-Sluichd	NJ 112027
26	Carn Allt an Aitinn	NO 134992
27	Stuc Gharbh Bheag	NO 145998
28	Stob Dubh an Eas Bhig	NJ 114002
29	Leabaidh an Daimh Bhuidhe	NJ 132019
30	Stob Bac an Fhurain	NJ 138034
31	Clach Bun Rudhtair	NJ 140039
32	Allt an Sgòir Riabhach	NJ 157021
33	Clach Choutsaich	NJ 144018
34	West Meur Gorm Craig	NJ 150042
35	East Meur Gorm Craig	NJ 159042
36	Big Brae	NJ 153037
37	Meall Gaimeimh	NJ 167051
38	An Cnoidh	NJ 160058

* Included in cosmogenic dating

tor plinths and roots also occur on Craig Mhór (Group 18) and Dagrum (Group 19). The slabs in the latter area carry pits up to 46 cm deep, together with erratics of psammite, diorite and fresh granite. Two shallow weathering pits contain erratic clasts, providing evidence that these pits existed prior to the deposition of the erratics (Fig. 9).

Blockfields and other plateau regolith

The Cairngorm plateau displays extensive regolith covers of two types (Ballantyne 1996; Paine 1982) – block-rich and block-poor – both with a matrix of quartzo-feldspathic grit and sand. The restricted development of these types of regolith from the floors of valleys and corries that escaped glaciation

during the Loch Lomond Stadial indicates that the regolith is not primarily of post-glacial origin and that it developed prior to the last ice sheet (Ballantyne 1996; Gordon 1993). Both blockfields and debris covers have been locally disrupted or removed by glacier ice (Fig. 10) but the timing of this phase (or phases) of erosion is unclear.

Weathering pits up to 20 cm deep occur locally on large tabular blocks within both types of plateau regolith. Examples occur on the Ben Macdui plateau and on Ben Avon. On the north ridge of Derry Cairngorm and elsewhere blockfields have been disrupted by ice flow and pass downslope into stripped granite surfaces in which joint systems are exposed. These stripped surfaces display weathering pits up to 12 cm deep (Fig. 10).

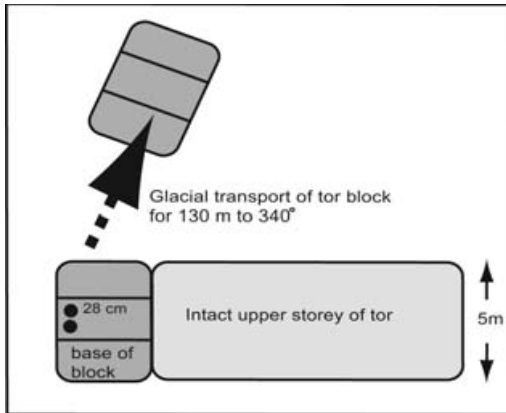


Fig. 8. Schematic plan of Tor 1136, Ben Avon (NJ 137024). The depths of weathering pits (dots) on the tor surface revealed by glacial erosion indicate that block entrainment predates OIS 5

Relative timescales for weathering pit development

Post-glacial pit development

The absence of pits deeper than 5 cm from surfaces scoured by ice at the **Last Glacial Maximum (LGM)** indicates that the initiation of weathering pits in the Cairngorms is slow. The maximum depth of post-glacial pit development remains unclear, however, as areas of ice-scoured granite are of restricted extent in the mountains. It is possible that pits >5 cm deep may have been created elsewhere in the Cairngorms during the postglacial period on surfaces newly exposed from beneath but not abraded by the last glaciers. Glacially abraded surfaces originally would have been polished, prior to surficial granular disintegration in the postglacial period. Such freshly exposed surfaces can be expected to offer the greatest resistance to weathering and to pit initiation due to their hardness (Ericson 2004) and low surface permeability (Kessler *et al.* 1940). At other sites, prior or incipient weathering would weaken the surface and increase its permeability allowing faster pit initiation. Such sites would include granite surfaces that were covered and protected by cold-based ice during OIS 4–2. In

