Mass Movements in Great Britain

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Chapter 2

Mass-movement GCR sites in Precambrian and Cambrian rocks

INTRODUCTION TO THE MASS MOVEMENTS IN THE OLDER MOUNTAIN AREAS OF GREAT BRITAIN

D. Jarman

The older mountain ranges of Britain – the Scottish Highlands, the Southern Uplands, the Lake District, and the northern half of Wales (Figure 2.1) – have long been prized for both their exceptional landscape value and their scientific interest. They were fashioned during the Caledonian Orogeny 480–390 million years ago, mainly in metamorphic rocks of Precambrian, Cambrian, Ordovician, and Silurian age, but with some contemporaneous igneous intrusions. Mass movements in these ranges differ considerably in character, cause, mechanism, and geomorphological effect from those on the Devonian, Carboniferous, Mesozoic and Cenozoic cliffs, escarpments and valley

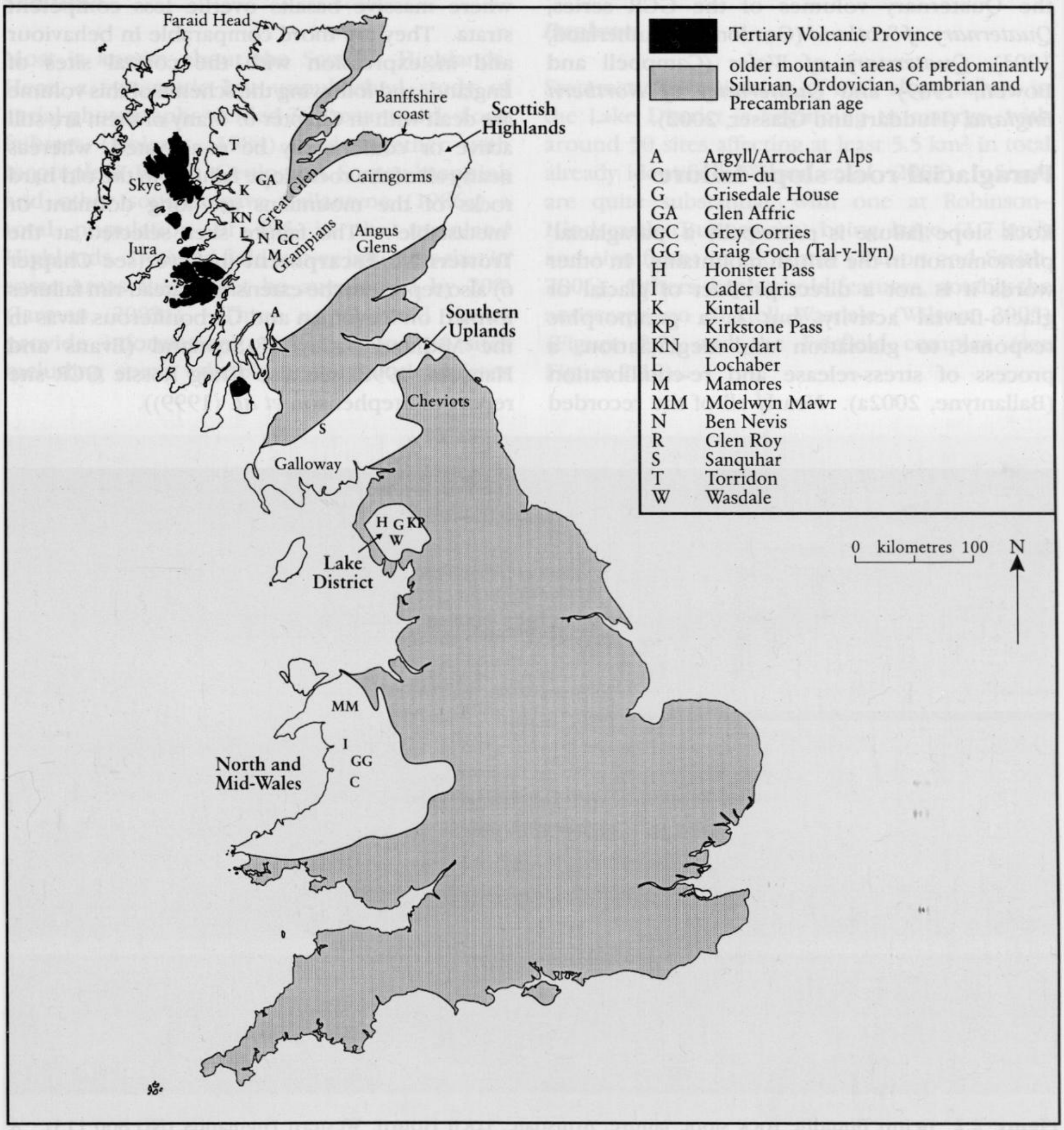


Figure 2.1 General location map of the older mountain ranges in Britain. Locations of GCR sites in this chapter are shown in Figure 2.13. Other sites within the older mountain areas are **Cwm-du** (see GCR site report, Chapter 3) and **Coire Gabhail** (see GCR site report, Chapter 4).

slopes described in following chapters of the present volume.

This chapter focuses on deep-seated mass movements in bedrock ('rock slope failure' – RSF). Mass movement in superficial deposits and mass wasting of rockfaces, both active and relict, is of course prevalent in many parts of these mountains, and may become more significant again as climate change favours more extreme events. However manifestations such as screes, debris cones, solifluction terraces, and rock glaciers are well represented by sites in the Quaternary volumes of the GCR series, *Quaternary of Scotland* (Gordon and Sutherland, 1993), *Quaternary of Wales* (Campbell and Bowen, 1989) and *Quaternary of Northern England* (Huddart and Glasser, 2002).

