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Cosmogenic ^{10}Be and ^{26}Al exposure ages of tors and erratics, Cairngorm Mountains, Scotland: Timescales for the development of a classic landscape of selective linear glacial erosion

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Abstract

The occurrence of tors within glaciated regions has been widely cited as evidence for the preservation of relic pre-Quaternary landscapes beneath protective covers of non-erosive dry-based ice. Here, we test for the preservation of pre-Quaternary landscapes with cosmogenic surface exposure dating of tors. Numerous granite tors are present on summit plateaus in the Cairngorm Mountains of Scotland where they were covered by local ice caps many times during the Pleistocene. Cosmogenic ^{10}Be and ^{26}Al data together with geomorphic relationships reveal that these landforms are more dynamic and younger than previously suspected. Many Cairngorm tors have been bulldozed and toppled along horizontal joints by ice motion, leaving event surfaces on tor remnants and erratics that can be dated with cosmogenic nuclides. As the surfaces have been subject to episodic burial by ice, an exposure model based upon ice and marine sediment core proxies for local glacial cover is necessary to interpret the cosmogenic nuclide data. Exposure ages and weathering characteristics of tors are closely correlated. Glacially modified tors and boulder erratics with slightly weathered surfaces have ^{10}Be exposure ages of about 15 to 43 ka. Nuclide inheritance is present in many of these surfaces. Correction for inheritance indicates that the eastern Cairngorms were deglaciated at 15.6 ± 0.9 ka. Glacially modified tors with moderate to advanced weathering features have ^{10}Be exposure ages of 19 to 92 ka. These surfaces were only slightly modified during the last glacial cycle and gained much of their exposure during the interstadial of marine Oxygen Isotope Stage 5 or earlier. Tors lacking evidence of glacial modification and exhibiting advanced weathering have ^{10}Be exposure ages between 52 and 297 ka. Nuclide concentrations in these surfaces are probably controlled by bedrock erosion rates instead of discrete glacial events. Maximum erosion rates estimated from ^{10}Be range from 2.8 to 12.0 mm/ka, with an error weighted mean of 4.1 ± 0.2 mm/ka. Three of these surfaces yield model exposure-plus-burial ages of 295^{+84}_{-71}, 520^{+178}_{-141}, and 626^{+102}_{-85} ka. A vertical cosmogenic nuclide profile across the oldest sampled tor indicates a long-term emergence rate of 31 ± 2 mm/ka. These findings show that dry-based ice caps are capable of substantially eroding tors by entraining blocks previously detached by weathering processes. Bedrock surfaces and erratic boulders in such settings are likely to have nuclide inheritance and may yield erroneous (too old) exposure ages. While many Cairngorm tors have survived multiple glacial cycles,

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rates of regolith stripping and bedrock erosion are too high to permit the widespread preservation of pre-Quaternary rock surfaces.

Keywords: Cosmogenic elements; Tor formation; Exposure age; Erosion rates; Glaciation; Landform evolution

1. Introduction

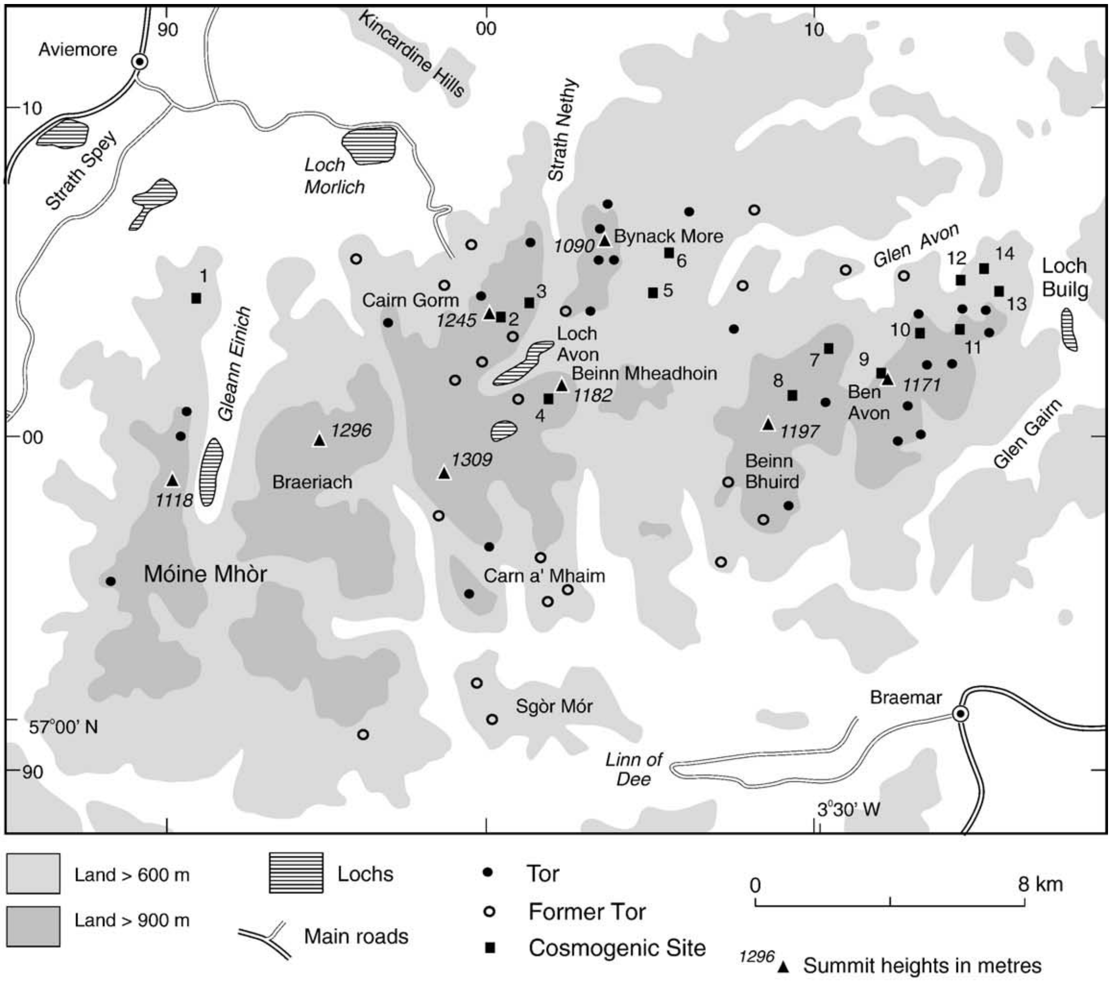
A tor is a residual, wart-like mass of bare bedrock rising conspicuously above its surroundings from a basal rock platform generally buried by regolith (Selby, 1982). In formerly glaciated regions, landform assemblages of tors, thick regolith, and blockfields have become widely recognised as indicating either the existence of unglaciated enclaves during all or part of the Pleistocene (Linton, 1952; Ives, 1958; Ballantyne and Harris, 1994; Brook et al., 1996; Small et al., 1997; Ballantyne, 1998; Steig et al., 1998; Anderson, 2002) or the former distribution of dry-based ice at the glacier bed and thereby zones of limited Pleistocene glacial erosion (Sugden, 1968; Sugden and Watts, 1977; Kleman, 1992; Hättestrand and Stroeven, 2002). As many tors are found on upland plateaus or along ridge crests, their existence places critical constraints on the thickness of glaciers and/or on rates of glacial erosion. For this reason, tors and associated landforms play an essential role in the accurate reconstruction of the extent, thickness, and internal dynamics of large Pleistocene ice sheets (Kleman and Borgström, 1994; Kleman and Stroeven, 1997; Hättestrand and Stroeven, 2002; Stroeven et al., 2002a; Briner et al., 2003; Landvik et al., 2003; André, 2004; Marquette et al., 2004).

In the case of preservation of landscapes by dry-based ice, tors and associated landforms have often been regarded as *preglacial* relic forms with an implied pre-Quaternary age (Linton, 1952; Sugden, 1968; Rea et al., 1996; Kleman and Stroeven, 1997; Hättestrand and Stroeven, 2002; André, 2004). The term "Quaternary" refers to the interval of oscillating glacial and interglacial periods initiated in the Pliocene at about 2.6 Ma and is not a formal chronostratigraphic unit according to the International Commission on Stratigraphy (Ogg, 2004). Other earth scientists informally use the term Quaternary to consist of the Holocene and Pleistocene epochs, with a lower boundary of 1.81 to 1.64 Ma (Hardland et al., 1990; Gradstein and Ogg, 1996).

Assessment of the age of tors generally has been made on the basis of tor height and rates of bedrock weathering. Because homogeneous crystalline bedrock abraded by glaciers in the last glacial period in arctic environments lowers at rates of about 0.1–1 m/Ma (André, 2002), the implication is that large tors with heights exceeding several meters may have required over 2.6 Ma to form and, in fact, could date from the Pliocene or earlier. This argument is strengthened in formerly glaciated areas by the fact that tor development proceeds only during interglacials and interstadials. One problem with this model is that bedrock weathering rates have been difficult to measure on a site-specific basis, and regional or average data have generally been applied. Another issue is that erosion rates for bare bedrock are likely much lower than rates of regolith formation and stripping. Tors grow because regolith is formed and removed more quickly from buried rock surfaces than from exposed surfaces. Differential weathering and erosion is reinforced by contrasts in fracture density between the relatively massive upstanding tor and its surroundings and by contrasts between the water-shedding surfaces of the tor and the water-holding properties of the surrounding regolith.

Cosmogenic nuclide surface exposure dating has begun to test the pre-Quaternary relic landform hypothesis by directly quantifying rates of bedrock erosion, rates of regolith formation, and ages of bedrock surfaces. These include studies in the Rocky Mountains (Small et al., 1997), Sweden (Fabel et al., 2002; Stroeven et al., 2002a,b), Arctic Canada and AK (Yuengling, 1998; Bierman et al., 1999; Marsella et al., 2000; Briner et al., 2003; Marquette et al., 2004), Svalbard (Landvik et al., 2003), and Antarctica (Sugden et al., 2005). They indicate maximum erosion rates of 0.5 to 19 mm/ka for exposed granite in alpine and arctic/antarctic environments. Rates of surrounding regolith formation and removal are several times to an order of magnitude greater (Small et al., 1999). Single nuclide (^{10}Be) exposure ages from these studies range from 42 to 173 ka and unambiguously establish that many tor surfaces have withstood multiple glaciations. When these ages are considered in light of probable ice cover histories and/or multiple nuclide ages based on the ^{10}Be and ^{26}Al pair, a small subset indicates tor survival for as long as 200 to 845 ka (Bierman et al., 1999; Fabel et al., 2002; Hättestrand et al., 2004; Stroeven et al., 2002a). However, cosmogenic evidence for tor surfaces older than the Pleistocene has not yet been reported. It is not clear if this represents a consequence of the tors sampled, as the tors studied are relatively subdued features with heights of ≤7 m, or if this represents a general finding.

Here, we present 31 cosmogenic nuclide analyses of large, well-developed tors from a key locality. With dozens of large tors and clear evidence for glaciation by local ice caps (Sugden, 1968; Brazier et al., 1996), the Cairngorm Mountains of Scotland (Fig. 1) offer



Cosmogenic Nuclide Sample Sites

Site	Sample ID	Locality
1	AS-1	Argyll Stone
2	CG-1A,1B	Cairn Gorm
3	CG-2	Cnap Coire na Spreidhe
4	BM-1, 2, 3A, 3B, 4	Beinn Mheadhoin
5	7/99/5	Creag Mhór
6	7/99/3, 6	Dagrum
7	RA-1, 2, 3, 4, 5	Clach na Gnùis near Stob an t Sluichd
8	BB	erratic west of Cnap à Chléirich
9	BA-1, BAA	Leabaidh an Daimh Bhuidhe (Ben Avon)
10	SBAF-1, 2	Stob Bac an Fhurain
11	MCB-1, 2	erratic at Mullach Lochan nan Gabhar
12	DDL-1, 2, 3	erratics on Dà Dhruim Lom
13	CB-1, 2	Clach Bhàn
14	CA-1, 2	An Cnoidh

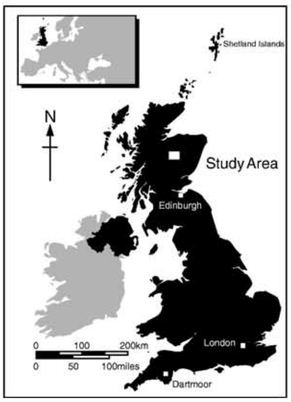


Fig. 1. Location of the Cairngorm Mountains showing tor groups and the location of cosmogenic nuclide samples.

exceptional opportunities to test the pre-Quaternary landscape preservation hypothesis. Many Cairngorm tors are palimpsest landforms (Kleman, 1992), with nonglacial features that have been clearly overprinted by glacial erosion. A continuum exists between Cairngorm tors exhibiting only subaerial weathering forms with no apparent evidence of glacial modification to those showing nearly complete demolition by glacial ice. We use cosmogenic ^{10}Be and ^{26}Al exposure dating (Lal, 1991; Bierman et al., 1999, 2002) of glacially exposed tor surfaces and glacially transported tor blocks to explore the timing of glacial modification and to place limits on rates of landscape development.

The cosmogenic exposure dating technique requires constant exposure and either independent knowledge of surface erosion rates or such low erosion rates that an assumption of zero erosion is applicable. Because Cairngorm tors have been subject to burial by multiple glaciations, exposure has not been constant and an ice cover duration model is required to interpret nuclide data as ages. For erosion rate corrections, we use measurements of quartz vein relief that are fully independent of the cosmogenic data. For ice cover duration estimates, we use a model developed from $\delta^{18}O$ records in ice and marine sediment cores. Finally, a vertical cosmogenic nuclide profile across a tor provides estimates of rates of bare bedrock erosion and regolith formation. These measurements permit testing of the hypothesis of a pre-Quaternary age for Cairngorm tors.