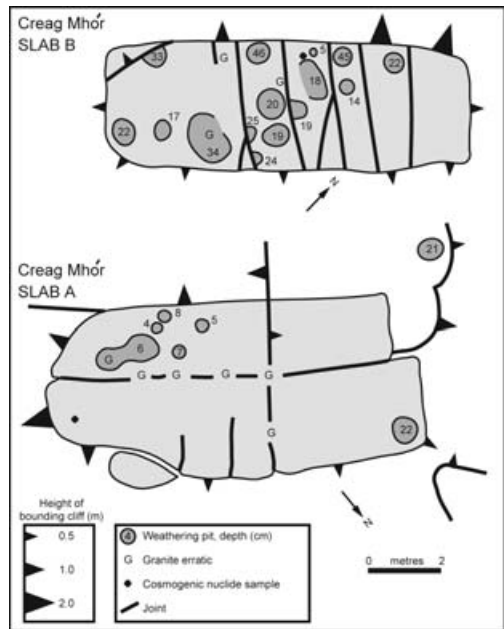


Fig. 9. Weathering pits on glacially exposed slabs on Creag Mhór and Dagrum

the light of these uncertainties, the conservative proposal is adopted that only pits greater than 10 cm deep can be taken as reliable indicators that the rock surface into which they are set was not deeply abraded or stripped by glacial action in OIS 4–2.

Deepening of weathering pits is relative to surrounding rock surfaces which are themselves being lowered at long-term mean rates of 4.1 ± 0.2 mm/ka (Phillips *et al.* 2006). The maximum observed rate of postglacial pit deepening on glacially abraded surfaces in the Cairngorms is 3.3 mm/ka and may reach 8 mm/ka on non-abraded surfaces. These rates are below those reported from 5000-year-old granite menhirs in western France (4–30 mm/ka) (Lageat *et al.* 1994; Sellier 1997) but closely equivalent to those of other formerly glaciated areas. Observations of roches moutonnées indicate that depths of postglacial weathering pits reach only 1.0–6.3 cm in various environments including Arctic Labrador and sub-Arctic Scandinavia (André 2002) and the cool temperate mountains of Mourne and Donegal, Ireland (Le Coeur 1980; Sellier 1998) and the eastern French Pyrennées (Delmas 1998). André (2002) makes a simple extrapolation of postglacial rates of pit deepening in northern Sweden (2–3.5 mm/ka) to suggest that the



Fig. 10. Weathering pits in areas of glacially stripped regolith. Block with 12 cm deep weathering pit in stripped blockfield at 1135 m OD on Derry Cairngorm (NO 0155 9820)

deepest pits in the Cairngorms date from over 1 Ma but an assumption of a constant rate of deepening is probably unjustified. The restricted depths of postglacial pits in the Cairngorms and elsewhere suggest that initiation of pits occurs slowly due to the factors identified earlier.

The problem of inheritance

The finding that pits in the Cairngorms deeper than 5–10 cm predate the last glacial cycle means that many weathering pits have been reoccupied and probably deepened in the postglacial period. The rate of deepening of preformed pits is uncertain, as no datum is recognized within the pit that marks the start of postglacial deepening. Such deepening is likely to be faster than that of pit development on fresh surfaces as the preformed pit can collect water at the start of the postglacial period. The importance of inheritance is apparent on ice-moulded granite surfaces in Bohuslän, southwestern Sweden, where glacial microforms including sichelwannen and pot holes have been enlarged by postglacial weathering (Lidmar-Bergström 1988).

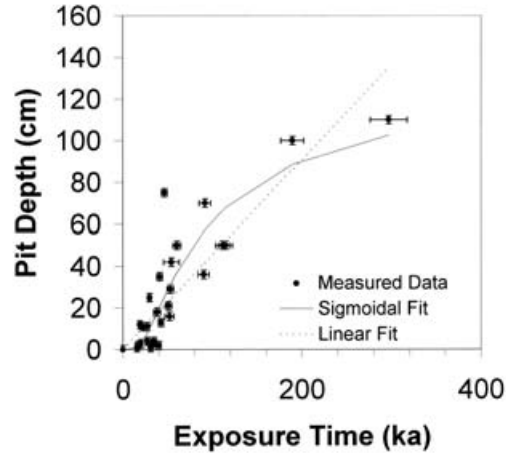


Fig. 11. Pit depths and cosmogenic exposure ages

Reoccupation during successive ice-free periods is likely to have occurred in all parts of the Cairngorms where glacial erosion has been insufficient to remove pre-existing pits. Pits set into large, joint-bounded granite slabs are inherently difficult for glacial erosion to remove as it requires either deep abrasion of the slab surface or the removal of the entire slab through entrainment at the glacier base. Weathering pits thus have a high survival potential. Pit depths can be seen as the sum of cumulative deepening during ice-free periods since initiation, minus any lowering of the surrounding rock surface during one or more phases of glacial erosion.