Paraglacial rock slope failure

Rock slope failure is principally a 'paraglacial' phenomenon in the British mountains. In other words it is not a direct product of glacial or glacio-fluvial activity, but is a geomorphic response to glaciation and deglaciation, a process of stress-release and re-equilibration (Ballantyne, 2002a). Nearly all of the recorded rock slope failures are on the flanks of glacial troughs (including those submerged as fjords), or in the corries/cwms which feed them. Non-paraglacial failures can also be found on sea cliffs (e.g. Faraid Head, Durness; the Banffshire coast), and with instructive rarity above fluvial gorges (e.g. Arnisdale by Loch Hourn (Figure 2.2), Craig Maskeldie in the Angus glens (NO 386 795)).

A special case arises with the Tertiary [Palaeogene] Volcanic Province of the Western Highlands and Inner Hebrides (Figure 2.1). Here numerous extensive mass movements occur where massive basalts overlie less competent strata. They are more comparable in behaviour and in expression with the coastal sites of England, and following the scheme of this volume are dealt with in Chapter 6. Many of them are still active or could easily be re-activated, whereas nearly all of the rock slope failures in the old hard rocks of the mountains are long dormant or 'metastable'. The failure sites selected at the **Trotternish Escarpment** in Skye (see Chapter 6) also represent the extensive plateau-rim failures formed on Devonian and Carboniferous lavas in the Midland Valley of Scotland (Evans and Hansom, 1998; see also Craig Rossie GCR site report in Stephenson *et al.* (1999)).

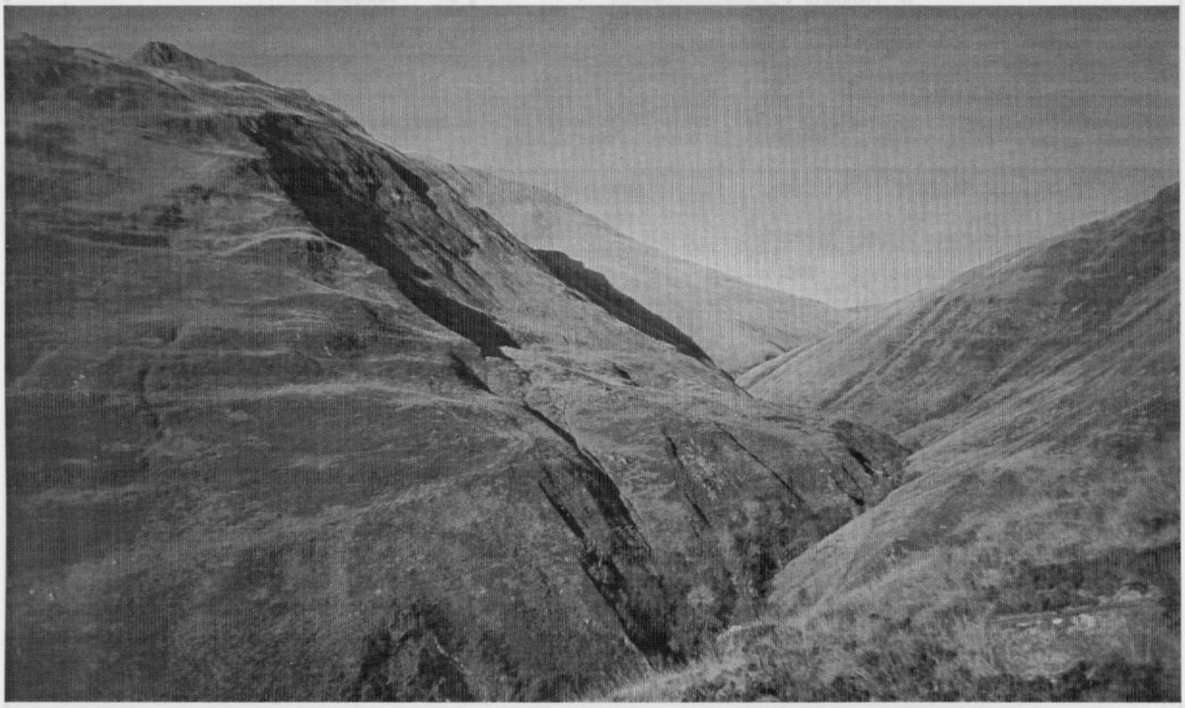


Figure 2.2 Beinn Bhuidhe rock slope failure, Arnisdale, Loch Hourn, Western Highlands (NG 860 113). A typical armchair slide with slope toe exceptionally undercut by deep fluvial (rather than glacial) incision, and thus not directly a paraglacial rock slope failure. (Photo: D. Jarman.)

Extent of rock slope failure and state of knowledge

By contrast with mass movement in the sedimentary slopes of Britain, there has been remarkably little research into rock slope failures in the mountain areas. This is partly because of their isolation and low geohazard status, and partly because they are enigmatic features, difficult to address within the canons of either geomorphology or engineering geology.

Scotland

Most is known about the Scottish Highlands. Here, a systematic but unpublished study of aerial photographs yielded 364 extant rock slope failures (Holmes, 1984), and together with incomplete British Geological Survey mapping and other sources gave Ballantyne (1986a) a total population of 495 in the mainland Highlands. Detailed field survey indicates that in some areas this might be augmented by 20% (Jarman, 2003a). Three unpublished theses provide information on collections of sites including some valuable geotechnical analyses (Watters, 1972 – 20 cases; Holmes, 1984 – 27 cases; Fenton, 1991 – 44 cases). A few individual sites have been recorded in the literature, but these have generally not been of seminal status (e.g. Beinn nan Cnaimhseag; Sellier and Lawson, 1998).

In the Southern Uplands, rock slope failure is sparse and low-key, with isolated cases, for example in the Galloway mountains (Cornish, 1981), north-east of Sanqhuar, and in the Cheviots (W. Mitchell, University of Durham, pers. comm.). Ballantyne (1986a) recorded 24 sites.

