SCOTTISH LANDFORM EXAMPLES

THE CAIRNGORMS – A PRE-GLACIAL UPLAND GRANITE LANDSCAPE

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INTRODUCTION

The Cairngorm massif in NE Scotland (Figure 1) is an excellent example of a pre-glacial upland landscape formed in granite. Glacial erosion in the mountains has been largely confined to valleys and corries (Rea, 1998) and so has acted to dissect a pre-existing upland (Figure 2). Intervening areas of the massif experienced negligible glacial erosion due to protective covers of cold-based ice (Sugden, 1968) and preserve a wide range of pre-glacial and non-glacial landforms and regolith. This assemblage is typical for many formerly glaciated upland and mountains areas around the world.

Figure 1. Location

The cliffs that sharply demarcate the edges of glacial valleys and corries allow the main pre-glacial landforms to be easily identified. The former shape of pre-glacial valleys and valley heads can then be reconstructed by extrapolation of contours to provide a model of the pre-glacial relief of the Cairngorms (Thomas et al., 2004). This relief model (Figure 3) provides a basis for understanding the development of the landscape over timescales of many millions of years, including the role of geology, weathering, fluvial erosion and, lately, glacial erosion in shaping the relief.

Figure 2. Cairngorms DEM with tors and weathered rock

Figure 3. Pre-glacial relief model

GEOLOGY AND GLACIAL HISTORY

GEOLOGY

The Cairngorm Granite pluton was intruded at ~425 Ma into metamorphosed sedimentary rocks in the later stages of the Caledonian mountain building period (Thomas et al., 2004). The pink granite is composed of plagioclase feldspar, alkali feldspar and quartz, with small amounts of biotite mica (Highton, 1999). The granite is cut by *linear alteration zones*, up to 200 metres wide, and several kilometres long, which formed during the final stages of granite cooling. The zones developed where heated groundwater circulated through the rock in fractures, causing feldspar and mica in adjacent rock to alter to secondary minerals, including green chlorite and red hematite (Thomas et al., 2004). Such *hydrothermal* processes are typically focussed in the roof zone of plutons, and the survival of these alteration zones indicates that the current erosion level lies within the original roof zone of the intrusion. The granite is also cut by sets of *joints* - open fractures formed in all orientations by contraction during granite cooling and other processes. The joints typically divide the granite into orthogonal blocks of centimetre to metre scale. Two sets of *sheet joints* (which form in the near-surface zone, broadly parallel to the adjacent land surface) also occur: an older set of widely-spaced, gently inclined sheets that run parallel to gentle plateau surfaces, and a younger set with steep dips developed parallel to the sides of glacial troughs (Glasser, 1997).

GLACIAL HISTORY

Comparison with marine oxygen isotope records suggests that the first glaciation of the Cairngorms was at ~2.6 Ma (Clapperton, 1997), coincident with the first appearance of ice-rafted debris in the North Atlantic Ocean off Scotland (Thierens et al.). Little evidence has been found of Scottish ice reaching the continental shelf west of Scotland before 1.2 Ma (Holmes, 1997) implying that, whilst glaciers probably formed in Scotland during cold stages, ice sheets remained largely land-based. A step change in the magnitude of Pleistocene climatic oscillations from 0.8 Ma to present led to the repeated development of extensive and long-lived ice sheets across NE Scotland (Merritt et al., 2003).

The history of glacier ice cover in the Cairngorms suggests that three contrasting relief-forming environments operated in the recent geological past:

- Before 2.6 Ma, with weathering, mass movement and stream action operating under the warm, then temperate to cool, non-glacial climates that prevailed in the Neogene Period.
- From 2.6-0.8 Ma (the Early Pleistocene), with phases of mountain and ice cap glaciation alternating with long periods of cool to cold, largely *periglacial* conditions. Estimates based on application of the method of Li et al. (2008) to the cosmogenic nuclide inventories of Phillips et al. (2006) indicate that the Cairngorm plateau was ice-covered for ~1.0 Ma during this period, leaving ~0.8 Ma for the operation of periglacial processes.
- From 0.8 Ma (the Middle and Late Pleistocene), with prolonged ice sheet and ice cap glaciation alternating with shorter periods of cool to cold, ice-free periglacial conditions on the plateau.

Here *pre-glacial* refers to the period before the onset of mountain glaciation in the Cairngorms. *Non-glacial* landforms and regolith may have formed in this period or later in the ice-free intervals of the Pleistocene.

PRE-GLACIAL AND NON-GLACIAL RELIEF OF THE CAIRNGORMS

The pre- and non-glacial relief of the Cairngorms can be viewed at three scales: the entire massif, the major pre-glacial landforms, and the minor non-glacial landforms and regolith types.

THE MASSIF

In pre-glacial times, the Cairngorm massif formed a steep-sided, elongate plateau centred on the Cairngorm Granite Pluton. Whilst fringing slopes generally remain close to the pluton margin, three areas of the granite pluton underlie relatively low ground: the Glen Avon embayment, the Glen More basin and the area around Sgòr Mòr (Linton, 1950a)(Figure 4).

Figure 4. Pre-glacial landforms

MAJOR PRE-GLACIAL LANDFORMS

PALAEOSURFACES AND BREAKS OF SLOPE

The term *palaeosurface* is widely used in the geomorphological literature to describe old landsurfaces of low relief (Ebert, 2009). Such features are widespread in the uplands of the British Isles but have generally been referred to as *erosion surfaces*. Although low angle surfaces are not developed extensively in the central Cairngorms (Ringrose and Migoń, 1997), major breaks of slope clearly separate two palaeosurfaces in and around the Cairngorm massif (Figure 4).

The hilly terrain that culminates in the highest summits of the Cairngorms has a relative relief of up to 200 m and shows convex-concave slope profiles, domed summits, wide shallow valleys, and open cols (Linton, 1950a). This *Cairngorm Summit Surface* (Sugden, 1968) is clearly demarcated by a well-defined break of slope (Figure 3) that forms an impressive 200 m high scarp along the south side of the Glen Avon Embayment (Figure 5a).