Cosmogenic exposure ages

The timing of the first exposure of granite surfaces can be established independently by dating using cosmogenic nuclide concentrations. In order to use CRNs to constrain the duration of exposure of a rock surface, it is important to identify an *event surface* (Phillips *et al.* 2006) from which a minimum of 2–3 m of rock has been removed. The newly exposed event surface would largely lack inherited

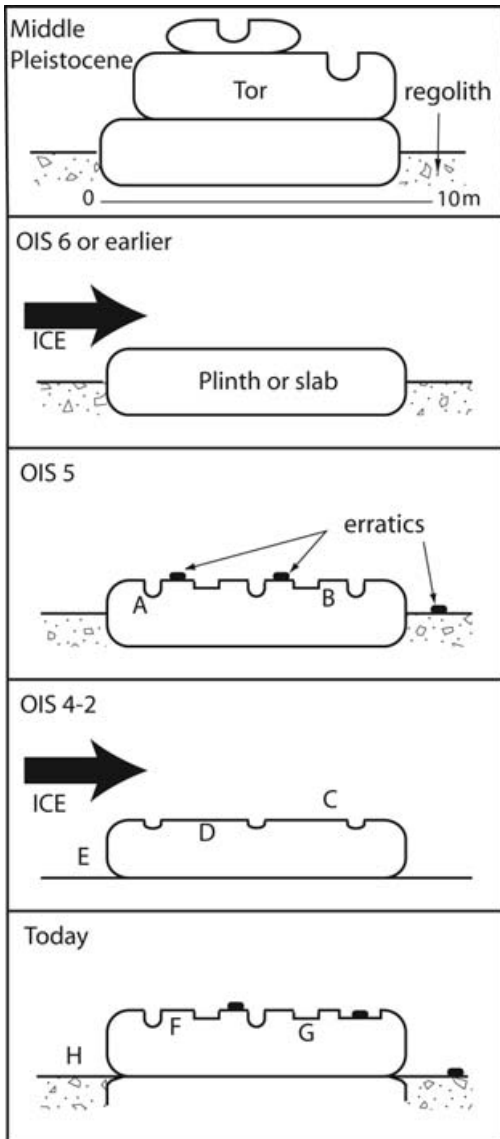


Fig. 12. A model sequence of pit development on a glacially modified tor base, based on observations on Creag Mhór and Dagrur. The original tor has weathering pits up to 1 m deep and is surrounded by thin regolith. During OIS 6 or an earlier interval, the superstructure of the tor is removed by glacial entrainment of blocks. Glacial erratics are deposited. Exposure of the tor base allows pit development to various depths (A and B). Deeper pits may be inherited from earlier ice-free intervals. Loose material is then removed during the next phase of glacial erosion and the block surface may be abraded and lowered (C). Pre-existing shallow pits are removed and deeper pits are truncated (D). Regolith is stripped (E). Deglaciation leaves erratics on the tor surface, in weathering pits and on the surrounding surface. Surviving pits are reoccupied and deepen relatively rapidly (F). New pits develop (G) and regolith starts to reform around the slab (H)

CRNs and thus the accumulated CRNs would provide a good estimate of the time that had elapsed since exposure. In the Cairngorms, the stripping of blocks by glacial erosion from tors, roches moutonnées and blockfields has the potential to create pristine event surfaces but in practice a significant component of inherited CRNs is identified, probably because the thickness of the removed blocks is generally < 3 m (Phillips *et al.* 2006).

Both the accumulation of CRNs and the development of weathering pits require ice-free conditions and so a correlation is to be expected between exposure age and pit depth. There is, however, unlikely to be a simple relationship between exposure age and pit depth for the following reasons.