England

Systematic investigation of rock slope failure in the Lake District is beginning to emerge, with around 50 sites affecting at least 5.5 km^2 in total already identified (Wilson *et al.*, 2004), . Some are quite substantial, with one at Robinson–Hindscarth (Buttermere) being large (1.7 km^2) and significant in UK terms (Wilson and Smith, 2006). Others display bold features, notably the antiscarps on Kirkfell, Wasdale (Wilson, 2005) (Figure 2.3) and the Fairfield complex (see Figure 2.10).

Figure 2.3 Kirk Fell rock slope failure, Wasdale, Lake District. A classic virtually in-situ slope deformation, with an antiscarp 600 m long crossing the summit plateau and others on the south-west flanks. (Photo: P. Wilson.)

Wales

In northern and mid Wales, there is no systematic survey of paraglacial mountain rock slope failure, although active failure in coastal old hard-rock exposures is of continuing interest (cf. Nichol, 2002). A few individual sites have been reported in Snowdonia (e.g. Curry *et al.*, 2001; Rose, 2001), and some in the Berwyns such as that damming Llyn Moelfre (SJ 180 285) (Hutchinson, unpublished data). One substantial site selected here at **Cwm-du** (see Chapter 3) represents behaviour in weakly indurated Silurian metasediments, but is most noted for the uncertainty surrounding its origins. Another site at Tal-y-llyn near Cader Idris has been thoroughly investigated (Hutchinson and Millar, 2001, fig. 48) and is notable as the largest landslide dam in Britain. A kilometre of glacial trough wall cut in Ordovician metasediments collapsed, with 50×10^6 m^3 of debris impounding the lake of Tal-y-llyn, once 2.5 km and now 1.6 km long. A substantial extension to the failure scar has become arrested after short travel. This site is of international significance (Nichol, 2002).

GCR site selection

When the original shortlisting of mass-movement sites was made in 1982, only three sites were put forward in the mainland Highlands, reflecting the dearth of published investigations. Of these, two were major discoveries arising out of unpublished PhD theses – Glen Pean (de Freitas and Watters, 1973) and **Beinn Fhada** (Holmes and Jarvis, 1985). The third Scottish site at **Coire Gabhail** (see Chapter 4) was famous as the landslide-blocked Lost Valley of Glencoe; it is the only known rock slope failure on high-strength Devonian lavas in the Highlands.

Three GCR sites selected for the Quaternary of Scotland GCR Block (Gordon and Sutherland, 1993) are also relevant to the subject of the present volume. One is in Dalradian quartzite and two are in Precambrian Torridonian sandstone: Beinn Shiantaidh on Jura (Gordon and Mactaggart, 1997) and Baosbheinn in Torridon are now regarded as more probably rock slope failures rather than rock glacier and protalus rampart cases respectively, while **Beinn Alligin** has been described in the present volume (as well as in Gordon and Sutherland, 1993), as cosmogenic dating (Ballantyne and Stone, 2004) has largely resolved the controversy over its mode of emplacement (although it still does not fully merit the designation of 'sturzstrom').

Systematic characterization of rock slope failures in several parts of the Highlands (Jarman, 2003a,b; Hall and Jarman, 2004), and of all 140 larger failures in the Highlands (Jarman, 2006) has demonstrated their great diversity. It has also underlined the previously overlooked importance of their contribution to erosion and landscape shaping over Quaternary times. It became clear that rock slope failure in the older mountain areas could not adequately be represented by just six sites, of which three were in lithologies where failure is exceptional and relatively small-scale. Of the three in metasedimentary rocks, **Cwm-du** (Chapter 3) has been studied mainly as a quasi-glacial deposit; and while Glen Pean and **Beinn Fhada** are two of the largest and most impressive failures in Britain, they are of rather similar character and setting, and both occur within similar geological contexts in the North-west Highlands.

In reviewing the Highland rock slope failure sites in 2003, to ensure that the GCR encompassed the full spectrum of characteristics (including geological context, type of failure, landshaping effects), eight additional GCR sites were proposed and are described in the present chapter – **Beinn Alligin**, **Ben Hee**, **Benvane**, **Carn Dubh**, **The Cobbler**, **Druim Shionnach**, **Glen Ample** and **Sgurr na Ciste Duibhe**. The Glen Pean site was recommended for deletion (where the original interpretation is now found to be implausible, cf. Jarman and Ballantyne, 2002); this type of rock slope failure is better represented by **Beinn Fhada**.

This introduction sets out the general context for understanding the diversity and significance of rock slope failure in the older mountain areas, starting with the main characteristics that the selected sites seek to represent.

Representing the diversity of geology and structure

Lithological controls

The vast majority of rock slope failures occur in the metamorphic lithologies (Ballantyne, 1986a). This is unsurprising given that most of the older mountain ranges are constructed from them.

But significant failure can occur in every lithology, including Torridonian sandstone (e.g. **Beinn Alligin**), volcanic lavas (e.g. **Coire Gabhail**, Chapter 4), and granite (e.g. Lundie, NH 164 114). A notable complex on granite affects 3 km on both sides of Strath Nethy, beside Cairn Gorm (Hall, 2003). This complex falls within the Cairngorms GCR site, selected for the Quaternary of Scotland GCR Block (Gordon and Sutherland, 1993). Current investigations at this site by the British Geological Survey suggest an unusual combination of glacial, periglacial and paraglacial activity.

Metamorphic rocks in the British mountains range in age from dominantly Precambrian in the Scottish Highlands and Islands, to mainly Ordovician and Silurian in the Southern Uplands, Lake District and North Wales. In the Highlands, the Moine and Dalradian Supergroup rocks are mainly composed of metamorphosed and deformed sandstones, siltstones and mudstones. Here the term 'schist' has been applied commonly to the more indurated Highland rocks, with the dominant psammitic (i.e. sandy) variants being termed 'quartz schists'. In the Palaeozoic ranges the metasedimentary rocks are often less indurated, with the generic term 'slate' including friable greywackes (see **Cwm-du** GCR site report, Chapter 3). But rock slope failure occurs across all metamorphic types and grades, including those of igneous origin such as the ancient Lewisian gneisses and the Borrowdale volcanic rocks. It tends to be more widespread in slaty and interbedded strata, where mica-rich cleavage and foliation surfaces facilitate sliding, but can equally well operate in blocky to massive and relatively uniform psammite terrains such as the central Grampian Highlands (Hall and Jarman, 2004).

