

### 3. THE SHAPING OF LOCHNAGAR: PRE-GLACIAL, GLACIAL AND POST-GLACIAL PROCESSES

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*Key words:* Lochnagar, Granite, Glaciation, Pre-Glacial Landforms, Corrie, Moraine.

#### **Introduction**

The massif nowadays named after Lochnagar dominates the skyline of southern Deeside. The granite batholith that underlies Balmoral Forest forms a rolling summit terrain which reaches 1155 m above sea level at Cac Carn Beag and rises from the high plateau of The Mounth, developed largely in metamorphic and basic igneous rocks (Chapter 2: Goodman this volume). Set into the edge of the massif are the spectacular corries which scallop the north face of the mountain, including the great amphitheatre that holds Lochnagar. Incised also into the plateau is the broad glacial trough occupied by Loch Muick, curving with the margin of the granite ring complex (Figure 1). The geomorphology of the area is also of considerable interest for the detail of its glacial and periglacial landforms (Gordon and Ballantyne 1993). The international significance of the corrie lochan of Lochnagar for studies of Holocene environmental change means that it is important to first set the basin in the context of the processes which have shaped the surrounding terrain and which continue to operate today.

The scenery of Lochnagar and its environs is in many ways a microcosm of the wider Cairngorms, where three generations of relief conventionally are recognised (Gordon and Ballantyne 1993; Sugden 1968):

1. Major non-glacial landforms which predate the onset of regional glaciation in the Pleistocene around 1 million years ago.
2. Major landforms of glacial erosion, including corries and troughs.
3. Minor landforms produced by processes operating under glacial, periglacial and cool temperate processes which ornament the relief and which have developed largely over the past 15 ka.

This chapter examines the origins of these relief forms, together with the development of the lake basin and its surroundings through the Lateglacial and Holocene periods.

#### **Ancient landforms**

The preglacial relief of Lochnagar and its surroundings developed during the Tertiary period (65-2.5 Ma) under climates probably warmer than today but continued to evolve