Figure 5. Glen Avon embayment and the Moine Bhealaidh

The Embayment is itself dominated by a surface of low relief at 800-700 m that covers ~65 km^2 (Figure 4). Breaks of slope at ~800 m also back low angle slopes on the flanks of the Glen More basin and around Sgòr Mór and along the north side of the Dee valley (Figure 4). Together these remnants represent the inner margin of the *Eastern Grampian Surface* (Hall, 1991), a regionally-extensive palaeosurface which dominates the relief of north-east Scotland between the rivers Spey and North Esk. Palaeosurfaces in NE Scotland are generally developed across complex geology and were formed over long periods of deep weathering and fluvial erosion during and before the Neogene (Hall, 2005).

TOPOGRAPHIC BASINS

Two sets of high- and low-level basins occur in and around the Cairngorms (Hall, 1991). The high-level Mòine Mhór and Moine Bhealaidh basins lie in partly-dissected hollows enclosed by scarps at the edge of the Cairngorm Summit Surface. The Mòine Mhór basin has a floor on psammite at 920-950 m, whilst the Mòine Bhealaidh basin is developed on diorite, psammite, quartzite and granite, with the ridges of the northern watershed on quartzite (Figure 5b). In contrast, the Glen More, Dorback and Nethy basins have floors at 250-320 m (Figure 4). The Glen More basin is also developed on psammite, with a break of slope along its margin that generally corresponds to contacts with the Cairngorm Granite Pluton and quartzite of the Kincardine Hills. Hence each of the basin floors is preferentially located on rocks with less resistance to chemical weathering than the Cairngorm Granite. Topographic basins in the Cairngorms reflect the long term operation of differential weathering and erosion, as elsewhere in NE Scotland (Hall, 1991).

VALLEYS

The main valleys, glens Avon, Derry, Dee and Einich, already extended deep into the massif before the Pleistocene (Figures 3 and 6). The valleys channelled ice flow in the Pleistocene, with glacial erosion leading to valley deepening, straightening and breaching (Linton, 1949; 1950b; 1954; Sugden, 1968; Hall and Glasser, 2003), but the character of the pre-glacial drainage network and its component valleys remains clear.

Pre-glacial headwater valleys on the Cairngorm Summit Surface are commonly broad, shallow features set between domes that often hang above the main glacial valleys. Along the main valleys, the pre-glacial relief model indicates that valley incision was well advanced before glaciation, with narrow river valleys with steep long profiles extending into the core of the massif (Figure 6). Even beside the main troughs, however, traces of the pre-glacial valley cross section are easily discerned from valley benches or breaks of slope on the valley side. A valley-in-valley form is evident above the Loch Avon trough. Gleann Einich has breaks of slope on its east side at ~800 and 1000 m that appear to relate to former benches on the side of the pre-glacial valley. Even along the side of the Glen Dee trough, the deepest glacial valley in the massif, the corrie floors appear to be located in pre-glacial valley heads at around 950 m OD (Sugden, 1969). The major pre-glacial valleys in the Cairngorms show preferred orientations to the NE and ENE, parallel to that of linear alteration zones in the granite and to the exhumed Devonian valleys of Strath Spey and Glen Rinnes. Valley excavation was probably initiated along these lines of weakness during unroofing of the Cairngorm pluton and perpetuated by weathering and fluvial erosion throughout the Neogene, with a final phase of valley deepening and widening by glacial erosion during the Pleistocene.

Figure 6. Northern Cairngorm models

NON-GLACIAL LANDFORMS AND REGOLITH

DOMES

Many of the major and minor summits formed on the Cairngorm plateau have dome-like forms. Individual dome surfaces are typically 0.1-1.0 km^2 in area and from 10-120 m high. On Ben Avon, the domes are elongate in plan, with crests studded by tors. By contrast, those on the northern slopes of Ben Macdui are more circular and lack tors.

Extensive sections through dome flanks found along glacial valley sides provide clues as to the bedrock controls on the location and form of the Cairngorm domes. Domes are locally delimited by valleys aligned along linear alteration zones, as above the Northern Corries (Figure 7). Sections provided by glacial cliffs show that domes are developed on lenticular masses of massive rock, up to 1 km long. These sections also show that, as in other classic granite terrains (Migoń, 2006), there is a general parallelism between curved sheet joints and dome surfaces.

Figure 7. Northern Corries and domes

TORS

The Cairngorms hold perhaps the best example of a glaciated tor field in the world (Ballantyne, 1994; Hall and Phillips, 2006a; Phillips et al., 2006). The tors occur at altitudes of 600-1240 m O.D., spanning almost the entire elevation range of the exposed Cairngorm pluton (Figure 2). Individual tors range in height from 1-24 m, with a mean of 4.3 m. In plan, the tors are generally elongate (a/b=2.1), and around 20% include avenues between tors (Mottram, 2002). The largest tors have footprints of >2000 m^2 but the many small tors comprise little more than a few joint-bounded blocks. Many tors display delicately sculpted surfaces etched by weathering microforms, including spectacular weathering pits up to 1 m deep (Hall and Phillips, 2006b).

Figure 8. Tors on Beinn Mheadhoin

Tor location and morphology may be determined by a range of litho-structural controls (Ehlen, 1992). Joint orientation provides the rectilinear plan form typical of the Cairngorm tors through the intersection of two or three sets of steeply inclined joints. Joint density affects both tor form and tor location. Tor height (n=54) is a function of the spacing of horizontal joints ($R^2 = 0.64$), rather than of vertical joints ($R^2 = 0.17$). Few tors have vertical joints < 1m apart, but block sizes in tor avenues and within surrounding regolith indicate that such closely-spaced joints are usual in the bedrock around tor bases (Figure 8). The largest tors are developed mainly, but not exclusively, on dome summits in zones of massive granite that contain monoliths of dimensions >4 x 3 x 3 m. These rock cores are widely spaced, with a mean spacing of 0.7 km on Ben Avon.