Structural controls

Structurally, the metamorphic rocks are more prone to develop deep-seated failure planes, by virtue of profound tectonic activity during the Caledonian Orogeny and (in the North-west Highlands) earlier orogenies. As well as the foliation (schistosity) surface, three or more joint-sets are commonly present (Watters, 1972) (Figure 2.4), so that potential sliding surfaces, depending on their pervasiveness, can be available on most slope aspects. By contrast, granite is generally more sparsely jointed, and it 'springs' on shallow fracture surfaces that develop parallel to the present or original slope. Torridonian sandstone also tends to fail at joint-block scale, although slices of cliff have collapsed on near-vertical joints, and mass creep

Figure 2.4 A typical small crag in Moine psammites displays four distinct discontinuities (the foliation or schistosity surface and three joint-sets), which have released a miniature wedge failure. (Photo: D. Jarman.)

has occurred on gently dipping bedding planes (e.g. Beinn Bhàn, Applecross (NG 800 450)).

Mountain-building processes have left the metasedimentary rocks inclined at all angles from sub-horizontal to sub-vertical, and in all scales and intensities of folding. The textbook ideal for large-scale sliding is a smooth surface inclined close to the peak or residual friction angle (Hoek and Bray, 1981), typically 20°–40° for schists. Any gentler, and friction prevents sliding, any steeper, and the surface becomes less likely to have been undercut by glacial trough steepening; ultimately it becomes a self-supporting wall. However, rock slope failure occurs freely in rocks inclined at all angles and showing every degree of folding and contortion, if not on the foliation or bedding surface then on joint-sets that cut through the contortions, and if not by sliding alone then by creep, sag, buckle or topple, or any combination.

The sites selected here show that while geological controls can be direct and obvious (e.g. **Ben Hee**), rock slope failure can develop in a wide range of contexts, and in some cases without an obvious relationship to any observable structures (e.g. **Beinn Fhada**, **The Cobbler**). The relatively straightforward analyses and predictions that can be made for failures in the regular sedimentary strata of Britain become more elusive in the older mountain areas.

Representing the diversity of rock slope failure types

The general introduction to this volume follows the classification of Hutchinson (1988), but observes that any attempt to classify mass movements is unsatisfactory because firstly they are on a continuum, and secondly most are complex, embodying several modes of failure. This is especially true of the older mountain areas. Characterization of rock slope failures in the older mountain areas like the Scottish Highlands (Table 2.1; Figure 2.5) has adapted the Hutchinson schema to reflect prevailing modes there, with five broad categories spanning the continuum (Jarman, 2006):

- compressional deformation
- extensional deformation
- arrested translational sliding
- sub-cataclasmic slide/collapse
- cataclasmic slide/collapse

Slope deformation

The first two categories (compressional and extensional deformation) cover slope deformations where the lateral margins are diffuse, and downslope movement is limited. They tend to be extensive, and account for 64% of the larger (> 0.25 km²) Highland rock slope failures

Table 2.1 Characteristic types of large rock slope failures (RSFs) in the Scottish Highlands and Lake District. Adapted from Jarman (2006) and Wilson *et al.* (2004). See Figure 2.5 for explanation of terms.

		Scottish Highlands	Lake District
RSF size	0.25–0.49 km²	67	5
	0.5–0.99 km²	61	1
	1.0–1.99 km²	16	1
	2.0–3.0 km²	3	–
total RSFs	0.25–3.0 km²	**147**	**7**
RSF predominant mode			
rockslides (all degrees of arrestment/disintegration)		**54**	**4**
of which	cataclasmic	3	–
	sub-cataclasmic	14	–
	arrested short–medium travel	37	4
slope deformations		**92**	**3**
of which	extensional (sag and creep)	68	3
	compressional (rebound) including Cluanie hybrids	24	–
Association with glacial breaches (including tributary troughs)			
	main watersheds	55	1
	secondary watersheds	56	1
	no close association	36	5