2. Setting

The Cairngorm Mountains consist of low relief upland plateaus underlain almost entirely by granite, with altitudes mostly between 900 and 1100 m (Fig. 1). In a classic example of selective linear erosion (Sugden, 1968), plateaus are cut by steep-sided glacial troughs and corries in which glacial erosion has been concentrated. The Cairngorms contain perhaps the best example of a glaciated tor field in the world, with 38 groups of tors. The tors include granite towers and monoliths with a mean height of 4.3 m and a range of 1 m to 23.5 m (Ballantyne, 1994; Mottram, 2001). The dimensions and architecture of the tors and their constituent blocks are controlled by orthogonal vertical joint sets. Many tors are summit tors or are developed along summit ridges. Spur tors are also present. Some tors have closely spaced sheet joints or "pseudobeds" (Ballantyne, 1994), circa 0.6–1.5 m thick that cause the landform to appear fretted in outline. Adjacent, more massive tors are composed of joint-bounded blocks >3 m in diameter. Fallen blocks fringe some tors but many rise directly from the surrounding regolith. The regolith generally comprises granular grus, 0.5–1.5 m deep, with a varied content of blocks of different size. Alpine podzolic soils with a mean depth of 334 mm ($n=46$) are widely developed on the plateau's regolith (Haynes et al., 1998). The soils often show evidence of Holocene erosion, indicating that the depth of these soils provides a minimum estimate of the rate of soil formation over the postglacial period. Granular disintegration is present around the base of many tors, indicating that some grus are directly derived from tors. Exposures provided by corrie and trough headwalls show that tors are not spatially associated with deep regolith, except for narrow alteration zones. Notches around some tor bases suggest that these tors have emerged through episodic regolith formation and stripping.

The glacial history of the Cairngorms and the lowlands of NE Scotland is given in Gordon and Sutherland (1993), Brazier et al. (1996), and Gordon (1997) (see also Table 5 for a brief summary). No evidence has been found of Scottish ice reaching the continental shelf west of Scotland until after 1.2 Ma. Extensive glaciation probably took place in marine oxygen isotope stage (OIS) 36 and 22. A step change occurred in the magnitude of Pleistocene climatic oscillations after 0.78 Ma, with evidence from the North Sea of extensive ice sheet glaciation in NE Scotland in OIS 18, 16, 12, 6, 4, and 2 (Holmes, 1997). The maximum extent of ice in northeast Scotland during the last glacial cycle is assigned to the Dimlington Stadial (Merritt et al., 2003). By circa 14 to 15.2 cal ky BP, ice appears to have largely retreated from the valleys of the northern Cairngorms (Sissons and Walker, 1974; Clapperton et al., 1975; Everest and Golledge, 2004). Brief and limited reoccupation of high altitude Cairngorm corries by glaciers occurred during the Loch Lomond Stadial at 11.5–12.9 cal ky BP in response to Younger Dryas cooling (Gordon, 1993).

3. Methods

3.1. Evolutionary model of tor development

Geomorphic techniques were used to develop a model of tor formation for the Cairngorms. Fourteen field sites were examined, and relative ages of tor surfaces and evidence for glaciation recorded. Relative age criteria for tors and boulder erratics were based upon observations of weathering features indicative of exposure. These included depth of weathering pits, opening of exfoliation joints, rounding of block edges, degree of grus development, discoloration of granite surfaces, and quartz vein relief. Evidence for glaciation of tors included trains of boulders leading back to tors, erratic boulders (including rare examples lying within weathering pits on tors), and translation of detached blocks on tors in an uphill direction. The form of tors was also evaluated in terms of the presence or absence of delicate perched boulders forming a tower superstructure. Such features are typical of tors in unglaciated granitic terrains, including Dartmoor in SW England (Linton, 1955).

Detailed results and discussion of our geomorphic studies are given elsewhere (Hall and Phillips, in press-a,b). These studies demonstrate that glacial disturbance of tors is widespread in the Cairngorms but varied in its degree. Based on geomorphic observations, we present a five-stage evolutionary model of the glacial modification of tors that bears many similarities to that developed by André (2004) in northern Sweden but which was developed independently. We used this evolutionary model to guide our cosmogenic nuclide sampling.

Unmodified tors (stage 1) show a delicate superstructure of perched and rounded blocks (Fig. 2). Processes of granular disintegration have completely detached these blocks from underlying bedrock. Rock surfaces have been sculpted by long-term granular disintegration to produce weathering pits more than 2 m deep on horizontal surfaces and on some block edges. Such tors are rare in the Cairngorms, though common in unglaciated regions such as Dartmoor. Progressive glacial modification involves firstly the removal of the superstructure (stage 2), followed by the entrainment of tor blocks along open horizontal exfoliation joints (stage 3). Glacial erosion in stages 2 and 3 proceeds by enveloping tor blocks in ice and moving them off the tor as a consequence of internal ice deformation. Evidence for basal sliding associated with wet-based glaciation is absent with surface features such as weathering pits being preserved. Ice-transported debris from tors can, in places, be traced as boulder trains

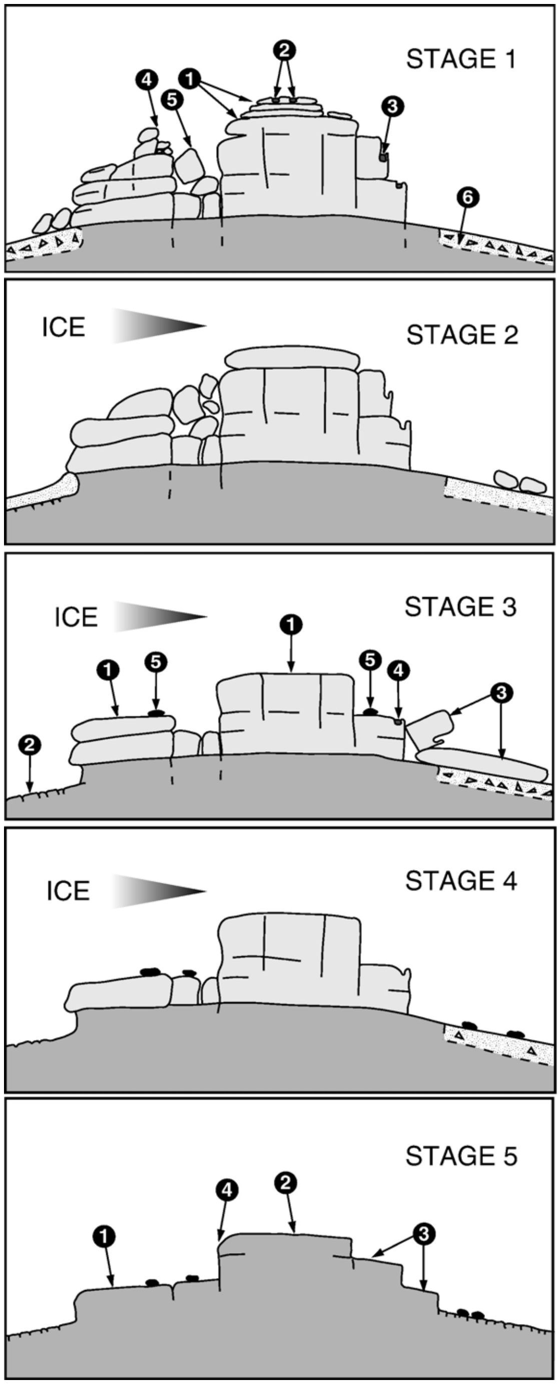


Fig. 2. Model of tor evolution (after Hall and Phillips, in press-a). Stage 1: tor is unmodified by glacial erosion. Features include 1: widening of exfoliation joints and rounding of block edges; 2: weathering pits on horizontal surfaces; 3: weathering pit spillway on vertical joint face; 4: superstructure of perched blocks; 5: toppled blocks; 6: regolith adjacent to tor. Stage 2: tor is encased in dry-based ice. Ice is frozen to ground surface but inter-ice flow occurs as indicated by arrow. Superstructure of detached blocks removed or translated short distances in downflow direction. Stage 3: continued modification of tor by flowing ice. Features include 1: unweathered surfaces with no weathering pits; 2: removal of regolith; 3: boulder train of translated blocks; 4: local preservation of weathered surface with weathering pits; 5: erratics overlying surfaces with and without weathering pits. Stage 4: tor reduced to upstanding plinth that resists further erosion by dry-based ice. Stage 5: wet-based, sliding basal ice reduces tor to low slab. Features include 1: erratics over low bedrock slab lacking open expansion joints; lack of regolith on stoss-side; 2: abraded surfaces lacking weathering pits; 3: lee-side plucking; 4: stoss-side abrasion.

along the former flow lines of the ice cap. Many small tors have been reduced to plinths or slabs (stage 4) by the wholesale removal of upstanding joint blocks. Tors composed of large monoliths cannot be demolished by movement of detached blocks within dry-based ice. When modified by wet-based ice, tors are shaped by block removal, abrasion, and lee-side plucking into roche moutonnées or whalebacks (stage 5). Such features in which basal sliding is implicated are concentrated adjacent to glacial troughs but also extend on plateau surfaces toward valley heads (Hall and Glasser, 2003).

3.2. Cosmogenic nuclide methods

In order to estimate the timing of glacial modification of the tors, we selected samples for cosmogenic ^{10}Be and ^{26}Al analysis from bedrock surfaces on stage 2–5 tors for which there is strong evidence that blocks have been removed by glacial entrainment. We also sampled several large glacial erratic boulders, including blocks traceable to individual tors, in order to develop a preliminary deglaciation chronology for the eastern Cairngorm summit plateaus. To constrain bedrock weathering rates and to place limits on the maximum exposure time of tors, the summits of deeply weathered stage 1 tors without clear evidence of glacial modification were sampled. Finally, we estimated the rate of tor emergence and regolith stripping (Heimsath et al., 2000, 2001) with a cosmogenic nuclide profile over the oldest sampled tor.

Samples for cosmogenic nuclide analysis were collected using a hammer and chisel from 14 sites (Fig. 1; Table 1). The location of each site was found using a GPS receiver to ± 10 m or better. Elevations were subsequently estimated to ± 5 m using a British Ordinance Survey 1:25,000 topographic map. Distant shielding from neighbouring objects was measured using a compass and inclinometer and corrected after Dunne et al. (1999). In all cases, except those

Table 1
Location of cosmogenic nuclide samples

Site	Sample ID	Locality	Latitude	Longitude	Altitude (m)	Grid reference
1	AS-1	Argyll Stone tor summit	57.1133	3.8083	829	NH 90515 04029
2	CG1A	Cairn Gorm tor replicate sample	57.1167	3.6383	1230	NJ 00850 04069
2	CG1B	Cairn Gorm tor replicate sample	57.1167	3.6383	1230	NJ 00850 04069
3	CG2	Tor summit at Cnap Coire na Spreidhe	57.1350	3.6267	1028	NJ 01605 05960
4	BM-1	Beinn Mheadhoin tor summit	57.0950	3.6133	1160	NJ 02313 01500
4	BM-2	Beinn Mheadhoin tor summit	57.0950	3.6133	1150	NJ 02335 01591
4	BM-3A	Beinn Mheadhoin tor summit near weathering pit	57.0967	3.6100	1182	NJ 02468 01683
4	BM-3B	Beinn Mheadhoin tor summit away from pit	57.0967	3.6100	1182	NJ 02468 01683
4	BM4	Beinn Mheadhoin tor summit roche moutonnée	57.1000	3.6067	1080	NJ 02710 02230
5	7/99/6	Creag Mhòr tor plinth	57.1250	3.5500	866	NJ 06158 04773
6	7/99/5	Dagrum tor plinth	57.1317	3.5500	848	NJ 06188 05503
6	7/99/3	Dagrum tor plinth	57.1350	3.5483	848	NJ 06365 05929
7	RF1	Clach na Gnùis tor summit	57.1100	3.4617	1010	NJ 11510 02971
7	RF2	Clach na Gnùis tor profile	57.1100	3.4617	1010	NJ 11507 02983
7	RF3	Clach na Gnùis tor profile	57.1100	3.4617	1010	NJ 11514 02981
7	RF4	Clach na Gnùis tor profile	57.1100	3.4617	1008	NJ 11524 02999
7	RF5	Tor plinth near Clach na Gnùis	57.1100	3.4600	1005	NJ 11581 03128
8	BB	Erratic west of Cnap à Chléirich	57.0933	3.4833	1156	NJ 10139 01181
9	BA 1	Leabaidh an Daimh Bruidhe tor summit	57.0983	3.4333	1171	NJ 13196 01840
9	BAA	Tor summit near Leabaidh an Daimh Bruidhe	57.1017	3.4317	1147	NJ 13368 01963
10	SBAF 1	Stob Bac an Fhurain tor plinth	57.1117	3.4233	1076	NJ 13759 03083
10	SBAF 2	Stob Bac an Fhurain tor plinth	57.1117	3.4233	1076	NJ 13759 03083
11	MCB 1	Mullach Lochan na Gabhar erratic	57.1100	3.4100	1070	NJ 14630 02952
11	MCB 2	Mullach Lochan na Gabhar erratic	57.1100	3.4100	1070	NJ 14630 02952
12	DDL 1	Da Dhruim Lom erratic	57.1300	3.4200	760	NJ 14148 05230
12	DDL 2	Da Dhruim Lom erratic at pit on side	57.1300	3.4200	760	NJ 14148 05230
12	DDL 3	Da Dhruim Lom erratic	57.1250	3.4200	813	NJ 13975 04685
13	CB-1	Tor summit southwest Clach Bhàn	57.1300	3.3817	860	NJ 16357 05187
13	CB-2	Clach Bhàn tor summit	57.1317	3.3850	869	NJ 16206 05367
14	CA 1	An Cnoidh unpitted surface	57.1350	3.3883	652	NJ 16005 05786
14	CA 2	An Cnoidh pitted surface	57.1350	3.3883	652	NJ 16005 05786

Site refers to site locality in Fig. 1.

involving nuclide inheritance corrections (samples CA-1 and DDL-1) and the tor vertical profile (samples RF-1 through RF-4), shielding was $<5^\circ$ and therefore negligible.