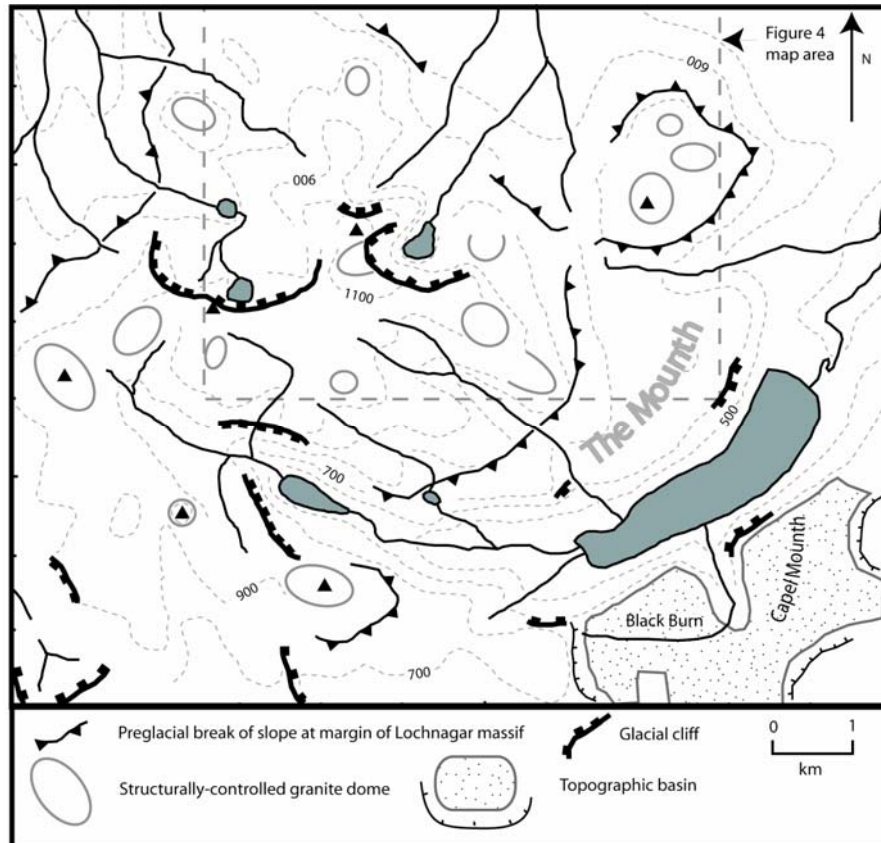


Figure 1. The Lochnagar massif and its pre-glacial and glacial landforms

through erosion throughout the Quaternary. The main elements are residual hill masses, erosion surfaces, topographic basins and valleys. The Lochnagar massif and Mount Keen form the largest areas of residual relief, rising from a marked break of slope at 730 - 750 m. The Mounth plateau abuts the massif and is one of a staircase of erosion surfaces that dominate the relief of northeast Scotland (Fleet 1938; Hall 1983; 1991). The remarkably gentle relief is probably a product of a prolonged phase of erosion close to sea level prior to uplift in the Late Oligocene, 28-23 million years ago (Hall and Bishop 2002). Set into the erosion surface are shallow basins of differential weathering and erosion, notably the diorite basin now occupied by the Black Burn. The Mounth carries a dendritic system of shallow headwater valleys which represent a little-modified preglacial drainage network (Bremner 1919). Incision of the drainage network into the uplifted surface commenced well before glaciation but has yet to penetrate fully the Lochnagar massif.

The Lochnagar massif displays typical granite terrain. Although the L3 granite forms low ground (Chapter 2: Goodman this volume), it is structural rather than lithological controls which dominate the relief. At least two vertical joint sets define cuboidal blocks, whilst alteration zones produced by hydro-fracturing at a late stage of cooling of the granite provide other major lines of weakness. Erosion of the granite and release of overburden leads to the opening of sheet joints that curve parallel to the slopes of the massif. Weathering and erosion have exploited these weaknesses to give a landscape with both curved and linear elements. The domes and rounded spurs are a reflection of the control of sheet structures over slope evolution (Figure 1). The valleys and cols often align with zones of closely-spaced jointing or of hydrothermal alteration. The linear zones of reddened, disintegrating granite in the headwall and gullies of the corrie of Lochnagar represent rocks weakened by late-stage alteration during granite cooling. Small tors rise from several domes (Figure 2), with a rectilinear geometry that displays the orientation of crossing joint sets.

Tors are minor landforms formed by non-glacial processes of weathering and erosion acting on uneven joint densities. The tors emerge from areas of low joint density. In the Cairngorms, recent work indicates that small tors emerged during the last few hundreds of thousands of years and that many have been modified by glacial erosion (Phillips et al. 2006). The subdued form of many tors in the vicinity of Lochnagar (Figure 3), including the summit tor (Addy 2005), leaves little doubt that these tors have also lost superstructure to flowing glacier ice (Hall and Phillips In Press-a).

### **Major glacial landforms**

The drama of the scenery around Lochnagar stems from a juxtaposition of the gentle slopes of the massif with the cliffs that define the margins of the corries and glacial valleys. This combination is typical of landscapes of selective linear glacial erosion (Sugden 1968). On the plateau, glacial erosion has been limited to the removal of a few metres of rock whereas in the corries and valleys there has been deep erosion. For Cairngorm corries, Gordon (2001) estimates rates of glacial deepening rates of 600 m/Ma and the scale of the Lochnagar amphitheatre requires similar rates of erosion. Glacial excavation of the over-deepened basin of Loch Muick has removed a depth of >250 m of rock. Both corries and glacial valleys must be the products of many cycles of glacial erosion during the Pleistocene.