Tors in glaciated regions have been referred to frequently as relict pre-glacial landforms, but it appears that many tors are not as old as formerly believed (Hall and Sugden, 2007). Whilst cosmogenic isotope data show that all Cairngorm tors are older than the last interglacial and so have survived multiple phases of glaciation, the oldest tor surface has an apparent exposure age of 675 ka and so the tors cannot be regarded as pre-Pleistocene features (Phillips et al., 2006). Tors in the Cairngorms are dynamic landforms which have emerged at rates of 12-38 m/Myr during the Pleistocene due to repeated formation and stripping of thin regolith from around the tors. The tors are therefore non-glacial forms that represent continuing, long term, differential weathering and erosion of unevenly jointed granite.

PLATEAU REGOLITH

Debris covers on the Cairngorm plateau include soils (Mellor and Wilson, 1989), block-rich regolith (matrix-rich and matrix-poor blockfields), block-poor sandy gravel (Haynes et al., 1998) and weathered rock (Gordon, 1993). Almost all debris covers retain high proportions of polymineralic granules, together with quartz and feldspar sand and low amounts of fines.

The plateau regolith is generally shallow, especially close to tors, with deeper regolith confined to stream heads. Thaw of late-lying snow patches in recent warm summers has revealed 2-6 m of regolith, comprising occasional core stones in a matrix of sandy granular gravel and blocks (Figure 9). Previous suggestions (Ballantyne and Harris, 1994; Glasser and Hall, 1997) that the Cairngorm plateau supported a widespread cover of sandy weathered rock 10-20 m deep before glaciation are probably in error. Extensive cliff exposures show instead that unweathered granite extends close to the present landsurface except in narrow fracture zones. Weathering profiles up to 10 m deep are, however, found close to valley floors, especially towards the margin of the pluton (Figure 2).

Figure 9. Regolith types on Ben Avon

Bedrock controls on granite regolith formation operate at several scales and include the influence of jointing, hydrothermal alteration and stress release. Joint spacing affects block size and frequency in the regolith. The pervasive reddening by hematite of the weathered granite at the head of Coire Raibert and high on Ben Avon (Figure 9) indicates that, as at other stream heads, hydrothermal alteration has predisposed the rock to breakdown. Stress release in response to removal of overburden by erosion can operate at the granular scale and is responsible for the spalling of micro-sheets on crumbling granite surfaces. The low degree of chemical alteration of primary minerals in the disaggregated granite found close to the floors of glacial troughs also suggests the wider operation of stress release, here in response to glacial incision. The Cairngorm plateau regolith probably includes materials of widely different ages but its limited geochemical evolution indicates that little, if any, of the present regolith developed before the Pleistocene.

CONCLUSIONS

Glacial erosion in the Cairngorms has been confined mainly to the deepening and extension of pre-glacial valleys and the formation of corries in valley heads. Hence pre-glacial and non-glacial relief is exceptionally well preserved and comprises a hierarchy of typical granite landforms. Tors and regolith are superimposed on larger landforms such as domes and basins, which are themselves elements within the staircase of palaeosurfaces that is cut into the roof zone of the exposed granite pluton. These geomorphic features are expressions of bedrock controls that extend from the granular level to the scale of the entire intrusion. Regolith types appear to be largely a function of jointing and micro-fracturing, whereas tor forms are closely controlled by joint spacing and orientation. Kernels of massive granite at different scales give large tors and domes. The main valleys follow the weaknesses provided by the fractured rocks in linear alteration zones. The broad outline of the massif is itself probably a reflection of the large size and original flat upper surface of the granite pluton. The ages of the main landforms are not yet closely constrained but small landforms are largely non-glacial features formed within the Pleistocene. Known erosion rates indicate that larger landforms in the Cairngorms, such as domes, basins and major breaks of slope, have histories that exceed 1-10 Myr. The continuity of relief development extends back to unroofing of the Cairngorm pluton in the Devonian, when structurally-aligned precursors of the main valleys directed the headwaters of the regional river system.