Samples were sawn to 1.5 to 4 cm thick and crushed to between 500 and 250 μm. Pure quartz was separated using differential acid dissolution with HF and HNO_3 in an ultrasonic bath (procedure modified from Bierman et al., 2002). Acid etching removes all traces of meteoric ^{10}Be and reduced total Al values to between 77 and 157 ppm. From 16 to 47 g of pure quartz were dissolved in HF and HNO_3 after addition of 0.25 to 0.5 mg Be carrier (Spectrosol 1000 mg/L Be) with an error weighted mean $^{10}Be/^{9}Be$ ratio of $1.16 \pm 0.11 \times 10^{-14}$, then fumed with $HClO_4$ to break up fluoride complexes. No Al carrier addition was necessary. Total Al was estimated after dissolution by inductively coupled plasma atomic emission spectrometer (ICP-AES) (samples AS-1, CG-1A, CG-1B, CG-2, BM-1, BM-2, BM-3A, BM-3B, BM-4, 7/99/6, 7/99/5) or flame atomic absorption spectrometry (FAAS) (remainder of samples). In several instances, discrepancies between standard Al additions in procedural blanks and both ICP-AES and FAAS results pointed to Al loss, possibly from overheating of dissolved samples during $HClO_4$ fuming with subsequent loss of Al as $AlCl_3$ (Ivy-Ochs, 1996, p. 28). Loss of Al causes a reduction in the $^{26}Al/^{10}Be$ ratio and can lead to erroneous interpretations of complex exposure and burial (Bierman and Caffee, 2002). We checked, and in several instances corrected, Al concentrations in samples exhibiting $^{26}Al/^{10}Be$ ratios significantly lower than the production ratio of 6. This was accomplished by analysing multiple aliquots of samples dissolved and fumed using $HClO_4$ at temperatures no higher than 150 °C.

Be and Al were isolated and purified by anion and cation exchange, and by precipitation as hydroxides (procedures modified from Ivy-Ochs, 1996; Bierman et al., 2002). Accelerator mass spectrometry (AMS) on flame-fired Be and Al oxide targets was performed at the Nuclear Physics Department, Australian National University using the ANU 14UD pelletron accelerator (Fifield, 2000). All AMS results are corrected for procedural blanks prepared and measured at the same time as the samples. Isotopic ratios were normalised to the National Institute Standards and Testing (NIST) $^{10}Be/^{9}Be$ standard SRM 4325 with an assumed value of 3.00×10^{-11} and to a $^{26}Al/^{27}Al$ standard prepared by S. Vogt with an assumed $^{26}Al/^{27}Al$ value of 4.11×10^{-11}. Ages and erosion rates were computed using a half-life of 1.51×10^{6} years for ^{10}Be and 7.17×10^{5} years for ^{26}Al (National Nuclear Data Center, information extracted from the NuDat database 12/20/04, http://www.nndc.bnl.gov/nudat2).

Single nuclide exposure ages and erosion rates were computed using production rates of 5.02 ± 0.27 ^{10}Be atoms g^{-1} a^{-1} and 30.6 ± 1.6 ^{26}Al atoms g^{-1} a^{-1}. These rates are for high latitude and sea level, with neutron spallation reactions contributing 97.4% and 97.8% to ^{10}Be and ^{26}Al production, respectively (Barrows et al., 2001; Stone, 2000). Scaling of the rates to the latitude and altitude of our sample sites was conducted after Stone (2000). Because of the high latitude of our study area and because the production rate we use for ^{10}Be was calibrated on the Isle of Skye (Stone et al., 1998) within 150 km of the Cairngorms and within 500 m of the altitude of our samples, production rate scaling uncertainties induced by atmospheric pressure or geomagnetic field variations are small. All reported uncertainties are propagated analytical and production rate errors at the 1σ level.

Sample thickness corrections were applied using an exponential model of production rate decrease, measured thickness, bulk density of 2.68 g cm^{-3}, and a neutron mean path length of 155 g cm^{-2}. Thickness corrections averaged 2.8% (Table 2).

Shielding by snow or rime ice reduces the production rate of cosmogenic nuclides and, if uncorrected, results in underestimates of exposure ages and overestimates of erosion rates. Mean annual precipitation at Cairn Gorm summit is >2000 mm, with snow lying at 900 m for more than 150 days/year and high snow densities increasing from 0.4 g cm^{-3} in November to as much as 0.7 g cm^{-3} in May (Manley, 1971; Dunn and Colohan, 1999). Snow cover on level, wind-shielded Cairngorm ground surfaces at 900 m elevation computed for present-day conditions depresses nuclide production rates by a maximum of 9% (Schildgen et al., 2005). Because all our samples were taken from bedrock surfaces and boulders >0.75 m in height, snow shielding is likely much lower, particularly because mean hourly wind speeds on Cairngorm summits can be as high as 150 km/h (Barton, 1987) and snow from tors and boulders is often blown into corries and other areas prone to snow collection (Purves et al., 1999). For this reason, we do not perform snow shielding corrections.

3.2.1. Cairngorm granite erosion rates

The interpretation of cosmogenic nuclide data from tors is complicated by erosion during ice-free intervals. We discuss all exposure ages corrected for an erosion rate of 1.6 ± 0.6 mm/ka. Applying this erosion rate results in negligible corrections for exposure ages of

Table 2
Details of cosmogenic nuclide analyses

Sample ID	Sample weight (g)	Be carrier mass (mg)	[Al] (ppm)	$^{10}Be/^{9}Be$ ($\times 10^{-12}$)[a]	±	$^{26}Al/^{27}Al$ ($\times 10^{-12}$)[b]	±	Scaling factor[c]	Horizon correction[d]	Thickness correction[e]
RF-1	33.680	0.316	77.4	3.747	0.150	66.633	4.189	2.537	1.000	0.974
RF-2	33.286	0.313	77.4	1.722	0.073	42.329	2.841	2.537	0.963	0.946
RF-3	33.718	0.313	77.1	1.054	0.047	26.064	2.896	2.537	0.963	0.971
RF-4	31.320	0.310	77.6	0.525	0.021	13.398	1.997	2.533	0.974	0.969
RF-5	34.752	0.302	n/a[f]	1.022	0.040	17.739	4.133	2.527	0.991	0.967
CB-1	34.677	0.311	64.9	0.783	0.032	19.610	4.536	2.280	1.000	0.965
CB-2	27.798	0.309	88.3	1.174	0.047	31.960	2.266	2.255	1.000	0.973
DDL-1	31.048	0.254	99.7	0.352	0.014	6.069	0.687	2.055	1.000	1.000
DDL-2	33.803	0.254	99.4	0.796	0.032	10.347	2.672	2.055	1.000	0.969
DDL-3	32.480	0.255	119.3	0.533	0.022	5.795	0.928	2.151	n/a[f]	0.982
MCB-1	36.279	0.219	110.2	1.234	0.049	15.929	1.106	2.703	1.000	0.988
MCB-2	23.032	0.254	124.4	0.533	0.021	10.541	0.918	2.703	1.000	0.979
CA-1	29.392	0.254	n/a[f]	0.330	0.015	n/a[f]	n/a[f]	1.872	1.000	0.958
CA-2	32.812	0.253	n/a[f]	2.453	0.085	n/a[f]	n/a[f]	1.872	1.000	0.955
SBAF-1	37.083	0.255	81.5	0.515	0.019	5.456	0.633	2.679	1.000	0.982
SBAF-2	28.725	0.249	100.2	0.443	0.018	7.620	0.767	2.679	1.000	0.968
BA-1	31.495	0.261	98.3	2.426	0.092	33.720	1.980	2.925	1.000	0.972
BB	30.176	0.257	105.2	0.372	0.018	4.897	0.686	2.859	1.000	0.981
BAA	30.942	0.249	129.7	1.974	0.070	18.435	1.624	2.859	1.000	0.958
AS-1	18.971	0.494	152.7	0.307	0.023	8.426	1.408	2.180	1.000	0.980
BM-1	30.382	0.494	157.8	0.473	0.041	8.080	2.435	2.868	1.000	0.966
BM-2	16.059	0.494	143.0	0.221	0.020	7.382	1.134	2.845	1.000	0.962
BM-3A	30.464	0.494	153.7	0.279	0.022	5.453	1.931	2.920	1.000	0.988
BM-3B	25.928	0.494	140.8	0.570	0.083	19.173	0.968	2.920	1.000	0.971
BM4	18.600	0.494	117.6	0.231	0.014	10.019	0.929	2.687	1.000	0.971
7/99/6	46.549	0.524	95.8	0.571	0.033	12.042	0.125	2.249	1.000	0.968
7/99/5	37.229	0.495	119.8	0.582	0.028	10.949	0.173	2.215	1.000	0.968
7/99/3	35.313	0.494	n/a[f]	0.223	0.012	6.888	2.154	2.215	1.000	0.968
CG-1A	21.966	0.494	136.2	0.221	0.018	8.168	3.653	3.035	1.000	0.974
CG-1B	31.294	0.555	155.8	0.334	0.036	7.047	1.114	3.035	1.000	0.974
CG-2	32.272	0.494	131.0	0.421	0.031	13.788	1.297	2.575	1.000	0.988

[a] Blank correction of $0.0116 \pm 0.0011 \times 10^{-12}$ applied.
[b] No blank correction applied.
[c] Scaling factor computed after Stone (2000) using present-day geographic latitude and altitude.
[d] Shielding by distant objects computed after Dunne et al. (1999); corrections for <5° neglected.
[e] Thickness correction uses exponential decrease in nuclide production, bulk density of 2.68 g cm^{-3}, and Λ of 155 g cm^{-2}.
[f] n/a: Not analyzed or not applicable.

<30 ka, but has significant effects for older surfaces and for the correction of nuclide inheritance. Our erosion correction is based upon measurement of an average relief of 24 ± 7 mm for 74 upstanding quartz veins on exposed, slightly weathered Cairngorm granite surfaces scoured by Late Devensian ice. Quartz veins several millimeter to several centimeter thick are fairly common in Cairngorm granite. Measurements were made on fresh-appearing bedrock surfaces displaying clear evidence of glacial moulding, which we infer to have been formed in OIS 2 during the Dimlington Stadial. Applying a deglaciation age of 15 ± 3 ka for these surfaces, an average erosion rate for Cairngorm granite by non-glacial processes of 1.6 ± 0.6 mm/ka is indicated. The deglaciation age estimate is based upon radiocarbon ages indicating ice-free Cairngorm valleys at 13.5–15.5 cal ky BP (Sissons and Walker, 1974; Clapperton et al., 1975; Everest and Golledge, 2004). This average erosion rate is likely higher along joint planes, in weathering pits, and in regolith because of greater water availability (Small et al., 1999; André, 2002). We also found a few localities where erosion rates on exposed bedrock were more than 2σ higher than our average rate. For example, at Spion Rocks (grid reference NJ 07780 01945), granite whalebacks in the middle of Glen Avon lack deep weathering pits and have quartz vein relief of up to 80 mm, indicating an erosion rate of about 5.3 mm/ka. Support for our average rate of 1.6 ± 0.6 mm/ka is provided by an average rate of 1 mm/ka for biotite-bearing crystalline rocks in Swedish

Lapland estimated by similar methods but with a data-set of over 3200 measurements (André, 2002). Rates of 10 mm/ka have been used to interpret cosmogenic nuclide surface exposure ages of Cairngorm granite boulder erratics (Everest and Golledge, 2004). Such a high bare bedrock erosion rate appears possible for some types of Cairngorm granite for long exposure periods (see discussion of cosmogenic nuclide results for the Argyll Stone tor, sample AS-1, in Results). However, we are not aware of independent geomorphic evidence supporting such a high bare bedrock erosion rate in the postglacial period.

3.2.2. Event surfaces and nuclide inheritance

We introduce the term “event surface” for bedrock surfaces that have had in situ produced cosmogenic nuclide concentrations reduced to low levels by rapidly acting geomorphic processes. Estimating surface exposure ages for geomorphic surfaces is appropriate when the thickness of the removed block is several times that of the effective cosmic ray attenuation thickness, a distance of about 0.6 m for Cairngorm granite (Lal, 1991; Dunne et al., 1999). For bedrock surfaces undergoing slow, steady erosion by granular disaggregation or spalling of blocks on the decimeter scale by frost shattering, nuclide concentrations are best interpreted in terms of maximum erosion rates (Lal, 1991; Small et al., 1997).

Removal of granite blocks with thickness > three meters, or five times the effective attenuation thickness, is required to reduce the spallation component of cosmogenic ^{10}Be and ^{26}Al to our approximate analytical detection limit. Cosmogenic nuclides from muon production remain in such surfaces but is neglected here. Because many Cairngorm tors have horizontal exfoliation joint spacing of only 0.6–1.5 m, tor plinths and stumps as well as erratic boulders derived from tors are likely to contain measurable nuclide inheritance. Corrections for nuclide inheritance are made for two samples where evidence of prior exposure and geometrical relationships permit a relatively precise estimate to be made. These inheritance corrections are for neutron spallation only and use an exponential decrease in production rate with shielding. Nuclide inheritance is estimated iteratively as

$$N_m = \frac{P_0 e^{-z_\varepsilon \Lambda^{-1} \rho}}{\lambda} \left(1 - e^{-\lambda(t_w - t_f)}\right) \qquad (1)$$

where t_w is the exposure age of the weathered surface (a); t_f is the exposure age of the fresh surface (a); P_0 is the local neutron spallation production rate on the weathered surface (atoms g^{-1} a^{-1}); z_ε is shielding thickness (cm) corrected for erosion over the time of exposure of the weathered surface; ε is the bedrock erosion rate of 1.6 ± 0.6 mm/ka used to correct shielding thickness over the exposure age of the weathered surface; λ is the radionuclide decay constant (a^{-1}); Λ is the neutron attenuation coefficient (155 g cm^{-2}); and ρ is bulk density (taken as 2.68 g cm^{-3} from measurements made on Cairngorm granite). Nuclide inheritance expressed as an exposure age is subtracted from the apparent exposure age of the fresh surface and a new estimate of nuclide inheritance is computed. This continues until convergence occurs after several iterations. Reported errors for the inheritance-corrected exposure ages are propagated errors for shielding thickness and AMS uncertainties.

4. Results

Details of cosmogenic nuclide data are given in Table 2 and summarised in Table 3. All exposure ages are discussed on the basis of an erosion rate of 1.6 ± 0.6 mm/ka; we also report ages on the basis of zero erosion and 5 mm/ka in Table 3. Because of episodic ice cover, reported surface exposure ages generally do not reflect calendrical years before the present and a shielding duration model is required to interpret them. This model is presented in our Discussion section.

Cosmogenic ^{26}Al ages show good agreement with ^{10}Be ages for all but four samples that are discussed further below (Fig. 3A). Except for these samples, ^{26}Al/^{10}Be ratios are (within 1σ error) equivalent or greater than the ^{26}Al/^{10}Be production ratio of 6.10 ± 0.08 and plot within or above the erosion island (Fig. 3B). This precludes combined burial and exposure histories of over 200 ka for all but the four samples with discordant ^{26}Al and ^{10}Be ages (Bierman et al., 1999). For these reasons, only ^{10}Be ages are discussed below, except in the cases of the four discordant samples.