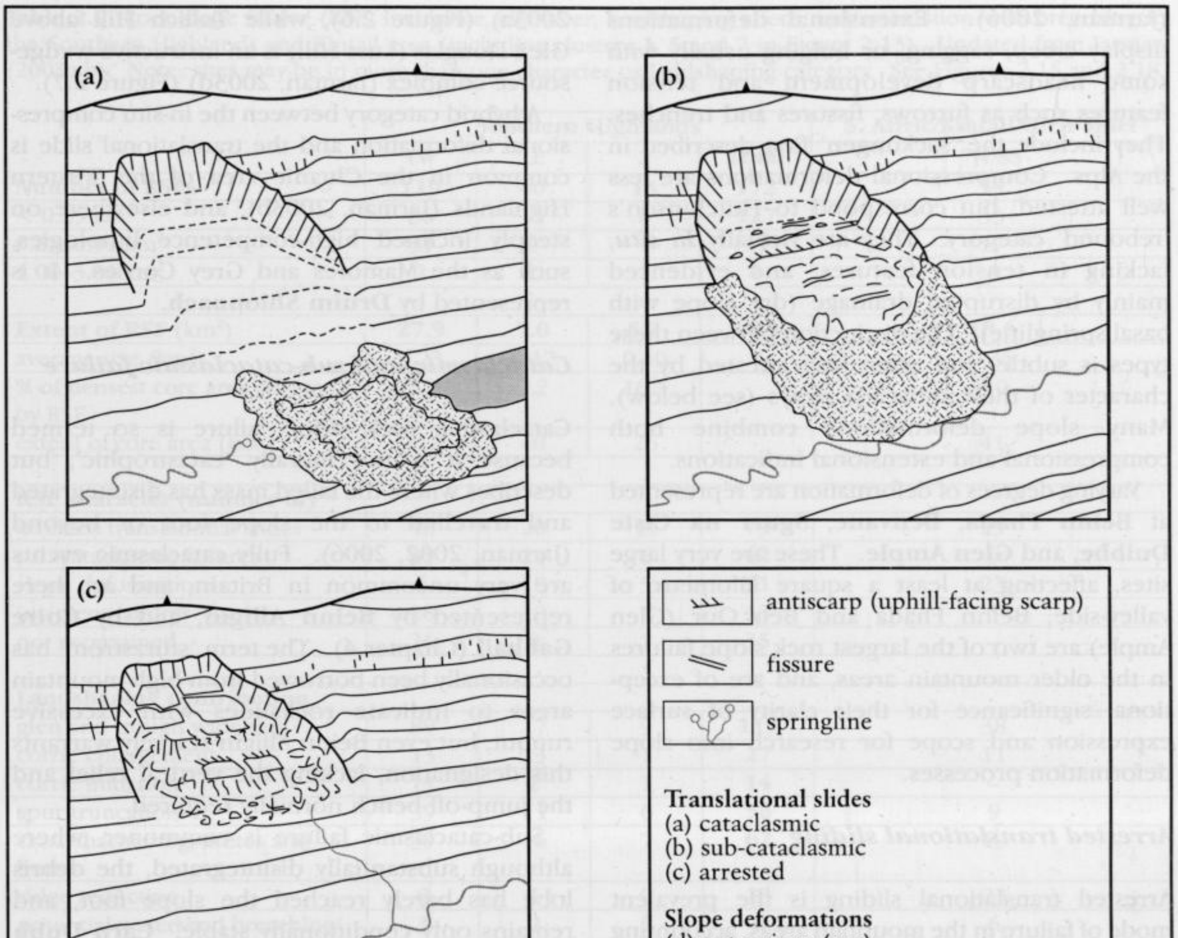


Figure 2.5 Characteristic types of larger-scale rock slope failure identified in the Scottish Highlands. The plateau rim location is typical of less intensely dissected terrain. In more acute relief, headscarps may daylight below or behind the crest, or split the ridge. After Jarman (2006).

(Jarman, 2006). Extensional deformations display creep, sagging, or bulging usually with some headscarp development and tension features such as furrows, fissures and trenches. They include the 'sackungen' first described in the Alps. Compressional deformations are less well attested, but correspond to Hutchinson's 'rebound' category. They are virtually *in situ*, lacking in tension features, and evidenced mainly by disrupted drainage (dry slope with basal springline). The distinction between these types is subtle, and often best attested by the character of their antiscarp arrays (see below). Many slope deformations combine both compressional and extensional indications.

Varying degrees of deformation are represented at **Beinn Fhada**, **Benvane**, **Sgurr na Ciste Duibhe**, and **Glen Ample**. These are very large sites, affecting at least a square kilometre of valley-side; Beinn Fhada and Ben Our (Glen Ample) are two of the largest rock slope failures in the older mountain areas, and are of exceptional significance for their clarity of surface expression and scope for research into slope deformation processes.

Arrested translational sliding

Arrested translational sliding is the prevalent mode of failure in the mountain areas, accounting for 60% of all rock slope failures in the South-west Highlands (Table 2.2), although only 25% of the larger sites across the Highlands. Here a well-defined mass has failed and travelled some distance downslope before becoming arrested in a more-or-less coherent state. There is usually a well-defined source cavity, which may be wedge or armchair-shaped. The failed mass may have antiscarps, open fissures, detached megablocks, and basal debris-lobes or block piles. The reasons for arrestment are poorly understood, but probably reflect inadequate lubrication, rough or corrugated failure planes, and lack of vertical relief; such arrested slides seem less apparent in higher mountain ranges of the world.

Arrested slides are represented at **The Cobbler** (very short travel from a headscarp but much dislocated), **Benvane** (long travel from a classic source bowl, low-key lobe) and **Ben Hee** (short travel from a corrie headwall). Good examples of armchair-source slides are at An Sornach in Glen Affric (Holmes, 1984; Jarman, 2003c), Glen Fintaig in Lochaber (Watters, 1972), and Beinn Tulaichean at Balquhidder (Jarman, 2003a) (Figure 2.6), while Tullich Hill above Glen Douglas (Luss Hill) is an instructive wedge-source complex (Jarman, 2003d) (Figure 2.7).

A hybrid category between the in-situ compressional deformation and the translational slide is common in the Cluanie area of the Western Highlands (Jarman, 2003b), and elsewhere on steeply inclined high-competence lithologies, such as the Mamores and Grey Corries. It is represented by **Druim Shionnach**.

Cataclasmic and sub-cataclasmic failure

Cataclasmic rock slope failure is so termed because it is not literally 'catastrophic', but describes where the failed mass has disintegrated and travelled to the slope foot or beyond (Jarman, 2002, 2006). Fully cataclasmic events are very uncommon in Britain, and are here represented by **Beinn Alligin**, and by **Coire Gabhail** (Chapter 4). The term 'sturzstrom' has occasionally been borrowed from high mountain areas to indicate rockslides with excessive runout, but even Beinn Alligin scarcely warrants this designation, lacking the vertical relief and the jump-off bench normally required.

Sub-cataclasmic failure is commoner, where although substantially disintegrated, the debris lobe has barely reached the slope foot, and remains only conditionally stable. **Carn Dubh** (Ben Gulabin) represents this mode with two small debris-tongues. Other tongues analysed include Mam na Cloiche Airde (Watters, 1972) and Gleann na Guiserein (Bennett and Langridge, 1990; Ballantyne, 1992), both in Knoydart, Mullach Fraoch-choire in Glen Affric (Holmes, 1984) (Figure 2.8), and Burtness Comb in the Lake District (Clark and Wilson, 2004). Moelwyn Mawr in Snowdonia (Rose, 2001) may well be similar.