- The continuing accumulation of CRNs beneath thin (< 3 m) rock cover and snow cover during periods when pit deepening is not possible.
- The disparity between approximately constant CRN production and non-linear rates of pit deepening (Norwick and Dexter 2002).
- The range of pit depths found on some surfaces indicates that pit formation may occur long after the surface is first exposed
- Variations across a surface. Limited data suggest that cosmogenic nuclide concentrations vary significantly across distances of ≤ 1 m. Cosmogenic samples taken from the edges of blocks and weathering pits have lower nuclide concentrations compared with samples from block centres as a consequence of both shielding effects and different rates of weathering (Phillips *et al.* 2006).

The CRN methods and results for granite surfaces in the Cairngorms are reported elsewhere (Phillips *et al.* 2006). Each surface sampled for CRN was also checked for the maximum depth of weathering pit development to allow direct comparison of surface exposure ages and pit depths. Reported ^{10}Be exposure ages are corrected for postglacial erosion rates of 1.6 mm/ka.

There is a positive correlation ($r^2 = 0.73$) between maximum pit depth and its ^{10}Be exposure age (as shown by the linear fit in Fig. 11). We use a sigmoidal curve to estimate variations in weathering pit depth against time for two reasons: (i) previous studies of tafoni development through time indicate that rates of deepening follow sigmoidal functions (Norwick and Dexter 2002; Sunamura 1996); and (ii) average rates of pit deepening in the Cairngorms are 4.5 mm/ka of exposure, signifi-

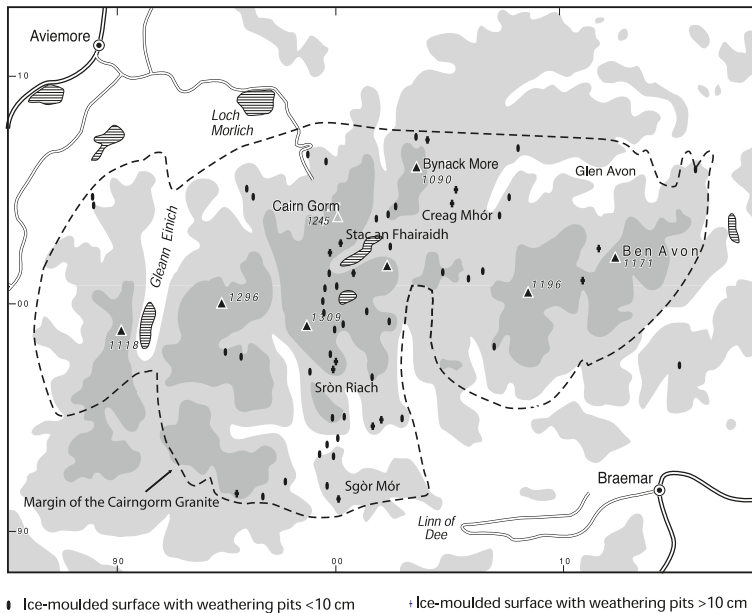


Fig. 13. Distribution of ice-moulded surfaces eroded in OIS 4–2 (weathering pits <10 cm deep) and OIS 6 and earlier (weathering pits >10 cm deep)

cantly above postglacial rates of 1–3.3 mm/ka and adding support to the idea that pit initiation is slow. Following Norwick and Dexter (2002), we computed best-fit solutions using Excel Solver to several types of equations using our weathering pit depth and surface exposure age data. A sigmoidal equation of the form $D = b1 + \exp(b2 + b3/t)$, with $b1$ forced to be equal to zero, yielded the most realistic fit (Fig. 11). A lag time of approximately 15 ka is evident, corresponding to our observation that postglacial weathering pits are generally < 5 cm in depth.