Based upon geomorphic observations, the sampled tors are placed into three classes based upon evidence for glacial modification and degree of weathering. The classes correspond to stage 1, stages 2 and 3, and stages 4 and 5 of our tor evolutionary model. Generally good agreement was found between these geomorphic classes and surface exposure ages.

4.1. Exposure ages and erosion rates from stage 1 tors unmodified by glacial erosion

Tors lacking clear evidence of glacial modification are relatively uncommon in the Cairngorms. Those

Table 3
Summary of cosmogenic ^{10}Be and ^{26}Al surface exposure ages, maximum ^{10}Be erosion rates, and interpreted ages after application of ice cover model (errors are 1σ analytical uncertainties; ε refers to erosion rate correction applied when computing age)

Sample ID	^{10}Be age (ka) ε=0 mm/ka	±	^{10}Be age (ka) ε=1.6 mm/ka	±	^{10}Be age (ka) ε=5 mm/ka	^{26}Al age (ka) ε=0 mm/ka	±	^{10}Be erosion rate (mm/ka)	±	Interpreted ages (ka BP)[a]
CA-1	20.7	1.6	21.4	1.6	22.9	n/a[b]	n/a[b]	27.7	2.5	115
CA-1[c]	n/a	n/a	15.8[b]	3.1	n/a	n/a[b]	n/a[b]	n/a[b]	n/a[b]	101
CA-2	146.6	9.9	189.5	12.8	–[d]	n/a[b]	n/a[b]	3.8	0.3	471[e]
DDL 1	19.2	1.4	19.7	1.4	21.0	22.0	3.0	30.0	2.6	111
DDL-1[a]	n/a[b]	n/a[b]	16.3[e]	2.3	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]	n/a[b]
DDL 3	26.3	1.9	27.3	2.0	29.8	23.4	4.1	21.9	1.9	123
DDL 2	40.2	2.9	42.6	3.0	49.5	37.7	10.1	14.2	1.2	183
BB	14.8	1.1	15.1	1.2	15.8	13.0	2.0	38.9	3.6	82
SBAF 1	17.8	1.2	18.2	1.3	19.3	n/a[b]	n/a	32.4	2.8	103
SBAF 2	19.5	1.4	20.1	1.5	21.4	21.2	2.6	29.5	2.6	115
7/99/3	18.5	1.5	18.9	1.5	20.1	n/a[b]	n/a	32.5	3.1	105
CG1A	21.3	2.2	21.9	2.3	23.4	27.5	12.5	28.8	3.3	116
CG1B	25.9	3.3	26.9	3.4	29.1	27.1	4.7	23.7	3.2	122
BM-1	36.4	3.8	38.3	4.0	43.7	34.2	5.0	15.8	1.8	138
BM-2	31.6	3.6	32.9	3.7	36.5	28.6	3.8	19.5	2.4	130
BM-3A	20.2	2.0	20.7	2.1	22.0	21.1	3.7	30.3	3.4	115
BM-3B	50.5	8.1	54.2	8.7	65.4	71.7	8.2	12.0	2.0	216
BM4	30.0	2.5	31.3	2.6	34.7	33.2	5.1	19.3	1.9	129
7/99/5	47.7	3.5	51.0	3.8	60.8	45.3	3.5	12.5	1.1	213
7/99/6	38.9	3.1	41.1	3.3	47.0	39.2	2.9	15.4	1.5	173
CB-1	42.8	3.0	45.6	3.2	53.5	42.8	10.4	13.4	1.2	195
CB-2	80.8	5.6	91.7	6.4	140.9	98.1	9.9	7.0	0.6	307[e]
MCB 1	37.4	2.7	39.5	2.9	45.3	48.7	4.9	15.3	1.3	171
MCB 2	29.5	2.1	30.8	2.2	34.1	36.2	4.1	19.5	1.7	128
CG2	33.1	3.1	34.6	3.2	38.6	n/a	n/a	18.3	1.9	132
BA 1	96.9	6.7	113.1	7.8	218.5	88.6	8.3	5.8	0.5	338[e]
BAA	79.1	5.4	89.4	6.1	135.0	65.2	7.4	7.2	0.6	305[e]
AS-1	48.6	4.7	52.1	5.0	62.8	45.0	12.1	12.0	1.3	214
RF1	199.9	13.9	297.0	20.7	–[d]	164.8	15.8	2.8	0.2	675[e]
RF2	95.6	6.8	111.4	7.9	209.9	108.8	10.7	5.9	0.5	337[e]
RF3	55.5	4.1	60.3	4.4	76.0	63.5	8.4	10.3	0.9	222
RF4	28.8	2.0	30.0	2.1	33.1	31.9	5.3	19.9	1.7	127
RF5	49.3	3.4	53.0	3.7	64.4	n/a[b]	n/a[b]	11.6	1.0	215

[a] Ages interpreted with ice cover duration model.
[b] n/a: Not applicable or not analyzed.
[c] Indicates correction for nuclide inheritance.
[d] Age cannot be computed for this erosion rate.
[e] Estimated with ODP 607 record; all other model ages estimated with GRIP record.

displaying the delicate superstructure typical of the "woolsack" tors of SW England are largely confined to the summits and ridge of Ben Avon (Hall and Phillips, in press-a). The defining characteristic of these tors is advanced weathering features indicative of long periods of weathering. Micro-weathering forms such as rill lapies and weathering pits up to 160 cm deep are extensively developed. While the best developed weathering forms are displayed on the uppermost surfaces of these tors, pits up to 70 cm deep have been found close to the base of the tor. Tors with these features are regarded as unmodified by glacial erosion. They are the best candidates for estimating the maximum exposure ages of tors in the Cairngorms. However, because nuclide concentrations in such landforms are approaching limits determined not by rapidly acting events such as glacial erosion but rather by long-term rates of granular disaggregation and/or small block spalling, interpreting their cosmogenic nuclide concentrations as maximum erosion rates rather than exposure ages may be more appropriate (Lal, 1991; Small et al., 1997).

We sampled four examples of unmodified tors in the Ben Avon area. Fulfilling expectations, the tors yielded by far the highest exposure ages and the lowest maximum erosion rates of our study. Three of the tors are unique in our dataset in possessing depressed $^{26}Al/^{10}Be$ ratios (Fig. 3B). This demonstrates long periods of ice

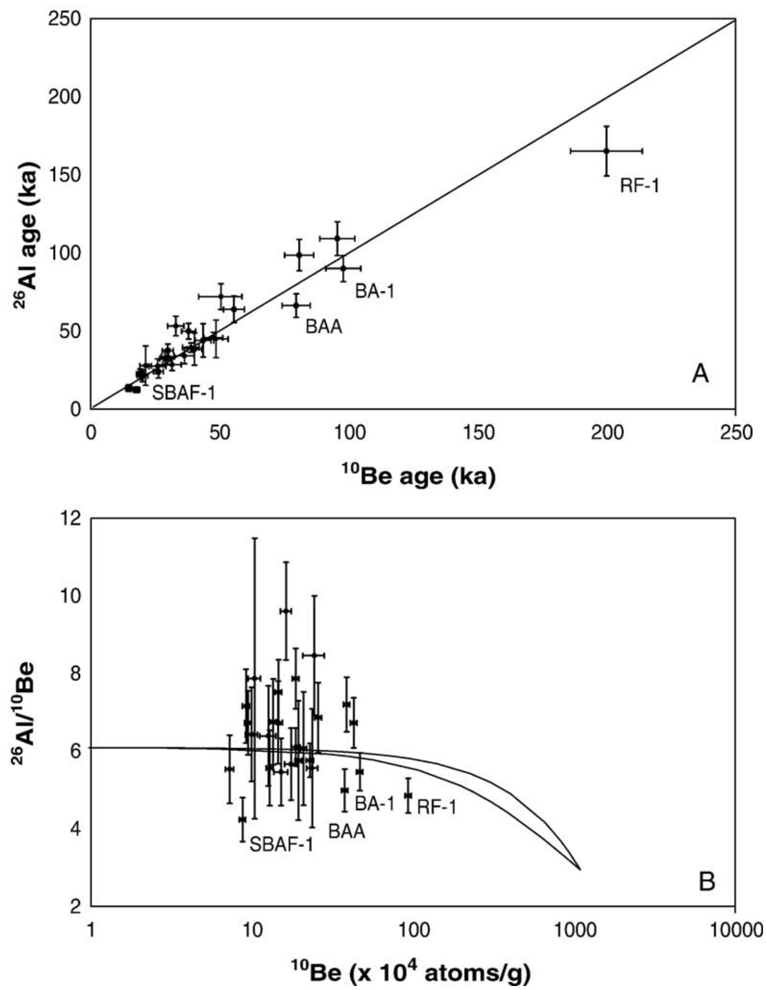


Fig. 3. (A) Plot of ^{10}Be and ^{26}Al ages with 1:1 line shown; (B) plot of ^{10}Be and ^{26}Al/^{10}Be; erosion island (Lal, 1991) indicated by solid lines. All errors are 1σ.

cover for the Ben Avon area. Model two-nuclide ages can be calculated for these samples (Table 4) by assuming a simplified exposure history whereby all exposure prior to deglaciation by the last ice sheet is gained first, followed by uninterrupted burial (Bierman et al., 1999; Fabel et al., 2002).

The large Ben Avon summit tor at Leabaidh an Daimh Bhuidhe has a ^{10}Be exposure age of 114.6 ± 7.9 ka and a two-nuclide age of 295_{-71}^{+84} ka (sample BA-1). The nearby unnamed tor about 200 m to the northeast yielded an ^{10}Be exposure age of 90.2 ± 6.1 ka and a two-nuclide age of 520_{-141}^{+178} ka (sample BAA). At Clach na Gnùis (Fig. 4), the tor's superstructure stands 10 m above the ground and has several 110-cm deep weathering pits. A sample from this surface (sample RF-1) yielded the oldest ^{10}Be exposure age observed in the Cairngorms of 297.0 ± 20.7 ka and a two-nuclide age of 626_{-85}^{+102} ka. Clach Bhàn is a prominent, highly weathered tor on the northeastern ridge of Ben Avon. The tor is notable for its remark-

Table 4
Two-nuclide ages for Ben Avon tors (method after Fabel et al., 2002)

Sample	Exposure prior to shielding (ky)	Shielded time (ky)	Time since deglaciation (ky)	Total history (ky)	+	−
BA-1	113	174	16	303	82	69
BAA	82	449	16	547	175	145
RF-1	297	319	16	632	76	64

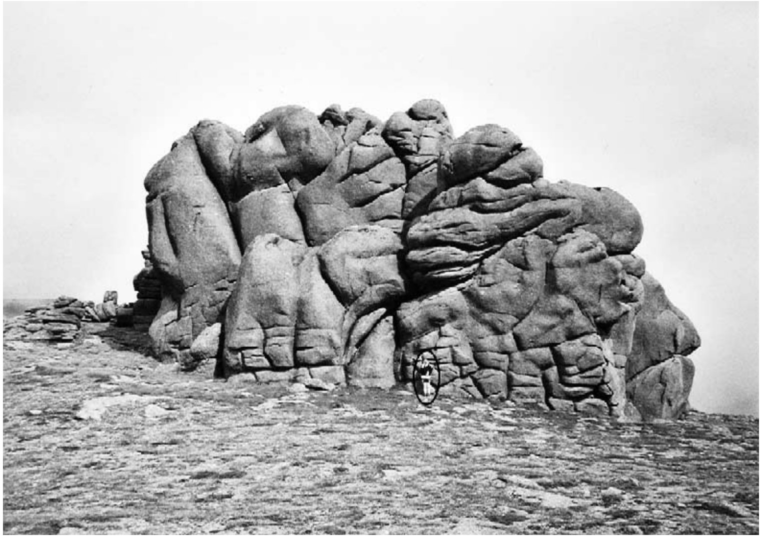


Fig. 4. Tor at Clach na Gnùis. Circled figure is 1.8 m in height.

able array of deep weathering pits, up to 140 cm deep, that were reputedly used for bathing. The summit surface yielded an exposure age of 91.7 ± 6.4 ka. The $^{26}Al/^{10}Be$ ratio for this sample was 7.2 ± 0.7. This value precludes burial by ice for periods exceeding about 200 ka, and a meaningful two-nuclide age cannot be calculated.

The Argyll Stone (Clach Mhic Cailein) is an unusual, relatively low elevation stage 1 tor found on the crest of a ridge above Gleann Einich at 845 m. Sugden (1968) found schist erratics around the Argyll Stone, indicating that this tor was overridden by active ice from the Spey valley to the SW of the tor. A sample from the summit (sample AS-1) has the lowest exposure age for a stage 1 tor of 52.1 ± 5.0 ka and the highest maximum erosion rate of 12.0 ± 1.3 mm/ka. No long-term burial by ice is indicated by the ^{26}Al and ^{10}Be data for this site.

We also place the highly weathered summit surface at An Cnoidh (Fig. 5; sample CA-2) into the category of glacially unmodified surfaces even though the tor block clearly has been translated slightly by flowing ice. This is because the weathered surface of the tor summit displays no features indicative of glacial mod-

Fig. 5. Tor at An Cnoidh that has been shoved ~2.8 m SW and uphill by ice motion along a horizontal joint surface; sample CA-2 from deeply pitted upper surface has ^{10}Be age of 189.5 ± 12.8 ka; sample CA-1 from slightly weathered lower surface has age of 21.4 ± 1.6 ka; correction of this age for nuclide inheritance gives a revised ^{10}Be age of 15.8 ± 1.7 ka.

ification. Its ^{10}Be age of 189.5 ± 12.8 ka mm/ka and maximum erosion rate of 3.8 ± 0.3 mm/ka show that this inference is well founded. We failed to obtain a ^{26}Al measurement for this sample and therefore cannot compute a two-nuclide age for it.