The selectivity of glacial erosion is superbly illustrated on the Capel Mounth, the path that crosses the high plateau from Loch Muick to Glen Clova. The steep slopes which rise from the valley floor are plastered with glacial deposits left by ice moving out of the Muick trough during the last ice sheet glaciation. Walking up towards the break of slope between the valley side and plateau, the till thins and pockets of weathered diorite appear and steadily increase in extent. The valley of the Black Burn carries many large diorite erratics, and sections show that these are derived in part from the excavation of unweathered rock kernels from within weathering profiles. On the plateau, the diorite is extensively weathered to granular sand and forms an extensive, shallow basin set within the surrounding schists. The Capel Mounth reveals an inverse correlation between erosion and altitude which is typical of landscapes of selective linear glacial erosion.

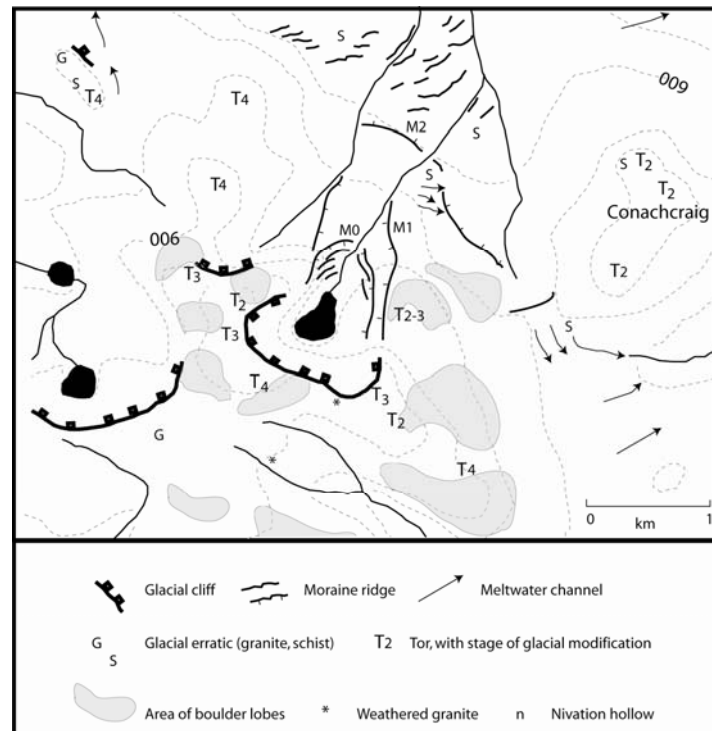


*Figure 2.* The granite dome of Meikle Pap, with glacially-modified summit tor and boulder fields.



*Figure 3.* Glacially-modified tor on the eastern spur above Lochnagar. The tor has lost superstructure to flowing glacier ice.

Such selectivity stems from the former basal thermal regimes of the glaciers that occupied the valley and covered the plateau. To be highly erosive, ice must slide across its bed and so the basal ice must be at the pressure melting point. The presence of meltwater not only promotes sliding and abrasion but also aids plucking of debris from protuberances on the glacier beds. In contrast, ice below the pressure melting point does not slide at the ice-rock interface but deforms internally. Although capable of the removal of loose blocks, as on tors, cold-based ice is essentially non-erosive and so protects the buried terrain from erosion. In general terms, the massif has been covered by cold-based ice whereas the lower ground has been scoured by thicker, warm-based glacier ice. The actual patterns are more complex, with parts of the plateau showing roughening due to glacial erosion by sliding ice, a reflection in part of the role of topography in channelling ice flow.