Pit development in the Cairngorms appears to have spanned 16 to at least 297 ^{10}Be ka of exposure. Unmodified top summit surfaces with pits deeper than 46 cm give ^{10}Be exposure durations of 47–297 ka. Both weathering pit depths and exposure ages indicate that these are amongst the longest exposed granite surfaces in the Cairngorms. Glacially modified surfaces that carry pits of 10–46 cm in depth provide ^{10}Be exposure durations of 21–79 ka. These timings exceed the estimated 15.6 ± 0.9 ka duration of the postglacial period (Phillips *et al.* 2006) and require either that the event surfaces were exposed prior to OIS 4–2 or that glacial erosion has been insufficient to remove inherited CRNs. Glacially modified surfaces that carry pits of 1–3 cm in depth have yielded ^{10}Be exposure ages of 16–40 ka. The exposure ages confirm that shall-

low pits may have formed in the postglacial period but also show that an absence of pits >5 cm deep does not imply a postglacial age for first exposure of a granite surface. The overlapping ranges of the exposure ages require cautious interpretation in the light of the factors listed above but suggest that pit development has been a continuous process during ice-free intervals.

Resolving the ages of key landforms in the Cairngorms

The availability of exposure age data is restricted to 17 localities in the mountains yet the correlation with weathering pit depths means that the age of surfaces can be constrained for any flat granite surface in the Cairngorms where weathering pits exist and where lithology is similar. We estimate that maximum pit depths of 15 cm were attained during the 30 ka of ice-free conditions during OIS 1–5 predicted by the ice-cover model.

Glacial slabs and roches moutonnées

Pit depths of >15 cm on glacial slabs and roches moutonnées on the margins of the plateau require that these features had already achieved much of their current morphology before OIS 5, implying that major glacial erosion occurred during OIS 6 or

earlier. Pit depths of 5–15 cm probably also reflect uncovering of event surfaces in OIS 6 or earlier but with lowering of surrounding surfaces by glacial erosion.

Large glacial erratics

Only three examples have been observed of erratics with weathering pits on their upper surfaces 10–11 cm deep that suggest transport prior to the LGM. All other blocks either show no pits or have pits <10 cm deep, a finding consistent with but not necessarily implying transport in OIS 4–2.

The boulder train on Dà Dhruim Lom has a complex history. Some blocks lack weathering pits on all faces and may have been transported in OIS 4–2 but others were transported before OIS 5. The tilted face of one block (Site 1: Fig. 7a) has provided an exposure age of 42.6 ± 3 ka. Self-shielding has prevented significant accumulation of CRNs on the tilted face during the postglacial period. Exposure to cosmogenic radiation is implied for a period beyond the estimated 30 ka duration of ice-free periods in OIS 1–5. The upper surface of a second block upslope (Site 2) gave a ^{10}Be exposure age of 27.3 ± 2.3 ka, again requiring transport before OIS 5. The presence of weathering pits 9–31 cm deep on the sides of other undated blocks is also consistent with formation of event surfaces in OIS 6 and earlier. Dà Dhruim Lom preserves a record of multiple phases of glacial transport of boulders over distances of just a few hundred metres.

Tors

On tor surfaces exposed by the passage of glacier ice, similar reasoning can be applied to that used for roches moutonnées. On slabs, glacial abrasion may have lowered the rock surface and pit depths may be regarded as minima. In contrast, where upstanding blocks survive on tors, abrasion of adjacent event surfaces must have been negligible and pit depth is an indicator of exposure time.

On most glacially modified tor surfaces, pit depths range from 10 to 45 cm. The range of pit depths allows the possibility of glacial entrainment of blocks occurring during OIS 2–4, 6 and 7. On the tor plinths in Groups 18–19 (Fig. 9), the presence of erratics in pits indicates that even shallow pits may predate glaciation in OIS 2. The existence of pits up to 35 cm and 21 cm deep elsewhere on the slabs demonstrates an earlier exposure. This is confirmed by exposure ages of 51.0 ± 3.8 ka and 41.1

± 3.3 ka, indicating block removal in OIS 6 at the earliest (Phillips *et al.* 2006). As these surfaces have probably lost mass to glacial erosion, the exposure ages and pit depths are minima and tor destruction may date from earlier cold stages.