If the stage 1 tor samples are interpreted as maximum erosion rates, they have a range from 2.8 to 12.0 mm/ka (Table 3), and an error weighted mean of 4.1 ± 0.2 m/ka. The lowest maximum erosion rate of 2.8 ± 0.3 mm/ka is from the summit of Clach na Gnùis; it has an averaging time of about 200 ka of exposure. This is in reasonable agreement with the rate of 1.6 ± 0.6 mm/ka estimated from Cairngorm granite quartz vein relief over a much shorter averaging time of 15 ± 3 ka. Cosmogenic nuclide averaging times reflect the time needed to erode a thickness of one neutron mean path length (Lal, 1991). Data presented in Section 4.4 suggest that sample RF-1 is not in erosional steady-state and that even this low erosion rate may be too high. Nevertheless, the error weighted mean of the maximum erosion rates from the stage 1 tors of about 4 mm/ka is our best cosmogenic nuclide estimate of the long-term rate at which intact, exposed Cairngorm granite weathers for three reasons. First, individual bedrock erosion rates vary over short distances likely in response to the proximity of weathering pits or joints where erosion proceeds more rapidly. Our stage 1 tor samples were obtained from highly weathered localities relatively close to deep weathering pits and may reflect this. Second, lithologic controls such as megacrystic porphyries may weather more rapidly than most Cairngorm granite. An example of this is the Argyll Stone (AS-1). Finally, we suspect that erosion rates do not proceed linearly with time. Samples from stage 1 tors were noticeably easier to remove than those from less weathered surfaces. The weathering of biotite and feldspar in the granite has produced a weakened surface layer 3 to 5 cm thick enriched in Fe and Mn oxides. Surfaces from these sites are indeed likely to erode more rapidly than those from the much fresher surfaces on which quartz vein relief was measured.

4.2. Exposure ages from stage 2 and 3 glacially modified tors with advanced weathering

This class of samples consists of tors with advanced weathering features such as deep pitting and widening of exfoliation joints into pseudobedding, yet also exhibit signs of glacial modification ranging from loss of superstructure and blocks to reduction of the tor to a stump (Hall and Phillips, in press-a). We sampled tor summit surfaces believed to have lost superstructure to glacial erosion. These tors generally have ^{10}Be exposure ages older than the OIS 2, although the range is considerable—from about 19 ka to 54 ka.

Multiple phases of glacial entrainment and erosion can be demonstrated at these tors. The clearest examples are the tor plinths at Dagrum (samples 7/99/6 and 7/99/3; Fig. 6) and Creag Mhór (sample 7/99/5). Glacial modification has removed all superstructure and most surrounding debris, reducing the tors to bedrock platforms about 1 m high. Prolonged exposure after glacial modification is indicated by weathering pits 21 to 35 cm deep on the plinth surface (Hall and Phillips, in press-b). Many slightly weathered erratics are present on adjacent ground. Evidence that these erratics date

Fig. 6. Tor plinth at Dagrum (sample 7/99/6) with a ^{10}Be age of 38.9 ± 3.1 ka. Note the presence of weathering pits on the glacially modified surface and glacial erratics in background (arrows).

from a second phase of ice movement younger than the development of the plinth form is given by the presence of small erratic cobbles in weathering pits (cf. Briner et al., 2003). The plinth surfaces have ^{10}Be exposure ages of 41.1 ± 3.3 ka (sample 7/99/6) and 51.0 ± 3.8 ka (sample 7/99/5). A nearby slab with weathering pits up to 12 cm deep has an exposure age of 18.5 ± 1.5 ka (sample 7/99/3).

At Beinn Mheadhoin, the lowermost of the tors (sample BM-4) has a streamlined, roche moutonnée form suggestive of erosion by wet-based ice (Sugden, 1968). The sampled surface is pitted, indicating that erosion likely occurred earlier than OIS 2 and that OIS 2 erosion was limited on the streamlined surface (cf Briner and Swanson, 1998). The ^{10}Be exposure age of 31.3 ± 2.6 supports this interpretation. Tors along the Beinn Mheadhoin summit ridge are much larger tower structures, up to 12 m high, with well-developed pseudobeds (Fig. 7). Weathering pits are locally present. Glacial modification is suggested by the lack of superstructure and the general absence of debris around the tors. A sample from the summit tor yielded a ^{10}Be exposure age of 54.2 ± 8.7 ka (sample BM-3B). An adjacent sample taken from near the side of a 60-cm deep weathering pit yielded a ^{10}Be age of 20.7 ± 2.1 ka (sample BM-3A). This age probably reflects increased rates of subaerial erosion associated with the weathering pit. Samples from two other tors at Beinn Mheadhoin gave ^{10}Be exposure ages of 38.3 ± 4.0 and 32.9 ± 3.7 ka (samples BM-1 and BM-2).

Similar relationships are present at the namesake summit of the study area, Cairn Gorm. On the slab-like summit tor SW of the weather station, replicate samples CG-1A and CG-1B have an error weighted-average ^{10}Be age of 24.4 ± 3.5 ka. The tor has relatively well-developed pseudobedding and at least eight weathering pits on its upper surface. The tor on the spur of Cairn Gorm, called Cnap Coire na Spreidhe, yielded a ^{10}Be exposure age of 34.6 ± 3.2 ka (sample CG-2). The tor is a glacially modified plinth with good development of pseudobeds.

At the tor lying to the SE of Clach Bhàn (sample CB-1), glacial modification is indicated by a lack of superstructure. This surface yielded an exposure age of 46.5 ±3.3 ka.

4.3. Exposure ages from stage 4 and 5 glacially modified tors with little weathering, and from erratic boulders

This sample group consists of tors reduced by glacial modification to plinths and stumps. The tors lack weathering pits >10 cm deep and have limited development of pseudobedding (Hall and Phillips, in press-a,b). Erratic boulders, all composed of locally derived Cairngorm granite, are also placed into this category. Exposure ages from this class of surface range from about 15 to 43 ka. We documented significant nuclide inheritance in two samples from this group and infer that inheritance is widespread in other samples. Inheritance complicates efforts to define the timing of deglaciation of the Cairngorm summit plateaus and is likely responsible for ages older than OIS 2 for many of these samples.

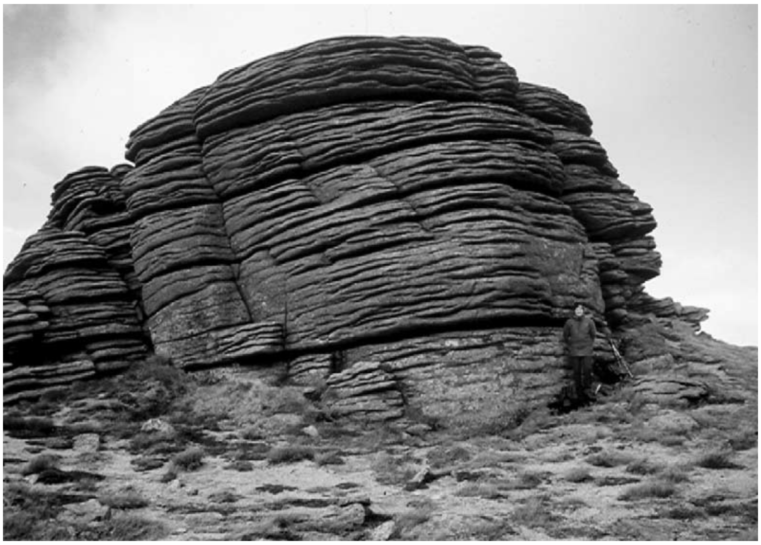


Fig. 7. Tor at Beinn Mheadhoin showing pseudobedding. Upper surface of tor has ^{10}Be exposure age of 38.3 ± 4.0 ka (sample BM-1). Figure at right is 1.5 m tall.

The relationship between weathering features, exposure age, and nuclide inheritance is best shown at An Cnoidh (Fig. 5). Here, the top of a small stage 1 tor with advanced weathering features has been translated by ice motion ~2.8 m SW and uphill along a horizontal exfoliation joint to reveal a much less weathered surface. The deeply pitted and weathered surface of the tor (sample CA-2) exhibits no visible ice modification features and yields a ^{10}Be age of 189.5 ± 12.8 ka and a maximum erosion rate of 3.8 ± 0.3 mm/ka. The unweathered surface (sample CA-1) lacks pitting and has a ^{10}Be age of 21.4 ± 1.6 ka. This age must include a component of nuclide inheritance as it lies only 1.80 m below the heavily weathered surface. Correction for nuclide inheritance using the method described in Section 3.2.2 gives a revised ^{10}Be age of 15.8 ± 1.7 ka.

On Dà Dhruim Lom, numerous large, locally derived erratic boulders are present. The sampled erratic boulder has weathering pits on one side indicating rotation of the erratic during transport from its original position on a weathered bedrock surface (Fig. 8). This erratic has a ^{10}Be exposure age of 19.7 ± 1.4 ka on its upper surface (sample DDL-1) and a ^{10}Be age of 42.6 ± 3.0 ka on the side with the weathering pits (sample DDL-2). Because the upper surface is separated by only 1.5 m from the weathered surface with prior exposure, it must contain significant nuclide inheritance. After correction using the method in Section 3.3, the upper surface yields a revised age of 16.8 ± 2.3 ka. This estimate incorporates an uncertainty of 25% in shielding thickness that reflects the irregular geometry of the erratic. Another erratic on Dà Dhruim Lom yields a ^{10}Be age of 27.3 ± 2.0 ka from its upper surface (sample DDL-3). We interpret that the original weathered surfaces of these blocks contain a substantial inherited nuclide component.

On the summit plateau west of Ben Avon, sample BB is an isolated erratic boulder with a ^{10}Be exposure age of 15.1 ± 1.2 ka. We interpret this age as being free of nuclide inheritance. The two inheritance-corrected ages from An Cnoidh and Dà Dhruim Lom together with the erratic sample BB have an error weighted mean of 15.6 ± 0.9 ka that is our best estimate of the timing of deglaciation of the eastern Cairngorm summit plateaus. This estimate is consistent with a radiocarbon date of 14,050–13,450 cal yBP at nearby Loch Builg (Clapperton et al., 1975) that shows that valleys of the eastern Cairngorms were deglaciated prior to ~14 ka.

On the summit plateau west of Ben Avon at Stob Bac an Fhurain, erratic boulders can be approximately matched to event surfaces on a tor plinth (Fig. 9; Hall and Phillips, in press-a). Two samples from the eroded tor surface were taken. Sample SBAF-1 is from a slightly weathered surface that can be matched with the erratic boulder on the left of Fig. 9. Sample SBAF-2 is from the edge of a weathered surface on the plinth with pits up to 22 cm deep. We could not identify a specific erratic boulder that formerly covered this sampling site, but it is not the large boulder on the right in Fig. 9. Despite the apparent differences in weathering, the samples yielded statistically equivalent ^{10}Be ages of 18.2 ± 1.3 and 20.5 ± 1.5 ka. We infer that both sam-

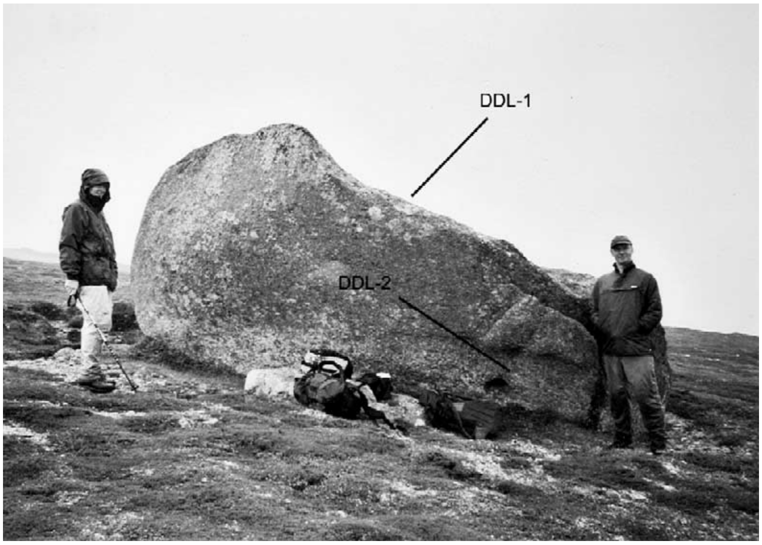


Fig. 8. Erratic boulder on Dà Dhruim Lom with weathering pit on side indicating rotation of the erratic during transport by glacial ice from dismembered tor or similar weathered bedrock surface. Sample DDL-1 from the top of the erratic; sample DDL-2 from the weathering pit side. When corrected for nuclide inheritance, the age of sample DDL-1 is 16.3 ± 2.3 ^{10}Be ka.

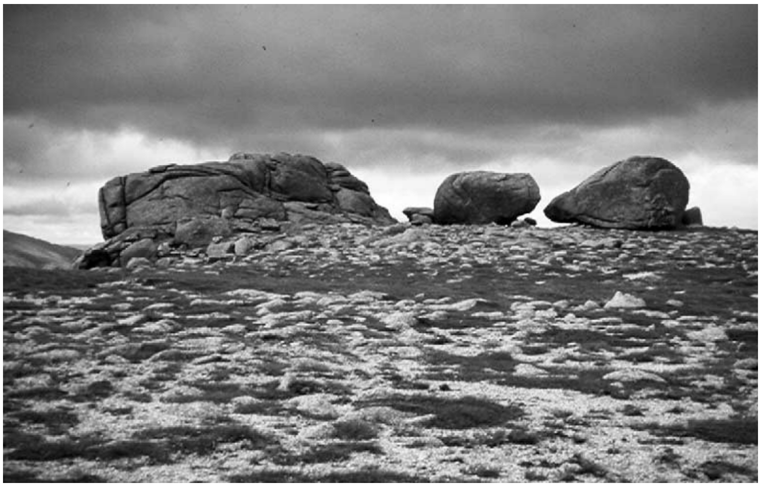


Fig. 9. Tor plinth on the Ben Avon summit plateau at Stob Bac an Fhurain. Erratics on right side of photo are traceable to the tor plinth (Hall and Phillips, in press-a). The plinth has ^{10}Be exposure ages of 18.2 ± 0.2 and 20.1 ± 0.3 ka (samples SBAF-1 and SBAF-2, respectively).

pling sites were initially covered by detached slabs that were transported off the tor during OIS 2. The ages for SBAF-1 and -2 must include ca. 16 ka of time since deglaciation together with an inherited component derived from penetration of cosmic radiation through the slabs that used to cover the present-day surfaces. Uncertainties regarding the shielding geometries are too large to permit a correction for this inheritance. However, we can place some limits on the exposure age of the former tor summit at this site before its dismemberment. Based upon the measured nuclide concentration in SBAF-1 and shielding of 150 to 200 cm by the erratic boulder that used to cover it, the former tor top had an exposure age in the range of 35 to 90 ka. Sample SBAF-1 also has a depressed $^{26}Al/^{10}Be$ ratio of 4.2 and plots below the erosion island (Fig. 3B). This appears to be the result of an erroneous Al concentration measurement, although we are unsure how this occurred. The two-nuclide age of 1.94 Ma computed with the SFAF-1 data is nonsensical in that it requires an exposure-time to burial-time ratio of 1% that is clearly at odds with the reconstructed exposure history of the site and the general glacial history of the Cairngorms (Table 5).