ACKNOWLEDGEMENTS

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FIGURES

FIGURE 1

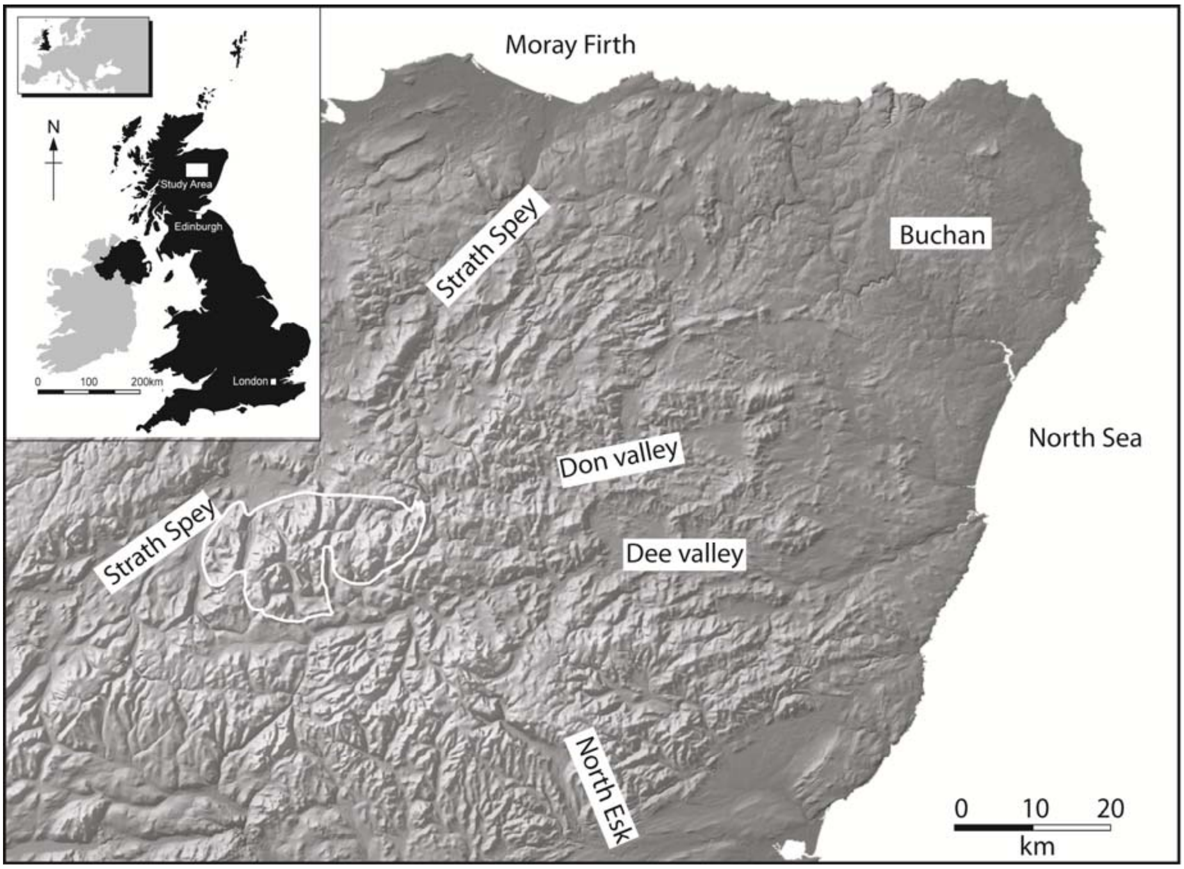

Figure 1. Location and regional relief, with the margin of the Cairngorm Granite outlined

FIGURE 2 DEM

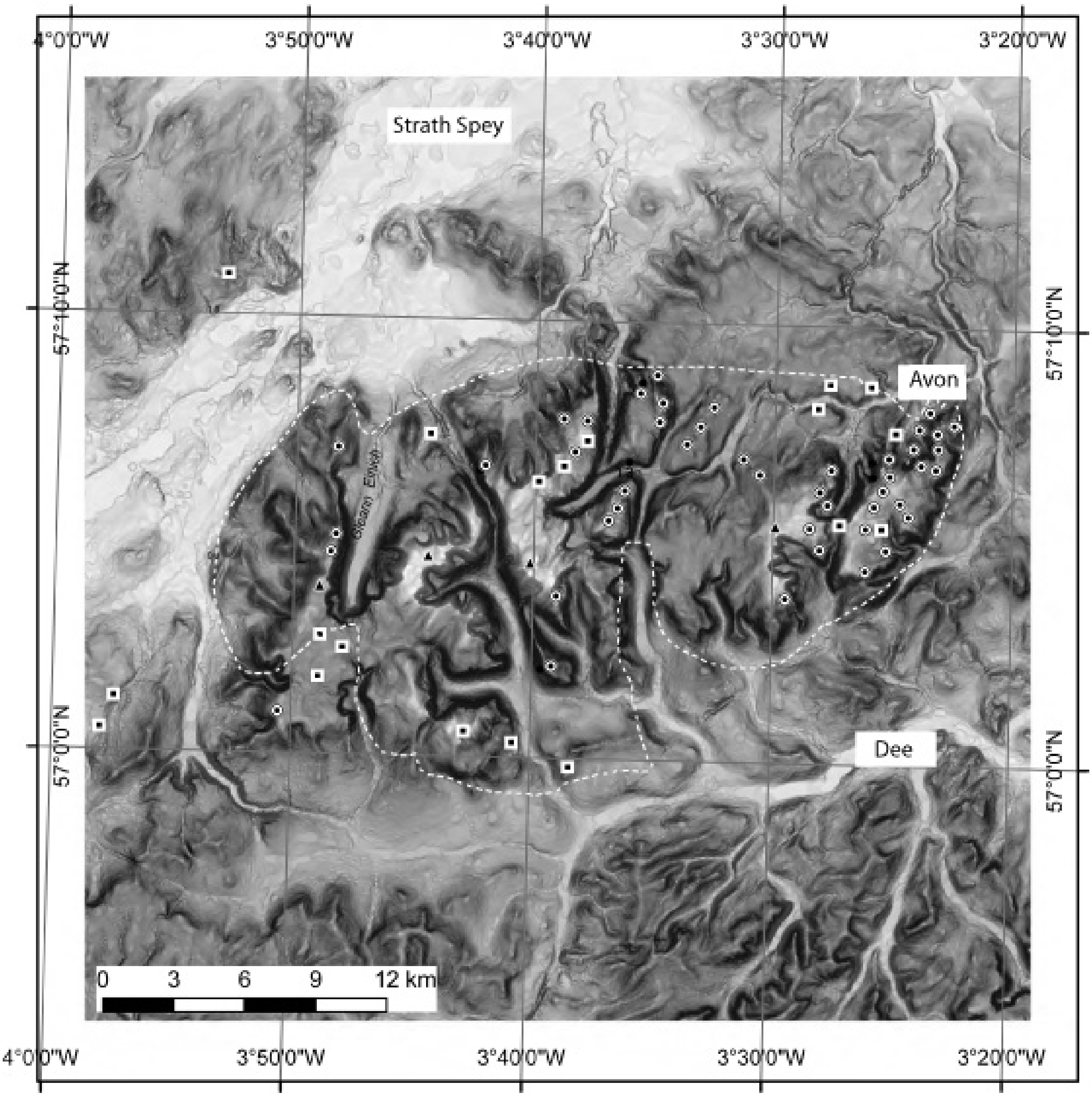

Figure 2. Digital surface model of the Cairngorms built from Intermap Technologies NEXTMap Britain topographic data.