*Figure 4.* Glacial and periglacial landforms around Lochnagar. Data on meltwater channels, erratics and M0-M2 moraines from Clapperton (1986). Data on moraines on northern slopes from Brown (1993) and for boulder lobes from Gordon and Ballantyne (1993). The stages of glacial modification of tors follow the model of Hall and Phillips (In press). Unmodified tors (T1) show a delicate superstructure of perched and rounded blocks. Progressive glacial modification involves firstly the removal of the superstructure (T2), followed by the entrainment of tor blocks along open horizontal sheet joints (T3). Many small tors have been reduced to plinths or slabs (T4) by the wholesale removal of upstanding joint blocks. When modified by wet-based ice, tors are shaped by block removal, abrasion, and lee-side plucking into roche moutonnées or whalebacks (T5).

### **The last ice sheet and its landforms**

The Lochnagar massif forms the highest ground in the southeast Grampians and is important for the evidence it provides for the reconstruction of the dynamics of the last ice sheet. The last (Late Devensian) ice sheet in Scotland built up from 32 ka cal yr (Whittington and Hall 2002), reached its maximum extent by 26 ka cal yr (Sejrup et al. 1994), then retreated, re-advanced and finally disappeared from low ground by around 15 ka cal yr (McCabe and Clark 2003). Clapperton (1986) used the distribution of metamorphic erratics and meltwater channels to identify the flow of external ice around the northern and eastern slopes of the Lochnagar massif. Schist erratics reach elevations of 850 m on Conachraig and channel systems incise the col between this hill and Lochnagar to 825 m (Figure 4). These features probably relate mainly to the last glacial maximum (LGM) when ice from Glen Clunie and Strath Dee deformed around the massif. The absence of schist erratics from higher elevations does not imply that the summit of Cac Carn Beag was ice-free. Granite erratics comprising large granite blocks rest in areas of different granite lithology or in zones of high joint density at high elevations on the plateau. Complete ice cover is indicated also by glacially-modified summit tors. Many modified tors show only shallow weathering pits on exposed surfaces indicating loss of blocks to or local abrasion by the last ice sheet. Glacially-exposed rock surfaces on the tors at Meikle Pap and Conachraig carry pits up to 35 cm deep (Addy 2005). Comparisons with Cairngorm tors suggest that such pits developed during the last interglacial or earlier and so glacial modification predates the LGM (Hall and Phillips In Press-b). The tors and erratics thus provide evidence of an ice sheet flowing to the northeast over the mountain during at least two stages of the Pleistocene.

The northern face of the mountain shows a striking sequence of ice-marginal landforms, including boulder lines, moraine ridges and meltwater channels (Brown 1993; Clapperton 1986). The highest channels in the col east of Meikle Pap reach over 800 m OD (Figure 4), requiring that the ice sheet was at that time flowing across the mouth of the corrie of Lochnagar. Other ice-marginal ridges form a roughly parallel sequence down to around 400 m (Figure 4) and formed as the ice sheet retreated from the flanks of the mountain and towards Braemar (Brown 1993).

### **Periglacial Landforms**

Large parts of the plateau are mantled by frost-weathered debris, with excellent examples of boulder lobes and terraces on Cuidhe Cròm and Cac Carn Beag (Galloway 1958). Detailed survey by Shaw (1977) revealed that lobes occur on slopes of 10-34° from 640-110 m OD. Many are structurally-controlled and developed from the steps between sheet joints. The lobes are stone-banked and up to 6 m high and 33 m across slope and comprise openwork boulders. The boulder terraces are found on gentler slopes (14 - 22°) but have comparable composition and thickness. Shaw considered both features to be inactive currently, but their age is uncertain. The absence of these features from within the limits of Loch Lomond Stadial glaciers suggests that the boulder lobes were actively forming under the intense periglacial conditions of that period (Sissons and Grant 1972) but the manner in which boulder mantles are absent



*Figure 5.* The corrie headwall above Lochnagar. Note the gullies acting as debris chutes and the overlapping debris cones at their exits. A rockfall scar from 1995 is visible on the Eagle Ridge. The deep gully at the angle of the corrie (centre) is the Black Spout: it feeds a debris flow that extends to the loch shore.