In a similar setting, two large erratic boulders at Mullach Lochan nan Gabhar (samples MCB-1 and MCB-2) appear to have been derived from dismemberment of one of the summit tors of Ben Avon by glacial ice. Samples taken from the top horizontal surfaces of the erratics yielded ^{10}Be exposure ages of 37.4 ± 2.7 and 29.5 ± 2.1 ka. While possible that these erratics were transported prior to OIS-2, we probably sampled surfaces with large nuclide inheritances.

Collectively, these results are consistent with limited glacial modification of tors by the last Scottish ice sheet and deglaciation of the summit plateaus at 15.6 ± 0.9 ka. Nuclide inheritance, reflecting partial removal of exposure gained prior to the Late Devensian, complicates establishing the timing of deglaciation of the Cairngorms. While erratic boulders are the most likely geomorphic surfaces free of nuclide inheritance, in settings like the Cairngorms in which boulders have undergone limited transport from stable sites with long exposure histories, inheritance can still be significant.

4.4. Tor emergence rates

Tor emergence rates are important for testing the relic pre-Quaternary landscape hypothesis. These rates are controlled by the interplay between two factors: bedrock erosion rates of intact granite and rates of regolith stripping. Tors exist because surrounding regolith is formed and removed faster than exposed bedrock is eroded. In order to place limits on rates of tor emergence, we sampled a vertical nuclide profile at Clach na Gnùis from the tor summit to a position 2 m above the ground (Fig. 4; samples RF-1 through RF-4). All of the latter samples were from horizontal surfaces with no apparent evidence of glacial modification. Nuclide concentrations are corrected for local shielding (Table 2). We also dated the event surface of a nearby glacially modified stage 4 plinth (RF-5) with weathering pits 29 cm deep. This event surface has a ^{10}Be exposure age of 53.0 ± 3.7 ka. The close proximity of this glacially eroded surface to an unmodified tor is typical of the Cairngorms.

Nuclide concentrations show a systematic decrease from the top of the tor toward the ground at Clach na Gnùis (Fig. 10). A function can be fit to the data and the

Table 5
Comparison of regional glacial history with the predicted duration of shielding by glacial ice during the past 2.46 Ma based upon δ^{18}O values in marine sediment and ice cores

Oxygen isotope stage	Shielding duration[a]	Shielding duration[b]	Regional palaeoclimatic reconstructions
1 (0–12.5 ka)	1.3 ka 10.7%	0.9 ka 6.9%	Glaciation during Younger Dryas at 11.5–12.9 cal ky BP confined largely to corries and valley heads. Remainder of stage ice-free.
2 (12.5–24.1 ka)	10.1 ka 95%	8.6 ka 75%	Deglaciation shown by ice-free conditions in several Cairngorm valleys at ca. 14–15 cal ka (Sissons and Walker, 1974; Clapperton et al., 1975; Everest and Golledge, 2004). Several large moraines and proglacial lakes in the Cairngorms formed between 13 and 17 ka (Everest and Golledge, 2004), indicating summits subject to glacial cover. Late Devensian ice sheet glacial maximum at ca. 22 ka and major re-advance at 18 ka (Sejrup et al., 1994).
3 (24.1–59.0 ka)	33.9 ka 97%	22.6 ka 64%	Partial ice cover in lowland NE Scotland during parts of OIS 3 (Hall et al., 1995) and full ice cover during part of OIS 4 (Merritt et al., 2003). Cold interstadial conditions in lowland Scotland at ca. 30 ka when much of Scotland was ice free (Whittington et al., 2003; Bos et al., 2004). No records of organic material in OIS 4 from sites in lowland NE Scotland.
4 (59.0–73.9 ka)	14.2 ka 96%	10.1 ka 73%	
5 (73.9–129.8 ka)	37 ka 66%	10.3 ka 18.4%	Cool temperate interstadial conditions, with forest cover in lowlands of NE Scotland during OIS 5c and 5a (Merritt et al., 2003). Intervening stadials in OIS 5b and 5d were cold in Scotland, with periglacial processes active at sea level (Hall et al., 2002). Full forest cover likely in OIS 5e.
6–22 (129.8–800 ka)	305 ka 45%	40 ka 5.9%	Multiple ice sheet glaciations with evidence for ice reaching the North Sea in OIS 6, 12, 16, and 18 (Holmes, 1997). Glaciation of the northern North Sea in OIS 22 and perhaps other cold stages (Holmes, 1997). Main phase of excavation of 200-m deep glacial valleys in the Cairngorms. Beginning of large-scale continental glaciations at OIS 22 (Bradley, 1999).
22–37 (0.8–1.1 Ma)	37 ka 9.5%	2.5 ka <1%	Glaciation of the shelf west of Shetland in OIS 36 (Stoker et al., 1993).
37–95 (1.1–2.46 Ma)	178 ka 13%	0 ka 0%	Few signs of ice sheets reaching the North Sea before 1.2 Ma (Holmes, 1997). Mountain glaciation likely in the Scottish Highlands, with the initiation of corrie formation in the Cairngorms (Gordon, 2001). First appearance of ice-rafted sediment in the North Atlantic at 2.4 Ma (Ruddiman et al., 1989). Progressive global cooling 3.1 to 2.7 Ma (Bradley, 1999).
Total	609 ka 45%	65 ka 5%	

The duration of shielding is given as time (ka) and as percent of the oxygen isotope stage (stage boundaries after Bradley, 1999, p. 212). The preferred ice cover model[a] uses δ^{18} O values of 3.7‰ and −37.0‰ (Fig. 11). The minimum ice cover model[b] uses values of 4.6‰ and −39.1.0‰.

nuclide concentration of regolith estimated by the x-intercept where height equals zero. A positive exponential fits the data well (r^2=0.998) and yields an estimate of ^{10}Be concentration in the regolith of $2.10 \pm 0.04 \times 10^5$ atoms/g. The regolith erosion rate computed from this concentration is 35 ± 2 mm/ka (1σ error includes production rate uncertainties). A tor emergence rate can be calculated from the regolith erosion rate minus the bedrock erosion rate. Using the error weighted mean for long-term bedrock erosion gives a rate of 31 ± 2 mm/ka.

The function required for a good fit indicates that the lower tor surfaces are far from approaching erosional steady state, as a negative exponential is characteristic of tor forms evolving under steady-state conditions (Heimsath et al., 2000, 2001). Projection of our fitted curve to greater tor heights implies unrealistically low bedrock erosion rates and exposure ages that are greatly in excess of those observed in our study. Nevertheless, the model regolith concentration is supported by a limiting nuclide concentration for the regolith computed from the amount of exposure gained since deglaciation. This is a conservative minimum concentration because of the nuclide inheritance from OIS-2 exposure observed in the many of our samples. Snow shielding and post-glacial erosion of the regolith complicate this interpretation by acting to reduce nuclide concentrations, but are contained within an error estimate of ±20%. Under these conditions, the nuclide concentration at Clach na Gnùis (gained in 15.8 ± 0.9 ka of unshielded exposure with no erosion) of $1.95 \pm 0.4 \times 10^5$ atoms g^{-1} agrees within error with the x-intercept value.

We note that tor emergence rates in the Cairngorms are likely variable in space and time. The evidence for this comes from the minimum single nuclide exposure age of about 190 ka for the summit block of the ~2 m high tor at An Cnoidh. This implies a rate of emergence of about 10.5 mm/ka at this site.

5. Discussion

Our single nuclide exposure age results clearly demonstrate that many Cairngorm tors were little affected

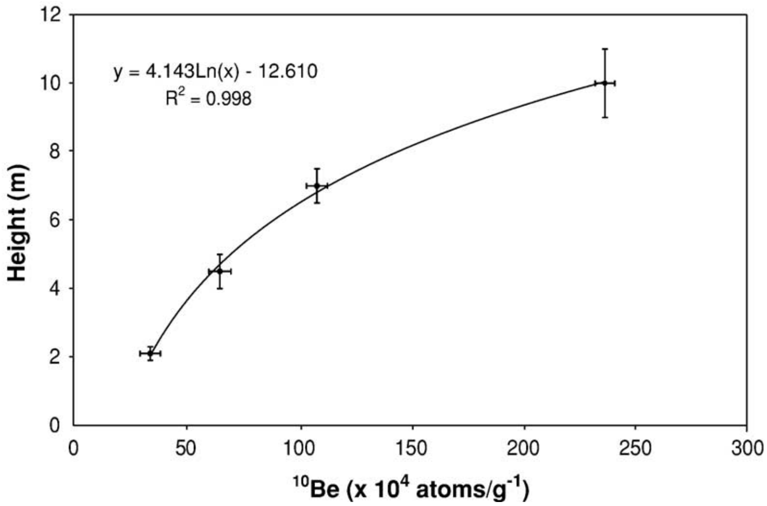


Fig. 10. Concentration of ^{10}Be at Clach na Gnùis plotted against height above present-day ground surface. The x-intercept value of 2.10×10^5 atoms g^{-1} corresponds to a rate of regolith formation of 35 mm/ka. Dashed line shows likely steady-state bedrock erosion rate attained by granite eroding at the rate indicated by quartz vein relief.

by the last glaciation and indeed have survived multiple glaciations. However, the single nuclide exposure ages do not indicate calendrical time before present because tors form by the differential weathering and erosion of bedrock and regolith operating under nonglacial conditions (Selby, 1982; Twidale, 1982). Hence, the exposure history of tors in formerly glaciated areas is a direct reflection of the duration and timing of ice-free periods. To strengthen our understanding of the timing of tor glacial modification and to better test for the survival of pre-Quaternary tor surfaces, we interpret single nuclide cosmogenic nuclide exposure ages in terms of total elapsed time before the present with an ice cover duration model.

5.1. Ice cover duration model

Following the approach of Clapperton (1997) and Kleman and Stroeven (1997), we use δ^{18}O proxies from ice core and marine sediment core records to infer the glacial history of the Cairngorms and, hence, the duration of shielded periods (Fig. 11). To use the ice and marine sediment core records as proxies for cosmogenic nuclide exposure conditions, δ^{18}O values corresponding to ice cover >7 m thick must be estimated. Glacial ice 7m thick is sufficient to reduce production of cosmogenic nuclides to ~2% of surface rates.

We approximate such conditions for the Cairngorm summit plateaus by δ^{18}O values, corresponding to the initiation of glaciation. The Cairngorm plateau includes the largest area of ground above 1000 m in the British Isles and is susceptible to glacier buildup. A small drop in temperature would lead to the development of permanent snow and ice fields, and glacial models indicate that a fall of 3–6 °C would cause small, stable ice caps to form in the Scottish Highlands (Manley, 1949, 1971; Payne and Sugden, 1990; Hubbard, 1999). A glaciation threshold of 3.7‰ in the ODP 607 core has been suggested for Scandinavia (Kleman and Stroeven, 1997; Stroeven et al., 2002a), while Clapperton (1997) proposed a glaciation threshold of −37.0‰ in the GRIP ice core record for Scotland based upon analysis of palaeoclimatic data for the Loch Lomond Stadial during the Younger Dryas. This is equivalent to a fall of ~3 °C in mean sea level temperature in July (Clapperton, 1997). Shielding estimates are likely a maximum in this model because at least some of the predicted shielding may be too thin to fully eliminate nuclide production and, in some cases, may be entirely absent because of snow removal by high winds (Purves et al., 1999) or snow shadow effects induced by the growth of the much larger main Scottish ice sheet to the west of the Cairngorms (Brazier et al., 1996). Exposure ages interpreted with this model yield maximum estimates of total elapsed time and therefore are most suited for testing the hypothesis of pre-Quaternary tors.

We evaluated the accuracy of the ice cover duration model with regional palaeoclimatic information (Table 5). The model appears to overestimate ice cover duration at the end of the Dimlington Stadial in OIS 2. The Cairngorm plateaus are inferred to have been covered in thick ice for almost the entire period before 13.4 ka, but

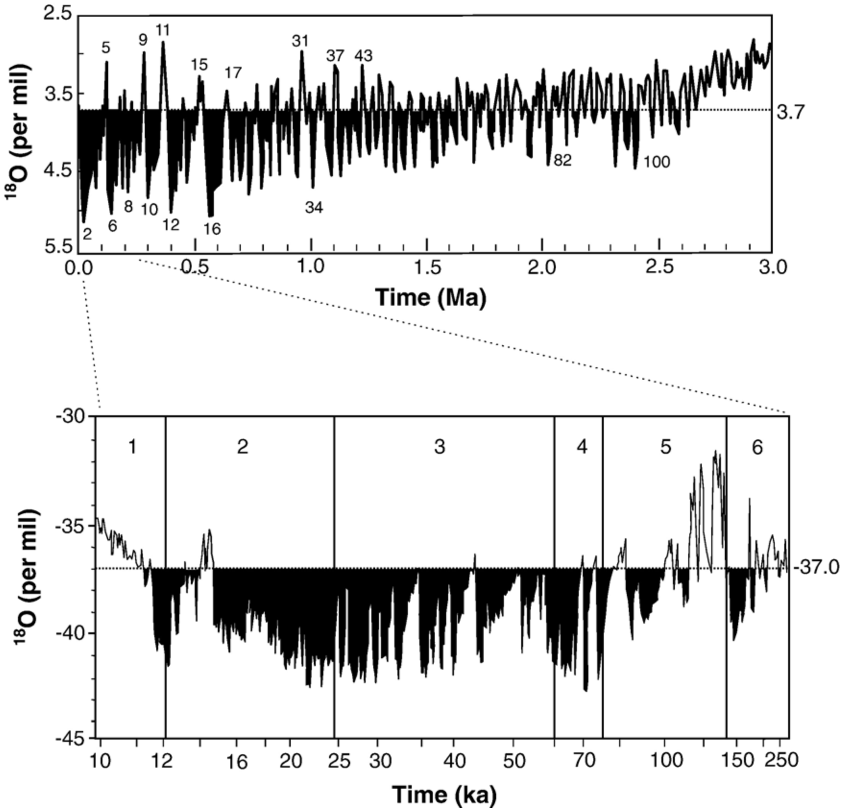


Fig. 11. $\delta^{18}O$ in marine sediment and ice core records used to infer the exposure history of Cairngorm tors; ODP 607 marine core (Raymo et al., 1989; Ruddiman et al., 1989) with oxygen isotope stages numbered. Dark shade indicates shielding under threshold glacial conditions; inset shows the GRIP ice core record (Dansgaard et al., 1993) with oxygen isotope stages indicated by numbers along top of figure.

radiocarbon evidence indicates ice-free conditions in several Cairngorm valleys at about 14 to 15 cal ka. However, over longer timescales, the model appears to reproduce key features of the Scottish Quaternary stratigraphic record. Specifically, a glaciation threshold of −37.0‰ provides a plausible ice cover model with prolonged glaciation during OIS 3 and 4; ice-free periods in the warm interstadials of OIS 5c and 5a and the last interglacial of OIS 5e; prolonged glaciation during OIS 6, 12, 16, and 18, when glaciers are known to have reached the bed of the North Sea; and a total duration of ice cover of 609 ka during the Pleistocene. The latter figure seems realistic when set against long-term rates of glacial valley deepening elsewhere in the Scottish Highlands of 500 mm/ka (Hebdon et al., 1998) in order for glaciers in the Cairngorms to excavate valleys to depths of ~200 m below Pliocene levels. In contrast, a minimum ice cover model based on Loch Lomond Stadial conditions and a glaciation threshold of 4.6‰ and −39.1‰ gives a better fit for the last Scottish deglaciation record, but implausibly low estimates of ice cover for major stadials and the Pleistocene as a whole (Table 5). The two-nuclide data for unmodified tors provides additional constraints on the ice cover model. The three samples give a mean duration of ice cover of 62 ± 16% for the last 295–626 ka. This compares reasonably well with the ice cover model estimate for 45% of the last 609 ka (Table 5).