FIGURE 3

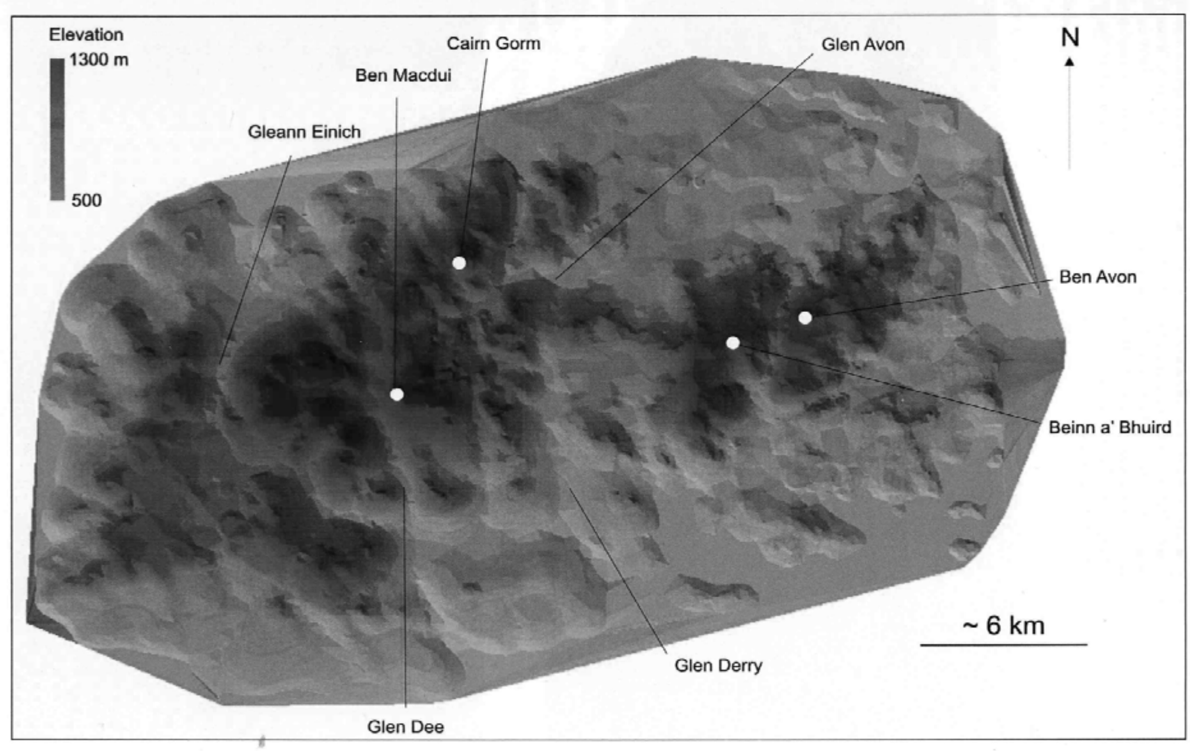

Figure 3. Model of the pre-glacial relief of the Cairngorms

FIGURE 4

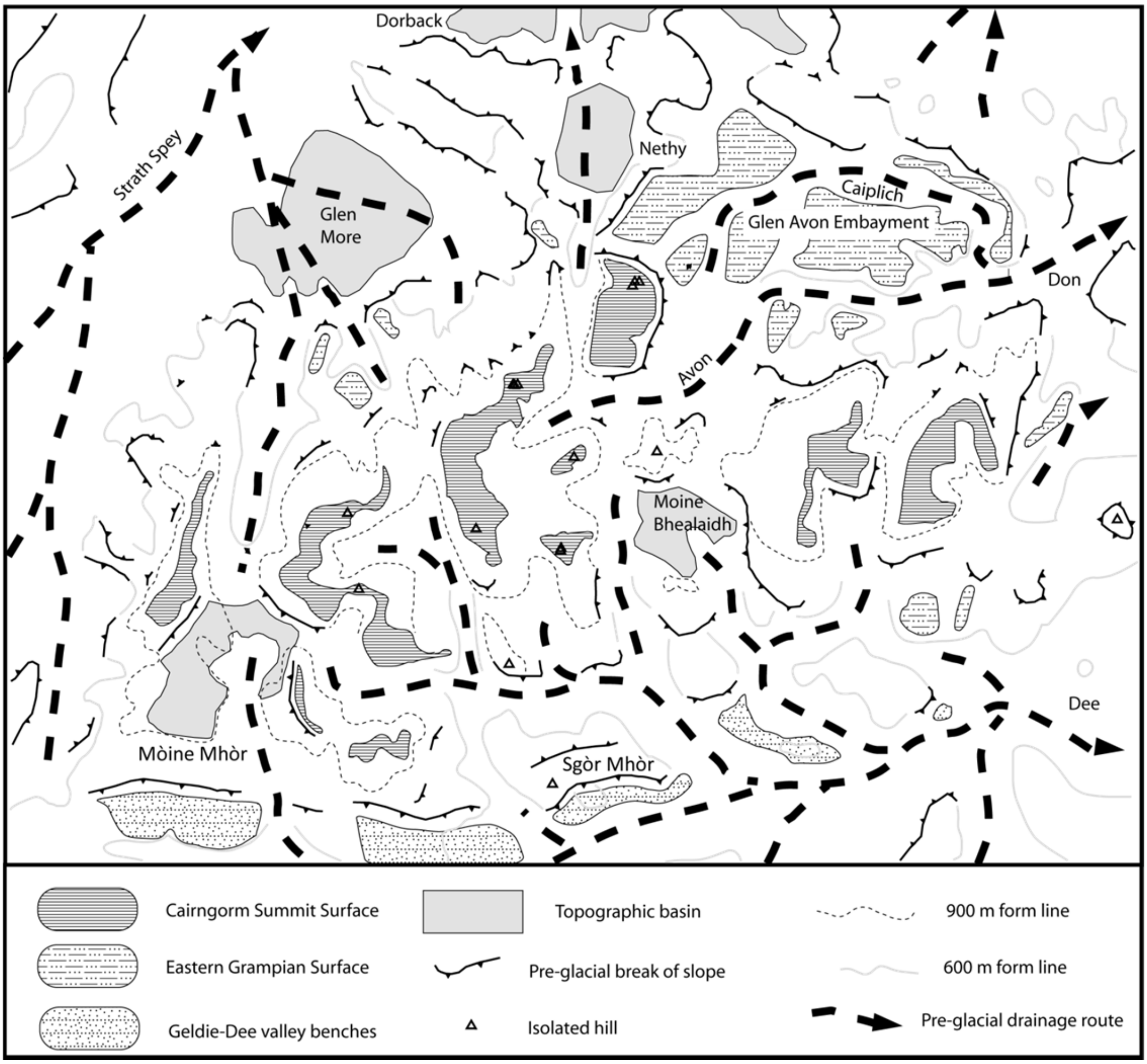

Figure 4. Pre-glacial and non-glacial landforms of the Cairngorms

FIGURE 5

Figure 5A. Looking east across the floor of the Glen Avon embayment towards the break of slope at the edge of the Cairngorm Summit Surface