A variant of sub-cataclasmic failure is the crag collapse leaving a coarse blocky debris-pile on the slope. In the South-west Highlands, 50% of sites display an element of (sub-)cataclasmic behaviour, the massive schistose grit lithology being more conducive to it than in areas of slabby metasediments. A fine example is on Beinn an Lochain North (Watters, 1972; Holmes, 1984) (Figure 2.9).

Complex failures

Many rock slope failures demonstrate several modes of failure, as at **Sgurr na Ciste Duibhe**.

Table 2.2 Rock slope failure (RSF) incidence, character, landshaping effect, and association with breaching in the Southern Highlands and Kintail area (including clusters 1, 5 and 7 in Figure 2.13). Updated from Jarman (2003a,b). Note: sites may be in more than one character or landshaping category. See Figures 2.15 and 2.18.

	Southern Highlands				S. Affric/Kintail/Glen Shiel
	1W	1E	2	**Total**	7N/8S
Number of RSFs	**119**	**40**	**13**	**172**	**54**
< 0.25 km^2	86	33	8	**127**	33
0.25–0.99 km^2	31	6	4	**41**	17
1.00–3.00 km^2	2	1	1	**4**	4
Extent of RSF (km^2)	**27.9**	**7.0**	**5.2**	**40.1**	**18.6**
average size (km^2)	0.23	0.17	0.40		0.35
% of densest core area affected by RSF	7.7	7.2	16.7		6.0
extent of core area (km^2)	112	40	26		41
RSF character (number of)					
arrested translational slides	48	20	11	**79**	25
sub-cataclasmic failures	35	21	6	**62**	6
slope deformations	6	10	5	**21**	23
incipient failures	28	10	5	**43**	5
not ascertained	26	8	1	**35**	–
Landshaping contribution					
glen and trough widening	89	17	9	**115**	38
corrie enlargement	13	13	1	**27**	11
corrie initiation	11	2	1	**14**	–
spur truncation	39	11	6	**56**	9
crest sharpening, arêtes and horns	39	16	7	**62**	19
ridge reduction	8	5	0	**13**	23
potential watershed breaching/ dissection	3	2	2	**7**	6
elimination of mountain blocks	12	4	1	**17**	2
Association with evolving glacial breaches					
at a 'recent' or enlarging breach	20	5	5	**30**	27
near a breach (< 2 km downflow)	24	15	4	**43**	
in a side trough rejuvenated by a breach below					11

Hell's Glen (Holmes, 1984) dramatically illustrates a progression from extensional deformation, producing a 15 m-deep antiscarp trench slanting across the midslope, with large translated masses breaking away into detached megablocks up to 60 m high, and some cataclasmic collapse debris reaching the glen floor.

Representing the landshaping effects of rock slope failure

Paraglacial rock slope failure has played a significant, if generally unremarked, role in shaping the present mountain topography. Its geomorphological impacts are numerous (Jarman, 2003a,b; Table 2.2), and may appear as isolated incidents (e.g. **Carn Dubh** (Ben Gulabin)) or, where its occurrence is dense, as a more generic contribution to Quaternary landscape evolution.

Arêtes and horns

The most striking effects of rock slope failure can be seen where summit ridges have been narrowed and incidented. This has been recognized in attributing arêtes in the ranges around Ben Nevis to rock slope failure (Bailey and

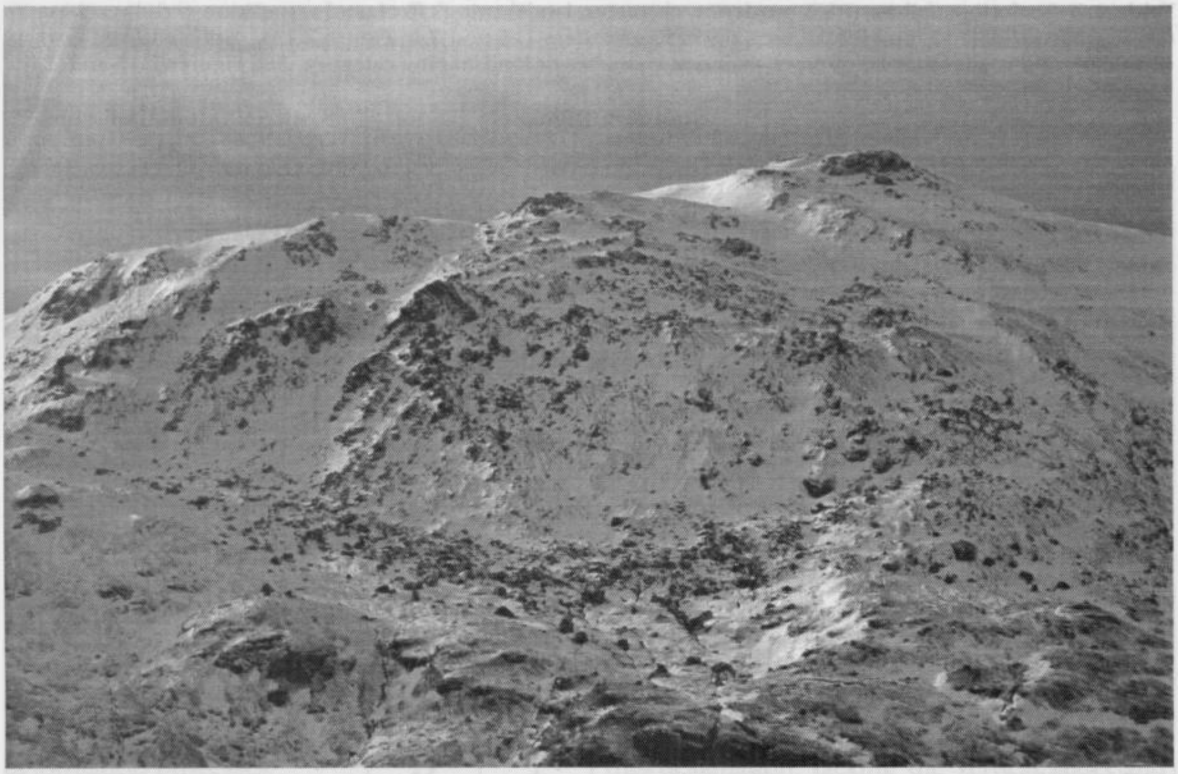


Figure 2.6 Beinn Tulaichean, Balquhidder, Southern Highlands (NN 420 196). A classic short-travel arrested translational slide from a splayed armchair source which splits the summit ridge. Despite the blocky veneer and spray fan, the failed mass is substantially intact, with double-decker-bus-sized fissures in the upper area. (Photo: D. Jarman.)