5.2. Age of the oldest tors

The oldest sampled tors in the Cairngorms have single nuclide (^{10}Be) exposure ages ranging from about 90 to 300 ka. When interpreted as years before present with the ice cover duration model, these samples indicate first exposure between about 300 and 675 ka BP (Table 3). Although we believe they are likely maximum estimates, uncertainties for these inferred ages are difficult to constrain. They probably represent relatively crude estimates of the total time elapsed since tor emergence. Nevertheless, the ages are supported by two-nuclide model ages of 295_{-71}^{+84}, 520_{-141}^{+178}, and 626_{-85}^{+102} ka and by a tor emergence rate of 31 ± 2 mm/ka. The emergence rate, which assumes that tor and regolith erosion ceases during glaciations, indicates that the average Cairngorm tor with a height of 4.3 m can be formed in about 140 ka of exposure. By extrapolation, the largest Cairngorm tors with heights of about 24 m require ca. 790 ka of exposure. Interpreted in light of the ice cover duration model, this implies a mid-Pleistocene time of first emergence of about 1.3 Ma BP.

5.3. Timing of glacial modification of tors

Little is known about the effect on Scottish mountain landscapes of glaciations before the Dimlington Stadial. For this reason, clues about the timing of glacial modification of tors are welcome. Action by Dimlington Stadial glaciers in OIS 2 is most clearly expressed by erratic boulders and tor surfaces in which nuclide inheritance is absent or can be quantified. They indicate OIS 2 deglaciation at 15.6 ± 0.9 ka. However, other stage 4 and 5 tors show cosmogenic nuclide evidence of glacial modification prior to OIS 2. These tors have ^{10}Be ages ranging from about 20 to 43 ka. When interpreted with the ice cover duration model (Table 3), these samples indicate glacial modification in the cold periods of OIS 5 or in the glacial conditions of OIS 6.

The timing of glacial modification of older event surfaces becomes progressively less certain with increasing age. Six out of 12 of our samples from glacially modified stage 2 and 3 tors have ^{10}Be exposure ages ranging from about 30 to 47 ka. When interpreted with the ice cover duration model, they suggest event surface generation between 116 and 195 ka in OIS 5 to 6. Of the remaining glacially modified samples, the three oldest range between 51 and 54 ka. The ice cover duration model suggests total elapsed times of about 215 ka for these samples and that these tor surfaces were modified by glaciers in OIS 7.

5.4. Implications

Our results strongly support earlier work demonstrating that tors beneath dry-based ice sheets on mountain plateaus can withstand multiple glaciations and that the erosive effect of the last glacial period was relatively minor (Sugden, 1968; Sugden and Watts, 1977; Kleman and Stroeven, 1997; Fabel et al., 2002; Hättestrand and Stroeven, 2002; Stroeven et al., 2002a,b; Briner et al., 2003; Sugden et al., 2005). However, the ability of dry-based ice to protect tors has been shown not to be absolute. Dry-based ice can topple and move large detached tor blocks short distances, thereby contributing to the denudation of alpine landscapes. This process complicates the measurement of deglaciation chronologies with cosmogenic nuclides because both erratic boulders and bedrock surfaces are likely to have significant nuclide inheritance.

The long-term maximum erosion rate of 4.1 ± 0.2 mm/ka estimated for Cairngorm granite exposed on tors is similar to rates of 7.6 ± 3.9 mm/ka, 6–11 mm/ka, and 5–14 mm/ka for unglaciated bare bedrock granitic surfaces in North America and Antarctica (Small et al., 1997; Granger et al., 2001; calculated from data in Sugden et al., 2005; respectively), but significantly faster than the 0.84 ± 0.23 mm/ka reported for Baffin Island tors (Bierman et al., 1999), the ~1 mm/ka estimated for biotite-bearing crystalline rocks in Swedish Lapland (André, 2002), and our short-term rate of 1.6 ± 0.6 mm/ka estimated for slightly weathered Cairngorm granite.

The imbalance between rapid regolith formation and removal and slower bedrock erosion creates tors. In the Cairngorms, tors can emerge at rates of ca. 30 mm/ka. While such rates probably vary significantly in the Cairngorm landscape, this rate is consistent with other studies from a variety of climates showing that granitic regolith forms about two to ten times faster than bare bedrock erodes (Small et al., 1997; Heimsath et al., 2000, 2001; Bierman and Caffee, 2001, 2002; Granger et al., 2001). Minimum rates of soil formation during the post-glacial period on the Cairngorm plateau of 20–25 mm/ka is also consistent with this rate (Haynes et al., 1998).

The tor emergence rate has great significance for the pre-Quaternary relic landscape hypothesis in that it shows that the largest of Cairngorm tors could be created in <1.3 Ma, even with episodic cold-based ice cover. Although we selected for sampling what appeared to be among the oldest rock surfaces in the Cairngorms, the greatest apparent single nuclide (^{10}Be) exposure age in our study was about 300 ka. Whilst this is among the oldest ^{10}Be age yet reported for a glaciated rock surface in the Northern Hemisphere, it is far less than the single nuclide age of >1.8 Ma expected if the Cairngorm tors were slowly eroding pre-Quaternary forms episodically protected by an ice cap. This finding appears to be shared by other high latitude relic landscapes. Cosmogenic ^{10}Be exposure ages for tor surfaces and blockfields in formerly glaciated parts of Baffin Island (Bierman et al., 1999; Briner et al., 2003), northern Scandinavia (Fabel et al., 2002; Stroeven et al., 2002a), and Svalbard (Landvik et al., 2003) lie in the range of 37–152 ka. The general absence of exposure ages of <37 ka implies limited modification by OIS 4-2 ice sheets, consistent with the discovery of glacial erratics in weathering pits on Baffin Island (Briner et al., 2003) and in the Cairngorms (Sugden, 1968; Hall and Phillips, in press-b). Yet, interpretation of these ages with regional exposure histories based upon proxy climate data and paired cosmogenic radionuclides shows that they can be accommodated within the total span of ice-free intervals over only the last 625 ka.

The potential for protective dry-based ice cover for the Cairngorm has varied over the course of the Quaternary (Fig. 11). At the end of the Pliocene and beginning of the Pleistocene, glacial periods were of short duration and limited intensity. Tors must have evolved much as those in nonglacial settings do, with forms dictated largely by differential erosion between Cairngorm granite bedrock and surrounding regolith. Cosmogenic nuclide data from unglaciated granitic landscapes suggest that such landforms are relatively dynamic, with erosion rates that preclude the preservation of extremely ancient surfaces (Heimsath et al., 2000, 2001; Bierman and Caffee, 2001, 2002; Granger et al., 2001). As mountain ice caps began to be more common occurrences in the Cairngorms, the potential to protect tors beneath protective covers of dry-based ice increased. This potential greatly increased in OIS 22 at ~800 ka when large-scale continental ice sheets became the norm (Bradley, 1999). Prior to that time, cold periods were brief and relatively warm. Several major interglacials during OIS 31 and 37 provided long periods of ice-free exposure and destructive erosion by subaerial processes. Given these considerations, it is not surprising that our cosmogenic nuclide evidence suggests that no Cairngorm tor surface dates from before about 625 ka. Preservation of tors by dry-based ice became much more likely after this time. Despite the tendency of deforming ice to bulldoze tors and the opportunities for major surface erosion during the interglacials of OIS 11, 9, 5, and 1, the form of favourably situated tors have been largely preserved since that time. Nonetheless, preservation of preglacial tor forms from the Pliocene or earlier appears unlikely.

6. Conclusions

Surfaces of erratic boulders and tors corrected for nuclide inheritance indicate deglaciation of the eastern Cairngorms at 15.6 ± 0.9 ka. Strong correlations exist between tor weathering characteristics and cosmogenic ^{10}Be surface exposure ages. Glacially modified tors with moderate to advanced weathering features have ^{10}Be exposure ages of 19 to 54 ka. These surfaces were only slightly modified during the last glacial cycle and gained much of their exposure during the interstadial of marine OIS 5 or earlier. Tors lacking evidence of glacial modification and exhibiting advanced weathering have ^{10}Be exposure ages between 52 and 297 ka. Three of these surfaces have discordant ^{10}Be and ^{26}Al data that yield model exposure-plus-burial ages of 295^{+84}_{-71}, 520^{+178}_{-141}, and 626^{+102}_{-85} ka. Maximum erosion rate estimates for these surfaces range from 2.8 to 12.0 mm/ka, with an error weighted mean of 4.1 ± 0.2 mm/ka. A vertical cosmogenic nuclide profile across the oldest sampled tor indicates a long-term emergence rate of 31 ± 2 mm/ka.

Collectively, the cosmogenic nuclide data and geomorphic observations indicate that Cairngorm tors are relatively young, continually developing landforms rather than pre-Quaternary relics. Many tors show elaborate surface etch forms that largely developed during the Late Pleistocene. Multiple cycles of glacial modification are identified in which tors have lost blocks and superstructure, indicating that protection by dry-based ice was neither complete nor constant during the Quaternary.

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References

Anderson, R.S., 2002. Modeling the tor-dotted crests, bedrock edges, and parabolic profiles of high alpine surfaces of the Wind River Range, Wyoming. Geomorphology 46, 35–58.

André, M-F., 2002. Rates of postglacial rock weathering on glacially scoured outcrops (Abisko-Riksgransen area, 68 degrees N). Geografiska Annaler 84A, 139–150.

André, M.-F., 2004. The geomorphic impact of glaciers as indicated by tors in North Sweden (Aurivaara, 68°N). Geomorphology 57, 403–421.

Ballantyne, C.K., 1994. Scottish landform examples—10: the tors of the Cairngorms. Scottish Geographical Magazine 110, 54–59.

Ballantyne, C.K., 1998. Age and significance of mountain-top detritus. Permafrost and Periglacial Processes 9, 327–345.

Ballantyne, C.K., Harris, C., 1994. The Periglacial of Great Britain. Cambridge University Press, Cambridge, UK.

Barrows, T.T., Stone, J.O., Fifield, L.K., Cresswell, R.G., 2001. Late Pleistocene glaciation of the Kosciuszko Massif,