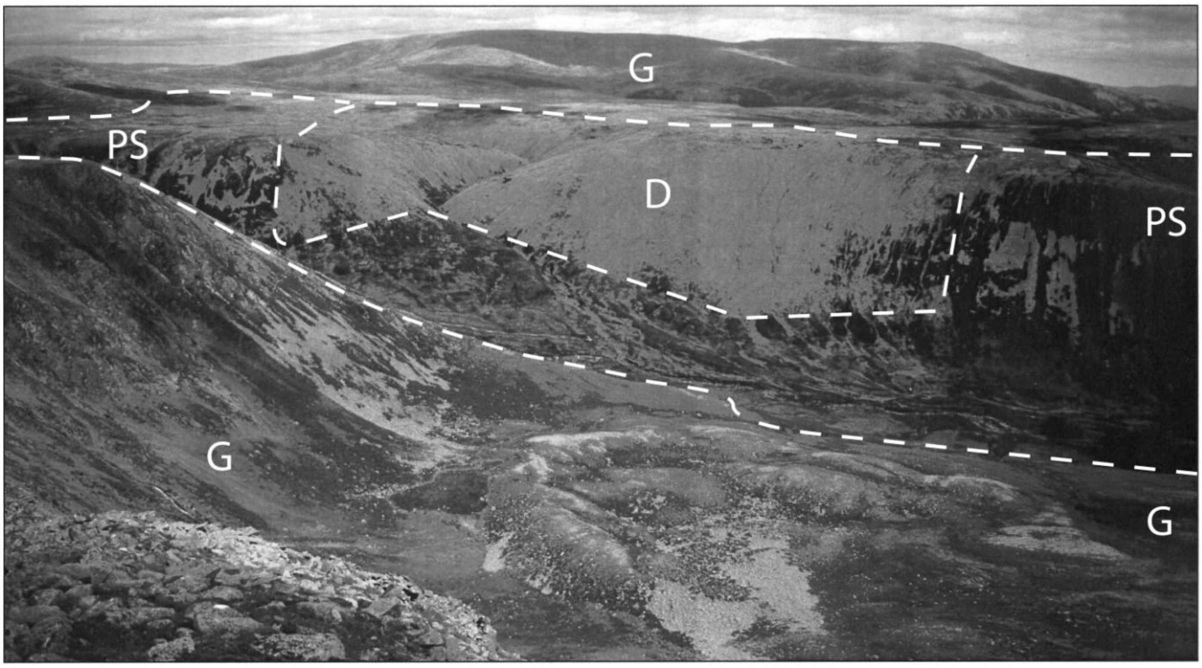

Figure 5B. Moine Bhealaidh, a high level basin in the heart of the Cairngorms. G granite; PS psammite, a metamorphosed feldspar-rich sandstone; D diorite, an intermediate igneous rock