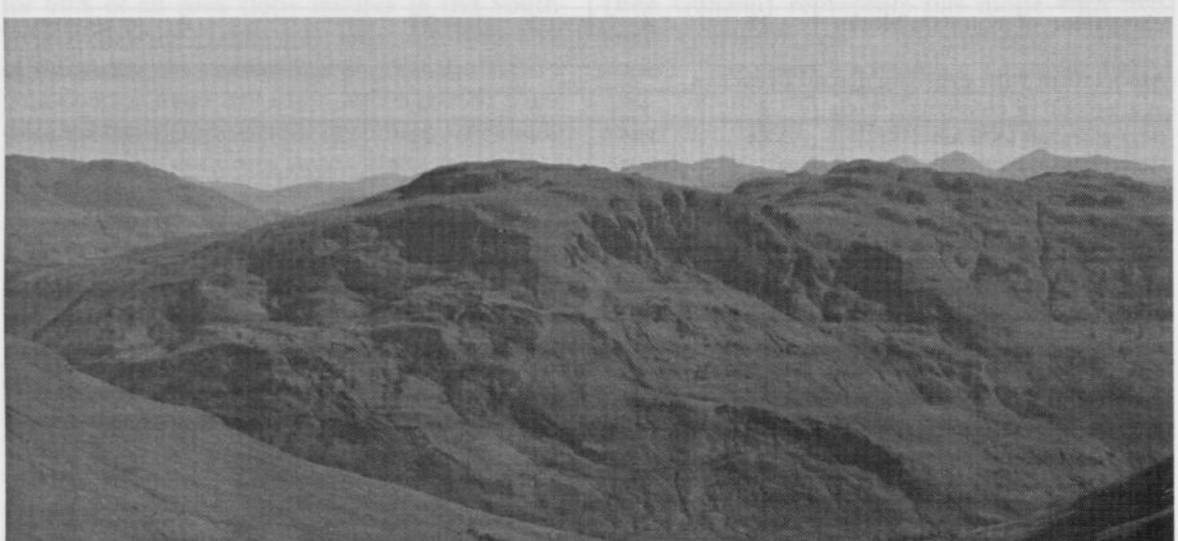
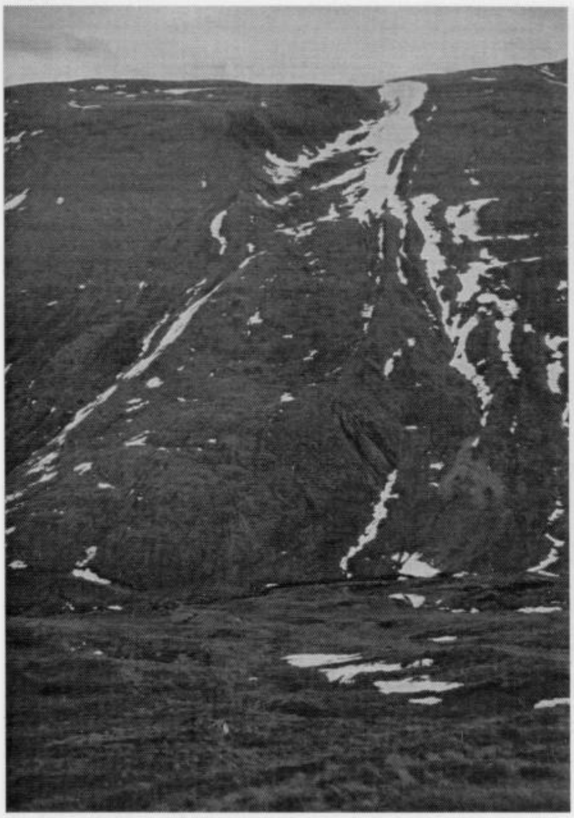


Figure 2.7 Tullich Hill rock slope failures, Luss Hills, South-west Highlands (NS 292 998). A translational slide complex from a multiple wedge source; the inner cavity in the west (left) rock slope failure is 30 m deep. (Photo: D. Jarman.)



◄**Figure 2.8** Mullach Fraoch-choire, Glen Affric (NH 102 187). A sub-cataclasmic debris-lobe 20 m thick with fine levées almost reaches the stream. It emanates from a narrow source pocket, and descends 380 m in 800 m. (Photo: D. Jarman.)

Maufe, 1916), and in interpreting the horn of Streap near Glenfinnan as a summit sliced by a slide scar (Watters, 1972). **The Cobbler** has been selected to display these summit ridge effects, while at **Sgurr na Ciste Duibhe** the summit mass has been lowered bodily by about 10 m, leaving a fretted arête. Good examples in the Lake District are the horns of Helm Crag (Grasmere (NY 325 090), and the Cofa Pike arête on Fairfield (NY 355 129; Figure 2.10).