Snowy Mountains, Australia. Quaternary Science Reviews 21, 159–173.
Barton, J.S., 1987. Weather observations on Cairn Gorm summit 1979–1986. Meteorological Magazine 116, 346–353.
Bierman, P.R., Caffee, M., 2001. Slow rates of rock surface erosion and sediment production across the Namib desert and escarpment, southern Africa. American Journal of Science 301, 326–358.
Bierman, P.R., Caffee, M.W., 2002. Cosmogenic exposure and erosion history of Australian bedrock landforms. Geological Society of America Bulletin 114, 787–803.
Bierman, P.R., Marsella, K.A., Patterson, C., Thomson Davis, P., Caffee, M., 1999. Mid-Pleistocene cosmogenic minimum age limits for pre-Wisconsin glacial surfaces in southwestern Minnesota and southern Baffin Island: a multiple nuclide approach. Geomorphology 27, 25–39.
Bierman, P.R., Caffee, M.W, Thompson Davis, P., Marsella, K., Pavich, M., Colgan, P., Mickelson, D., Larsen, J., 2002. Rates and timing of earth surface processes from in situ-produced cosmogenic Be-10. In: Grew, E.S. (Ed.), Beryllium: Mineralogy, Petrology, and Geochemistry, Reviews in Mineralogy and Geochemistry, vol. 50. Mineralogical Society of America and the Geochemical Society, Washington, DC, pp. 147–205.
Bos, J.A.A., Dickson, J.H., Coope, G.R., Jardine, W.G., 2004. Flora, fauna and climate of Scotland during the Weichselian Middle Pleniglacial: palynological, macrofossil and coleopteran investigations. Palaeogeography, Palaeoclimatology, Palaeoecology 204, 65–100.
Bradley, R.S., 1999. Paleoclimatology: reconstructing climates of the Quaternary. International Geophysics Series, vol. 64. Harcourt Academic Press, San Diego, CA, pp. 212–214.
Brazier, V., Gordon, J.E., Kirkbride, M.P., Sugden, D.E., 1996. The Late Devensian ice sheet and glaciers in the Cairngorm Mountains. In: Glasser, N.F., Bennett, M.R. (Eds.), The Quaternary of the Cairngorms. Quaternary Research Association, London, pp. 28–53.
Briner, J.P., Swanson, T.W., 1998. Using inherited cosmogenic ^{36}Cl to constrain glacial erosion rates of the Cordilleran ice sheet. Geology 26, 3–6.
Briner, J.P., Miller, G.H., Davis, P.T., Bierman, P.R., Caffee, M., 2003. Last Glacial Maximum ice sheet dynamics in Arctic Canada inferred from young erratics perched on ancient tors. Quaternary Science Reviews 22, 437–444.
Brook, E.J., Nesje, A., Lehman, S.J., Raisbeck, G.M., Yiou, F., 1996. Cosmogenic nuclide exposure ages along a vertical transect in western Norway: implications for the height of the Fennoscandian ice sheet. Geology 24, 207–210.
Clapperton, C.M., 1997. Greenland ice cores and North Atlantic sediments: implications for the last glaciation in Scotland. In: Gordon, J.E. (Ed.), Reflections on the Ice Age in Scotland. Scottish Natural Heritage, Edinburgh, pp. 45–58.
Clapperton, C.M., Gunson, A.R., Sugden, D.E., 1975. Loch Lomond readvance in the eastern Cairngorms. Nature 253, 710–712.
Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahljensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjornsdottir, A.E., Jouzel, J., Bond, G., 1993. Evidence for general instability of past climate from a 250-ka ice-core record. Nature 364, 218–220.
Dunn, S.M., Colohan, R.J.E., 1999. Developing the snow component of a distributed hydrological model: a step-wise approach based on multi-objective analysis. Journal of Hydrology 223, 1–16.
Dunne, J., Elmore, D., Muzikar, P., 1999. Scaling factors for the rates of production of cosmogenic nuclides for geometric shielding and attenuation at depth on sloped surfaces. Geomorphology 27, 3–11.
Everest, J.D., Golledge, N.R., 2004. Dating deglaciation in the Cairngorm Mountains and Strath Spey. In: Lukas, D., Merritt, J.W., Mitchell, W.A. (Eds.), Quaternary of the central Grampian Highlands: Field Guide. Quaternary Research Association, London, pp. 50–57.
Fabel, D., Stroeven, A.P., Harbor, J., Kleman, J., Elmore, D., Fink, D., 2002. Landscape preservation under Fennoscandian ice sheets determined from in situ produced ^{10}Be and ^{26}Al. Earth and Planetary Science Letters 201, 397–406.
Fifield, L.K., 2000. Advances in accelerator mass spectrometry. Nuclear Instruments and Methods in Physics Part B 172, 134–143.
Gordon, J.E., 1993. The Cairngorms. In: Gordon, J.E., Sutherland, D.G. (Eds.), Quaternary of Scotland. Chapman and Hall, London, pp. 259–276.
Gordon, J.E. (Ed.), 1997. Reflections on the Ice Age in Scotland. Scottish Natural Heritage, Edinburgh.
Gordon, J.E., 2001. The corries of the Cairngorm Mountains. Scottish Geographical Journal 117, 49–63.
Gordon, J.E., Sutherland, D.G. (Eds.), 1993. Quaternary of Scotland. Chapman and Hall, London.
Gradstein, F.M., Ogg, J., 1996. A Phanerozoic timescale. Episodes 19 (1–2), 3–5.
Granger, D.E., Riebe, C.S., Kirchner, J.W., Finkel, R.C., 2001. Modulation of erosion on steep granitic slopes by boulder armouring, as revealed by cosmogenic ^{26}Al and ^{10}Be. Earth and Planetary Science Letters 186, 269–281.
Hall, A.M., Glasser, N.F., 2003. Reconstructing former glacial basal thermal regimes in a landscape of selective linear erosion: Glen Avon, Cairngorm Mountains, Scotland. Boreas 32, 191–207.
Hall, A.M., Phillips, W.M., in press-a. Glacial modification of granite tors, Cairngorm Mountains, Scotland. Journal of Quaternary Science.
Hall, A.M., Phillips, W.M., in press-b. Weathering pits as indicators of the relative age of granite surfaces in the Cairngorm Mountains, Scotland. Geografiska Annaler. Series A.
Hall, A.M., Duller, G.A.T., Jarvis, J., Wintle, A.G., 1995. Middle Devensian ice-proximal gravels at Howe of Byth, Grampian Region. Scottish Journal of Geology 31, 61–64.
Hall, A.M., Gordon, J.E., Whittington, G., Duller, G.A.T., Heijnis, H., 2002. Sedimentology, palaeoecology and geochronology of Marine Isotope Stage 5 deposits on the Shetland Isles, Scotland. Journal of Quaternary Science 17, 51–68.
Hardland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., Smith, D.G., 1990. A Geologic Timescale, 1989. Cambridge University Press, Cambridge, UK. 263 pp.
Hättestrand, C., Stroeven, A.P., 2002. A relic landscape in the central Fennoscandian glaciation: geomorphological evidence of minimal Quaternary glacial erosion. Geomorphology 44, 127–143.
Hättestrand, C., Götz, S., Näslund, J.-O., Fabel, D., Stroeven, A.P., 2004. Drumlin formation time: evidence from northern and central Sweden. Geogr. Ann. 86 A (2), 155–167.
Haynes, V.M., Grieve, I.C., Price-Thomas, P., Salt, K., 1998. The Geomorphological Sensitivity of the Cairngorm High Plateaux. Survey and Monitoring Report, vol. 66. Scottish Natural Heritage, Edinburgh, UK.
Hebdon, N.J., Atkonson, T.C., Lawson, T.J., Young, I.R., 1998. Rate of glacial valley deepening during the late Quaternary in Assynt, Scotland. Earth Surface Processes and Landforms 22, 307–315.

Heimsath, A.M., Chappell, J., Dietrich, W.E., Nishiizumi, K., Finkel, R.C., 2000. Soil production on a retreating escarpment in southeastern Australia. Geology 28, 787–790.

Heimsath, A.M., Chappell, J., Dietrich, W.E., Nishiizumi, K., Finkel, R.C., 2001. Late Quaternary erosion in southeastern Australia: a field example using cosmogenic nuclides. Quaternary International 83–85, 169–185.

Holmes, R., 1997. Quaternary stratigraphy: the offshore record. In: Gordon, J.E. (Ed.), New Light on the Ice Age in Scotland. Scottish Natural Heritage, Edinburgh, pp. 72–94.

Hubbard, A., 1999. High-resolution modeling of the advance of the Younger Dryas ice sheet and its climate in Scotland. Quaternary Research 52, 27–43.

Ives, J.D., 1958. Glacial geomorphology of the Torngat Mountains, northern Labrador. Geographical Bulletin 12, 47–75.

Ivy-Ochs, S., 1996. The dating of rock surfaces using in situ-produced ^{10}Be, ^{26}Al, and ^{36}Cl, with examples from Antarctica and the Swiss Alps. PhD Dissertation, Swiss Federal Institute of Technology, Zürich, 196 pp.

Kleman, J., 1992. The palimpsest glacial landscape in northwestern Sweden: late Wiechselian deglaciation forms and traces of older west-centered ice sheets. Geografiska Annaler 74A, 305–325.

Kleman, J., Borgström, I., 1994. Glacial land forms indicative of a partially frozen bed. Journal of Glaciology 40, 255–264.

Kleman, J., Stroeven, A.P., 1997. Preglacial surface remnants and Quaternary glacial regimes in northwestern Sweden. Geomorophology 19, 35–54.

Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. Earth and Planetary Science Letters 104, 424–439.

Landvik, J.Y., Brook, E.J., Gualtieri, L., Raisbeck, G., Salvigsen, O., Yiou, F., 2003. Northwest Svalbard during the last glaciation: ice-free areas existed. Geology 31, 905–908.

Linton, D.L., 1952. The significance of Tors in glaciated lands. International Geographical Union, 17th International Congress, Washington, DC, pp. 354–357.

Linton, D.L., 1955. The problem of tors. Geographical Journal 121, 470–487.

Manley, G., 1949. The snowline in Britain. Geografiska Annaler 31, 179–193.

Manley, G., 1971. The mountain snows of Britain. Weather 26, 192–200.

Marquette, G.C., Gray, J.T., Gosse, J.C., Courchesne, F., Stockli, L., Macpherson, G., Finkel, R., 2004. Felsenmeer persistence under non-erosive ice in the Torngat and Kaumajet Mountains, Quebec and Labrador, as determined by soil weathering and cosmogenic nuclide exposure dating. Canadian Journal of Earth Sciences 41, 19–38.

Marsella, K.A., Bierman, P.R., Davis, P.T., Caffee, M.W., 2000. Cosmogenic Be-10 and Al-26 ages for the Last Glacial Maximum, eastern Baffin Island, Arctic Canada. Geological Society of America Bulletin 112, 1296–1312.

Merritt, J., Auton, C.A., Connell, E.R., Hall, A., Peacock, J.D., 2003. Cainozoic geology and landscape evolution of north-east Scotland: memoir for the drift editions of 1:50 000 geological sheets 66E Banchory, 67 Stonehaven, 76E Inverurie, 77 Aberdeen, 86E Turriff, 87W Ellon, 87E Peterhead, 95 Elgin, 96W Portsoy, 96E Banff and 97 Fraserburgh (Scotland). Memoir of the British Geological Survey, Edinburgh, UK. 178 pp.

Mottram, R., 2001. Mechanisms of tor formation and exposure age estimates in the Cairngorm Plateau, Scotland: an approach using in situ produced cosmogenic isotopes ^{10}Be and ^{26}Al. MS Thesis, University of Edinburgh. 78 pp.

Ogg, J.G., 2004. Status of divisions of the international geological timescale. Lethaia 37, 183–199.

Payne, A.J., Sugden, D.E., 1990. Topography and ice sheet growth. Earth Surface Processes and Landforms 15, 625–639.

Purves, R.S., Mackaness, W.A., Sugden, D.E., 1999. An approach to modelling the impact of snow drift on glaciation in the Cairngorm Mountains, Scotland. Journal of Quaternary Science 14, 313–321.

Raymo, M.E., Ruddiman, W.F., Backman, J., Clement, B.M., Martinson, D.G., 1989. Late Pleistocene variation in northern hemisphere ice sheets and North Atlantic deep water circulation. Paleoceanography 4, 413–446.

Rea, B.R, Whalley, W.B, Rainey, M.M., Gordon, J.E., 1996. Blockfields, old or new? Evidence and implications from some plateaus in northern Norway. Geomorphology 15, 109–121.

Ruddiman, W.F., Raymo, M.E., Martinson, D.G., Clement, B.M., Backman, J., 1989. Pleistocene evolution: Northern hemisphere ice sheets and North Atlantic Ocean. Paleoceanography 4, 353–412.

Schildgen, T.F., Phillips, W.M., Purves, R., 2005. Simulation of snow shielding corrections for cosmogenic nuclide surface exposure studies. Geomorphology 64, 67–85.

Sejrup, H.P., Haflidason, H., Aarseth, I., King, E., Forsberg, C.F., Long, D., Rokoengen, K., 1994. Late Weichselian glaciation history of the northern North Sea. Boreas 23, 1–13.

Selby, M.J., 1982. Hillslope Materials and Processes. Oxford University Press, Oxford, UK, pp. 186–187.

Sissons, J.B., Walker, M.J.C., 1974. Lateglacial site in the central Grampian Highlands. Nature 249, 822–824.

Small, E.E., Anderson, R.S., Repka, J.L., Finkel, R., 1997. Erosion rates of alpine bedrock summit surfaces deduced from in situ ^{10}Be and ^{26}Al. Earth and Planetary Science Letters 150, 413–425.

Small, E.E., Anderson, R.S., Hancock, G.S., 1999. Estimates of rates of regolith production using ^{10}Be and ^{26}Al from an alpine hillslope. Geomorphology 27, 131–150.

Steig, E.J., Wolfe, A.P., Miller, G.H., 1998. Wisconsinan refugia and the glacial history of eastern Baffin Island, Arctic Canada: coupled evidence from cosmogenic isotopes and lake sediments. Geology 26, 835–838.

Stoker, M.S., Hitchen, K., Graham, C.C., 1993. The geology of the hebrides and West Shetland Shelves, and adjacent deep-water areas. United Kingdom Offshore Report, vol. 2. Her Majesty's Stationary Office (HMSO) for the British Geological Survey, London, UK. 149 pp.

Stone, J.O., 2000. Air pressure and cosmogenic isotope production. Journal of Geophysical Research, [Solid Earth] 105, 23753–23759.

Stone, J.O., Ballantyne, C.K., Fifield, L.K., 1998. Exposure dating and validation of periglacial weathering limits, northwest Scotland. Geology 26, 587–590.

Stroeven, A.P., Fabel, D., Hättestrand, C., Harbor, J., 2002a. A relict landscape in the centre of Fennoscandian glaciation: cosmogenic radionuclide evidence of tors preserved through multiple glacial cycles. Geomorphology 44, 145–154.

Stroeven, A.P., Fabel, D., Harbor, J., Hättestrand, C., Kleman, J., 2002b. Quantifying the erosional impact of the Fennoscandian ice sheet in the Tornetrask–Närvik corridor, northern Sweden, based on cosmogenic radionuclide data. Geografiska Annaler 84A, 275–287.

Sugden, D.E., 1968. The selectivity of glacial erosion in the Cairngorm Mountains, Scotland. Transactions of the Institute of British Geographers 45, 79–92.

Sugden, D.E., Watts, S.H., 1977. Tors, felsenmeer, and glaciation in northern Cumberland Peninsula, Baffin Island. Canadian Journal of Earth Sciences 14, 2817–2823.

Sugden, D.E., Balco, G., Cowdery, S.G., Stone, J.O., Sass III, L.C., 2005. Selective glacial erosion and weathering zones in the coastal mountains of Marie Byrd Land, Antarctica. Geomorphology 67, 317–334.

Twidale, C.R., 1982. Granite Landforms. Elsevier, Amsterdam, The Netherlands. 395 pp.

Whittington, G., Buckland, P., Edwards, K.J., Greenwood, M., Hall, A.M., Robinson, M., 2003. Multi-proxy Devensian Lateglacial and Holocene environmental records at an Atlantic coastal site in Shetland. Journal of Quaternary Science 18, 152–168.

Yuengling, K.R., 1998. Cosmogenic $^{10}Be/^{26}Al$ exposure dating of Alaskan tors. MS Thesis, University of Alaska, Fairbanks. 158 pp.