FIGURE 6

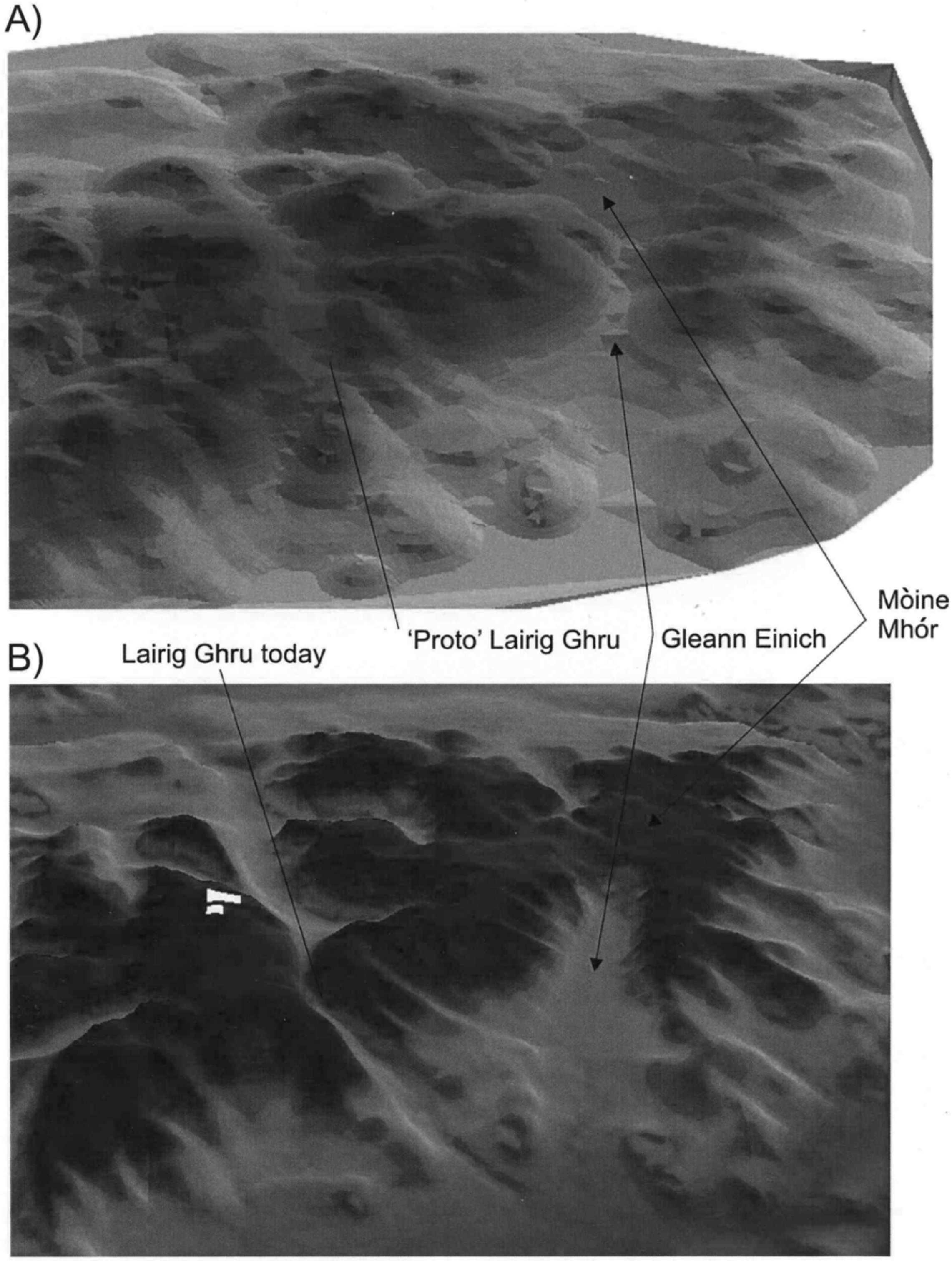

Figure 6. Northern Cairngorms, pre-glacial and present relief

FIGURE 7

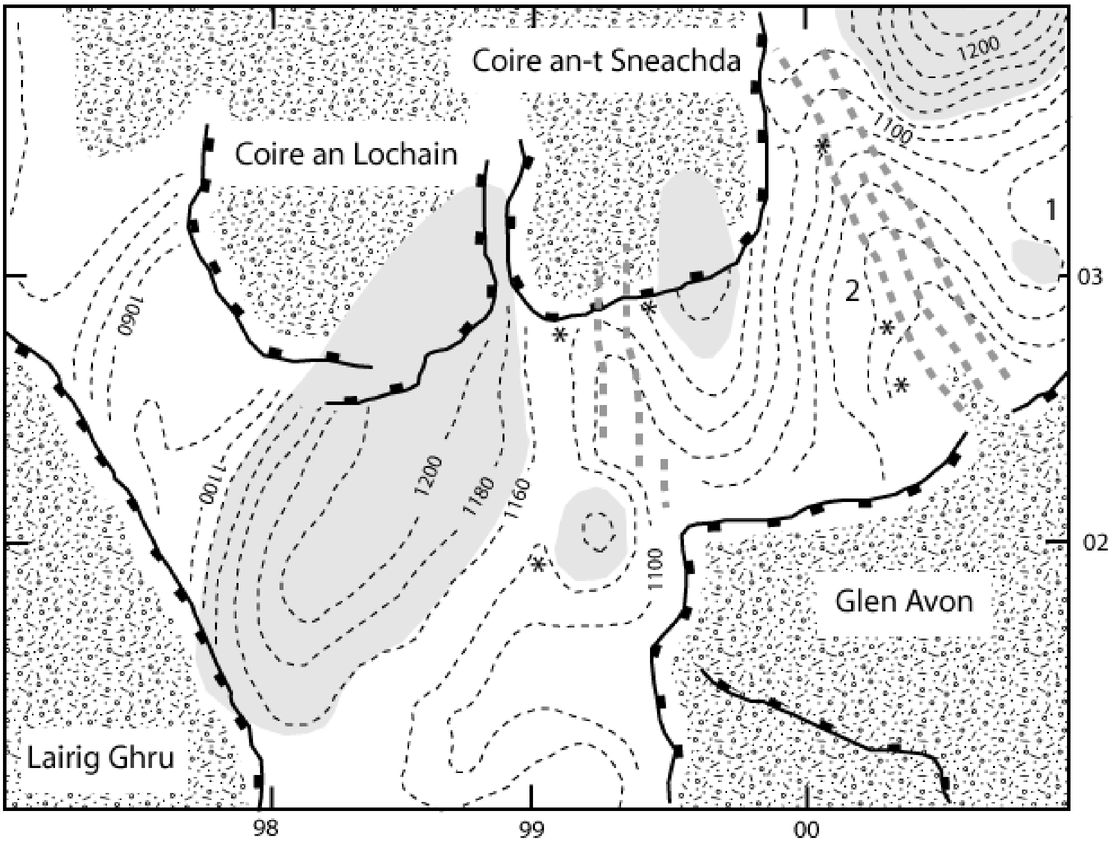

Figure 7. Granite domes above the Northern Corries. The original dome shapes are indicated by shading and zones of deep glacial erosion are stippled. The dome margins are delineated by alteration zones (dashed lines) in which reddened, weathered granite is exposed (stars, with depth in m). The domes have been truncated by headward growth of the corries during the Pleistocene.