Block detachment and transport can be viewed in a similar way. Weathering pits developed on surfaces revealed by the removal of tor blocks constrain the timing of glacial erosion (Fig. 12)

The 36–156 cm deep pits on the northern part of Clach Bàn (Group 37) are developed within a tor surface apparently stripped of superstructure by the passage of ice (Fig. 5). The extreme depths of these pits reflect in part the more rapid breakdown of this megacrystic granite lithology. Nonetheless the depth of the pits suggests that any glacial modification of this surface predates OIS 6 and thereby places the surface as one of the oldest possible glacial surfaces in the study area.

On Stage 1 tors and many Stage 2 tor surfaces, glacial modification is not apparent. The deepest pits on upper tor surfaces exceed significantly the maximum depth of those on most glacially stripped surfaces (45 cm). This implies that the upper tor surfaces are older than the period or periods of glaciation that led to the exposure of the stripped surfaces, i.e. prior to OIS Stage 6 at minimum. Exposure ages of 52–297 ka for tor summits confirm that surface weathering has extended over multiple interglacial phases. This is confirmed by combined ^{10}Be and ^{26}Al nuclide data for three tors in Groups 29 and 30 which indicate first exposure of these summit surfaces at 305–605 ka BP (Phillips *et al.* 2006). Weathering pit depths exceed 100 cm on these tors.

On large tors, there is a tendency for pits >0.5 m deep to occur on the highest points of the tor. On Clach na Gnùis (Group 30), ^{10}Be exposure ages range from 297 ka for the upper tier of the tor with its cascading system of edge pits up 110 cm deep, to 111 and 60 ka for the middle tier with a 50 cm deep pit, and 30 ka for the lower tier, where there may have been loss of blocks due to glacial disturbance and where maximum pit depth is 25 cm. Data from pit depth and exposure ages on this tor are consistent with the progressive emergence of the tor from regolith.

Relatively fast rates of regolith formation or recent stripping are implied by the general absence of deeper weathering pits around the lower storeys of many tors. In contrast, the small tor of An Cnoidh (Group 38), with pits ≤ 102 cm deep, has given an exposure plus burial age of 471 ka (Phillips *et al.*

2006). Deep pits near the bases of other tors imply local regolith stability over time periods extending back to OIS 12. Tor emergence, regolith formation and regolith stripping appear to be highly variable in time and space across the Cairngorm plateau.

Blockfields and other plateau regolith

It is widely recognized that the absence of blockfields from summit areas showing evidence of glacial scouring requires that the blockfields are older than the LGM (Caine 1968; Kleman and Borgström 1990; Lagerbäck 1988; Rea *et al.* 1996). Exposure ages for blockfields covered by ice at the LGM in northwest Svalbard have provided minimum ages of 42–140 ka (Landvik *et al.* 2003) and in northern Quebec and Labrador of 73–157 ka (Marquette *et al.* 2004), requiring survival of the blockfields through multiple glacial cycles. No cosmogenic nuclide data exist for blockfields in the Cairngorms but the presence of weathering pits up to 20 cm deep on tabular blocks set within plateau regolith confirms that formation of the regolith and exposure of the blocks in these locations predates OIS 4–2. The presence of pits up to 12 cm deep on blocks within stripped blockfields on Derry Cairngorm (Fig. 10) suggests that the blockfield had been already stripped by glacial erosion by OIS 5 and has not reformed since. The absence, however, of any pits >20 cm deep within the Cairngorm blockfields suggests that exposure of individual large blocks within blockfields is unlikely to have spanned more than the last interglacial, unless the development of weathering pits on blockfields has been inhibited by long periods of snow cover during interglacial periods.

Implications for glacial erosion

The absence of pits >5 cm deep from the floors of glacial valleys and corries implies that glacial erosion by the last ice sheet has been sufficient to remove any pre-existing pits. As pit development in OIS 5 probably reached depths of *c.* 10 cm then glaciers in OIS 4–2 were capable of lowering these granite surfaces by >10 cm and removing pre-existing pits. These depths of erosion fall well within the actual depths of erosion that are required to lower the floors of the major glacial valleys of the Cairngorms by 100–200 m during the glacial stages of the last 1 Ma.

Conversely, lower parts of the Cairngorm plateau show glacially modified tors and large roches

moutonnées with suites of weathering pits that allow a sequence of pit development to be established (Fig. 12). Deeper weathering pits which existed in OIS 5 cannot have been eliminated by glacial erosion in OIS 4–2. This implies that erosion of many granite surfaces was <10 cm.