*Figure 6.* Sand plume on the south-east margin of Lochnagar from recent debris flows. Note the vegetated boulder slopes in the background, with few signs of recent contributions of debris to the loch.

from areas of the plateau last covered by warm-based ice at the LGM suggests that some plateau regolith has a longer residence time.

### The north-east corrie of Lochnagar

This is an imposing example of a corrie, with a headwall up to 350 m high which overshadows Lochnagar. The lake occupies a rock basin over 20 m deep (Dalton et al. 2005). The corrie is the product of many periods of occupation by glaciers. Its northerly orientation ensured the trapping of snow blown from the plateau and ablation was suppressed by its elevation and shade. Well-defined boulder ridges (M1 on Figure 4) extend well beyond the confines of the corrie and appear to be the lateral moraines of a former glacier sourced in the corrie. These ridges terminate against boulder lines which run across the mouth of the corrie (M2) and which probably relate mainly to the margin of a glacier flowing down the Dee valley (Clapperton 1986). A series of 9 arcuate boulder ridges (M0), each less than 3 m high, sits inside these former ice limits and terminate abruptly down valley, suggesting separate and later deposition from ice in the corrie. Radial ridges on the east side of the corrie floor may represent fluted moraine from this late phase of corrie glaciation (Clapperton 1986).

These delicate depositional landforms almost certainly relate to the last phases of glaciation in the corrie and its environs. There is uncertainty whether the moraines belong to the period of the retreat of the last ice sheet, when a small glacier could have remained in the corrie, or to the Loch Lomond Stadial, a short period of intense cooling in which renewed glacier growth occurred extensively in the Scottish Highlands (Table 1). Uncorrected  $^{10}\text{Be}$  cosmogenic exposure duration times (Phillips et al. 2003) indicate

Table 1. Late Quaternary events and timescales in the Lochnagar area.

Age (cal. ka BP)	OI Stage	Period		Geomorphc environments
		Holocene		Weathering, soil formation and lake sedimentation. Mass movement, debris flows and avalanches. Cool temperate interglacial climate.
11.5	1	Loch Lomond Stadial	Late-glacial Late Devensian	Intense cold. Corrie glacier reforms. Periglacial activity renewed on surrounding slopes.
13		Windermere Interstadial		Rapid warming to near present levels. Vegetation colonisation of recently deglaciated slopes.
15	2	Dimlington Stadial		Ice sheet glaciation after 32 ka reaching a maximum at ~27 ka. Onset of final deglaciation after 15 ka.
26	3	Middle Devensian		Rapidly changing cool to cold temperatures. Long periods of ice cover, with corrie and valley glaciers and probable larger ice masses.
59	4	Early Devensian		Probable renewed ice sheet glaciation.
71	5a-5d			Two cool to warm intervals separated by cold phases when corrie glaciation probably recurred.
116	5e	Ipswichian		Cool temperate interglacial climate, with similar processes operating to those in the Holocene.
128	6	Wolstonian		Ice sheet glaciation.

that the M1 moraine ridges date from 10.4-15.2 ka. These dates imply that the M1 moraine dates from the Loch Lomond Stadial, as proposed by Sissons and Grant (1972). The M2 boulder ridge has provided a range of exposure ages from 24.9-13.4 ka. This implies that the M2 moraine relates to ice sheet deglaciation but incorporates boulders reworked from earlier glacial phases. Recent work on the edge-rounding of granite boulders demonstrates a clear difference between boulders from the M1 and M0 moraines (Kirkbride 2006). The greater edge rounding on the boulders from the M1 moraine suggests that the boulders were either exposed to a longer period of weathering spanning several thousand years or that the outer M1 moraine was exposed to intense weathering after it had retreated from its maximum position in the Loch Lomond Stadial (Kirkbride 2006). Alternatively, many boulders in the M1 moraine may have been resident on the corrie floor before the Loch Lomond Stadial and then entrained during the final advance of ice from the corrie.