FIGURE 8

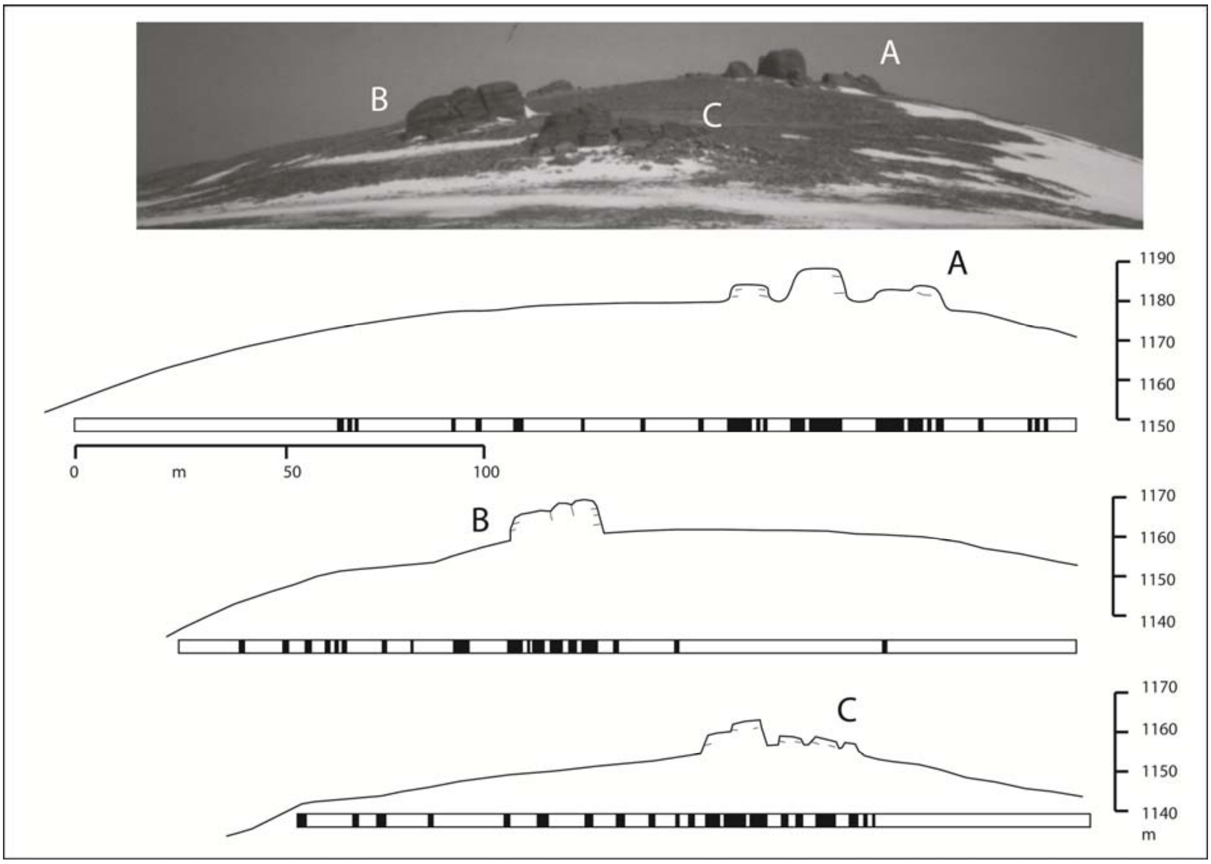

Figure 8. Tors on Beinn Mheadhoin. Note the conformity between slopes and the sheeting visible in the tors. Black shading in the slope profiles shows where joints are spaced >2 m apart, indicating that the tors are developed only in zones of massive granite.

FIGURE 9

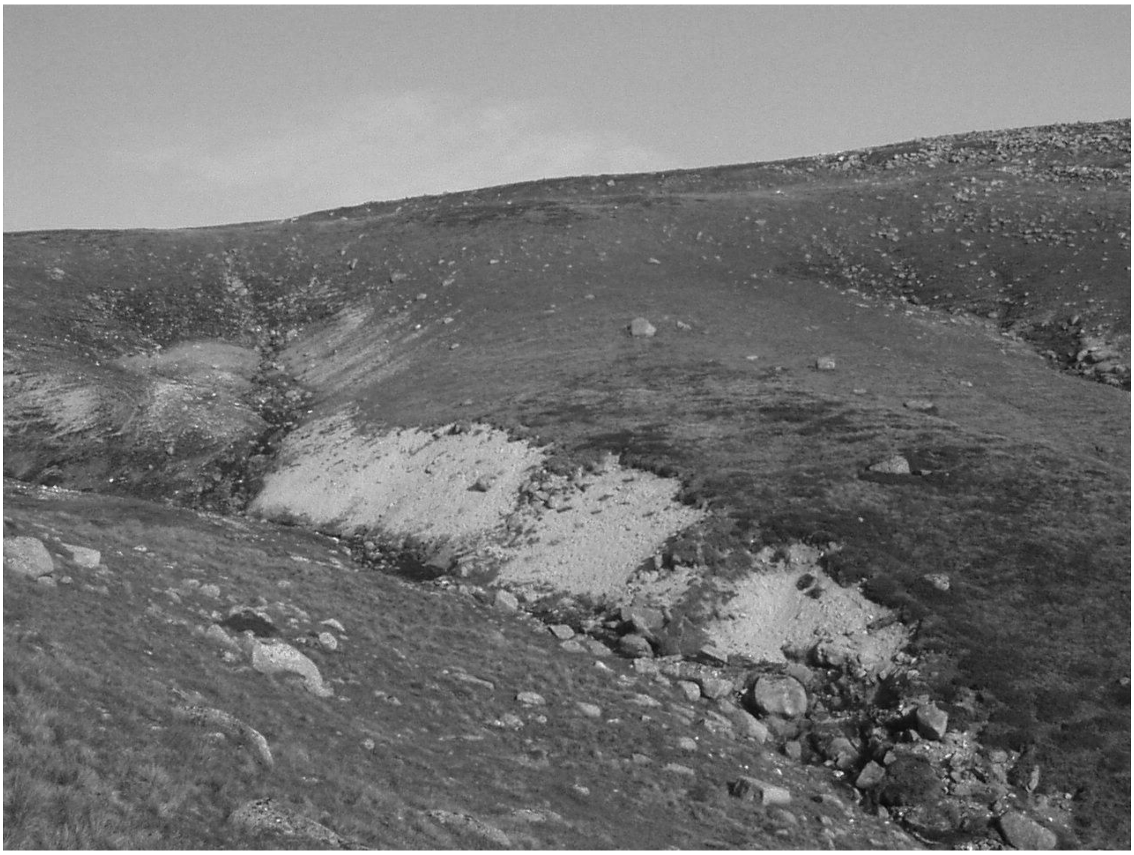

Figure 9. Regolith types on Ben Avon (NGR NJ 132014). The shallow headwater valleys hold long lasting snow patches except in late summer. Block-poor granular disintegration with occasional corestones is associated with the linear alteration zone in the foreground. Margin of block-rich regolith is seen on the top right.