The distribution of ice-moulded surfaces with pits of different depths (Fig. 13) indicates locations where glacial erosion in OIS 4–2 was and was not effective in lowering pre-existing glacial surfaces. At sites showing ice-moulding and lee-side plucking and lacking deep pits, erosion probably amounted to >10 cm. Other ice-moulded surfaces which retain deep pits must have existed prior to OIS 5 and experienced very limited glacial lowering in OIS 4–2. It is noteworthy that these scattered occurrences tend to be at higher elevations on the plateau margins. By implication, wet-based ice reached higher on the plateau during and perhaps before OIS 6 than in OIS 4–2.

Weathering pits as relative age indicators

The generally limited extent of postglacial pit development in shield areas is supported by extensive studies of glaciated bedrock surfaces in Ireland (Le Coeur 1980), northern Scandinavia (André 1995; 2002) and northern Canada (André 2002; Jansson and Lidmar-Bergström 2004). The cosmogenic exposure ages for Cairngorm granite surfaces confirm that deeper weathering pits must predate the LGM. In Scandinavia, there is a surprisingly widespread distribution of relatively deep weathering pits but they have traditionally been regarded as postglacial features. Dahl (1966) described weathering pits in granite up to 20 cm deep, but mainly less than 10 cm from the Narvik Mountains, Norway. The pits occur in a range of contexts, including blockfields, former glaciated surfaces and on small tors. Deep pits are also reported from ice-moulded surfaces on the Sörøy peninsula in northern Norway (Roberts 1968) and in southern and central Sweden (Johansson *et al.* 2001; Johnsson 1988; Lidmar-Bergström 1988; Swantesson 1992). Unless local lithologies are unusually susceptible to weathering pit development, the depths of these pits point to formation before the LGM. Elsewhere deeper weathering pits have been recognized as inherited forms from Marie Byrd Land, Antarctica (Sugden *et al.* 2005), islands in the Canadian Arctic (Boyer and Pheasant 1974; Dyke 1979; Ives 1966; Kaplan *et al.* 2001; Marsella *et al.* 2000; Watts 1983) and north-central Québec (Jansson and Lidmar-Bergström 2004). Surfaces adja-

cent to weathering pits up to 15–30 cm deep on small tors on eastern Baffin Island have given ^{10}Be exposure ages of 42–85 ka (Briner *et al.* 2003; Kaplan *et al.* 2001). Weathering pits are absent from granite domes covered by the last ice sheet in Yosemite, but present at sites at higher elevations covered by ice during pre-Wisconsin glaciations (Matthes 1930). Weathering pits may therefore help to constrain the distribution of non-erosive ice (Hall and Glasser 2003), the size of former nunataks (Le Coeur 1980; Matthes 1930; Sellier 1998) or depths of glacial erosion in the last glacial cycle in many formerly glaciated regions. Weathering pits should be seen as an important but often overlooked element in relict glacial landscapes (Kleman 1994; Kleman *et al.* 1994).

Conclusions

Weathering pits 1–140 cm deep occur on granite surfaces on a range of landforms in the Cairngorms. The absence of pits deeper than 5 cm from areas eroded by the last glaciers indicates that only shallow pits have formed in the postglacial period. Maximum pit depth is positively correlated with cosmogenic exposure age and the rate of pit deepening approximates to a sigmoidal function. Both measures show consistent relationships on individual rock landforms, indicating that pit depth can be used as a proxy for the age of rock surfaces on landforms across the mountains. Glacial modification of tor surfaces occurred in OIS 4–2 and 6, and perhaps also earlier periods. The deepest weathering pits occur on tors, where edge pits may exceed depths of 100 cm on tor summits. Cosmogenic exposure ages indicate that these surfaces have been exposed to weathering for 52–297 ^{10}Be ka and pit depths are consistent with exposure of tor summits before OIS 12. The combination of cosmogenic exposure ages with weathering pit depths greatly extends the area over which inferences can be made regarding the ages of rock surfaces in the Cairngorms and offers great potential for improving the understanding of age relationships in other rock landscapes, both within and beyond the limits of Pleistocene glaciation.

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