Pollen analysis of peat cores taken from within the arcuate moraines demonstrate that sedimentation commenced before 9700 radiocarbon years BP (Rapson 1985). Samples of peat and a pine stump in the same area gave radiocarbon ages of  $7170 \pm 80$  BP (SRR-2272) and  $6080 \pm 50$  BP (SRR-1808), respectively (Rapson 1985). Cores from Lochnagar indicate that organic sedimentation commenced before  $8430 \pm 80$  (Hela-403) radiocarbon years (Dalton et al. 2005).

Since the final disappearance of glacier ice at or after the end of the Loch Lomond Stadial, substantial volumes of debris have accumulated at the base of the headwall, a sign of recent and continuing mass movement (Figure 5). Many different processes are involved, of which the most important are rockfall and debris flows. Continuing rockfall from cliffs is indicated by the presence of fresh, angular clasts on debris slopes and on late-lying snow patches. A substantial rock slope failure has occurred in recent years at the foot of the Eagle Ridge (Figure 5). The debris slopes extend in places from the base of the cliffs down to the shoreline of the loch and include both unvegetated, active slopes and vegetated, currently inactive slopes. The main activity of snow avalanches in corries such as this lies in the erosion the upper parts of talus slopes (Ballantyne and Harris 1994) but such modification has been modest in scale at Lochnagar. Ward (1985) surveyed the debris slopes to find slope profiles virtually indistinguishable from those of unmodified rockfall debris. Although snow avalanches occur frequently in this corrie (Ward 1984), the majority are small in volume, confined to the snow layers and travel over beds protected by old snow (Ward 1985). The evidence for recent transport by debris flows is more compelling. Each of the main gullies in the headwall has been largely swept clear of rockfall debris which has accumulated on overlapping talus cones on the middle and lower slopes. The presence of unvegetated talus suggests recent activity and this is in accordance with an increase in debris flow activity throughout the Scottish Highlands over the last millennium (Ballantyne 2002; Brazier and Ballantyne 1989).

Sediment input to Lochnagar is largely restricted to its rim and may have come from a variety of sources. The corrie receives wind-blown snow and sand-sized and smaller particles from the adjacent plateau during southerly and south-westerly gales. Whilst it is conceivable that some of this material may reach the lochan directly, the corrie headwall is probably the dominant source of debris. The distribution of rockfall debris, which mainly stops short of the loch shore, suggests that few clasts enter the loch directly by rolling or sliding. Avalanche debris may have reached the loch in the past

but this was probably confined largely to the organic and inorganic materials held within the snow pack. Debris flows have reached the SW and SE edges of Lochnagar to leave plumes of grit and sand (Figure 6) but the debris is found only a short distance offshore. On the north-eastern side of the loch there is continuing and extensive peat erosion, dating from the last 100-150 years (Chapter 5: Helliwell et al. this volume), and this organic debris must now lie largely on the loch floor. Cores from the deepest parts of the lochan show that 1.55 m of largely organic debris has accumulated over the last 9470 years, with higher organic productivity during warmer climate phases (Dalton et al. 2005).

### Summary

The landforms of the area around Lochnagar belong to three generations:

- Preglacial, major non-glacial features produced by long-term differential weathering and erosion, and including erosion surfaces, residual hills, topographic basins and granite domes.
- Glacial features formed during the Pleistocene by ice sheets, valley and corrie glaciers. The corrie of Lochnagar and its surroundings display moraines which record the retreat of the last ice sheet from the flanks of the massif and the subsequent build-up and decay of a small glacier in the corrie now occupied by Lochnagar.
- Post-glacial features formed since the final disappearance of ice from the corrie 11.5 thousand years ago. Sediment input to Lochnagar has been limited, as most debris sourced from the corrie headwall appears to be retained on debris slopes that extend from the base of the headwall to the lake shore.

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