Corrie development

It has been speculated that rock slope failure may play a part in 'seeding' corrie development (Clough, 1897; Peacock *et al*., 1992; Turnbull and Davies, 2006; see **Cwm-du** GCR site report, Chapter 3). Certainly in the minority of cases where failure occurs within a corrie, it is contributing to corrie enlargement and ultimate

Figure 2.9 Beinn an Lochain North rock slope failure, Arrochar Alps (NN 217 083). A sub-cataclasmic rock-slide, partly fallen from the cliffs (behind which deep fissures indicate incipient increments), but with a sliding component that has sharpened the summit ridge (top left) to an arête. (Photo: D. Jarman.)

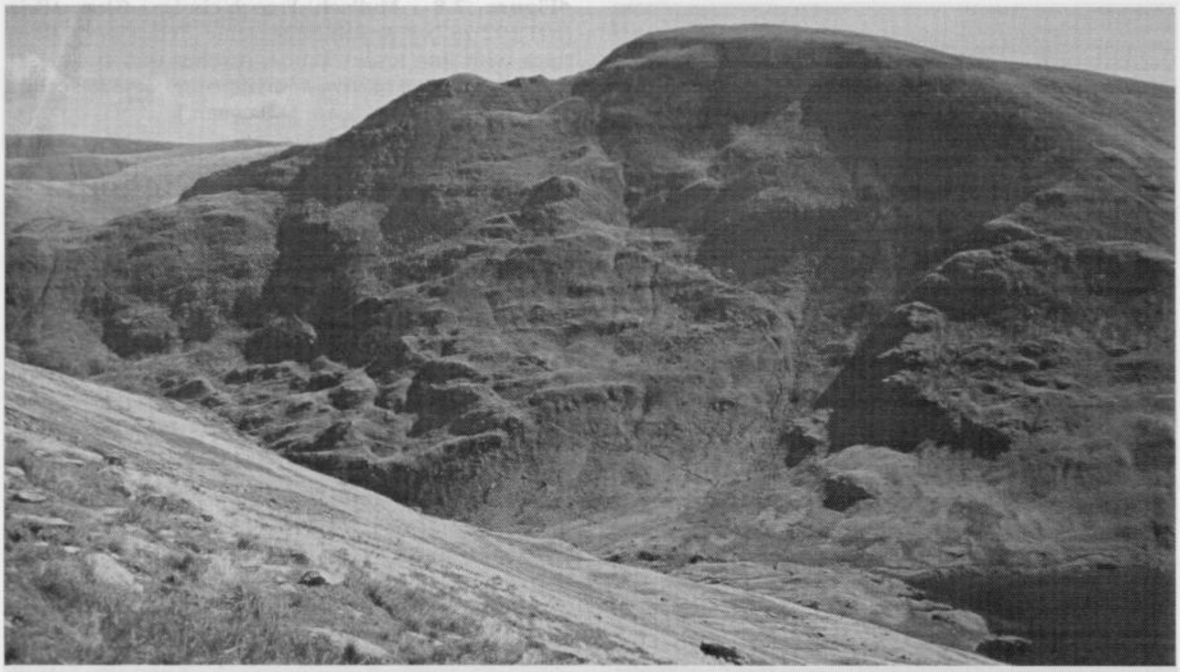


Figure 2.10 Fairfield rock slope failure, Lake District (NY 355 120). An extensive translational slide, with long-travel masses arrested above the floor of Grisedale, which breaches through to Grasmere and Dunmail Raise just to the west (right). The headscarp encroaches into the north-east ridge (left) to shape the arête of Cofa Pike. (Photo: D. Jarman.)

destruction, whether by reduction of the enclosing arms (e.g. **The Cobbler**) or breaking through the headwall (e.g. **Ben Hee**).

Valley widening and ridge reduction

Most rock slope failures contribute to the general processes of valley widening and spur truncation (Table 2.2), both directly and indirectly, by providing weakened slopes and debris masses ready for erosion and evacuation by glaciers in the next cycle (Bentley and Dugmore, 1998). By the same token, rock slope failures encroach into ridges and pre-glacial plateau remnants, with source scarps and fractures often daylighting by as much as 50–100 m behind the crest or rim (e.g. A' Chaoirnich in the Central Grampians) (Jarman, 2004a). Such effects are seen particularly well at **Beinn Fhada**, and in lower-relief contexts in **Glen Ample** and at **Benvane**.

Where mountain ranges are dissected by breaching, the isolated mountains become more vulnerable to concerted attrition by rock slope failure, until their crests are lowered sufficiently to permit glacial over-riding and reduction to subdued relief. Examples of mountains at various stages of isolation by breaching and where rock slope failure is encroaching on several fronts include Beinn an Lochain in Argyll (Watters, 1972), Ciste Dhubh in Kintail (Jarman, 2003b), An Dùn in the Gaick Pass (Jarman, 2004a), and Na Gruagaichean in the Mamores (Figure 2.11).

Antiscarps

Antiscarps are one of the most conspicuous indicators of rock slope failure in the mountain landscape. These uphill-facing scarplets occur both in translational slides, as the moving mass begins to disaggregate (**The Cobbler**), and in slope deformations, where they may extend laterally for hundreds of metres (e.g. the exceptionally fine array on **Beinn Fhada**). They may develop intricate lattices (**Benvane**) and platy structures (**Glen Ample**). In the Lake District, a notable case occurs on Kirk Fell (Wilson, 2005; Figure 2.3). Antiscarps typically reach up to a few metres high, and where only decimetric may be hard to see on the ground. In Glen Shiel and Kintail, and a few other isolated cases (including Kirkstone Pass in the Lake District – Wilson *et*

Figure 2.11 Na Gruagaichean rock slope failure complex, Mamores, Lochaber (NN 195 650). The twin summits (centre and right) are divided by a 140 m-deep gash, the source of a very large wedge slide that has been substantially evacuated leaving a SW-facing bowl that is not a corrie in origin or by adaptation, the floor of which is extensively ruptured with antiscarps up to 3 m high. Another large rock slope failure encroaches onto the south ridge (right), and a third slide lobe sharpens the north-west ridge (left-centre). (Photo: J. Digney.)

al., 2004), they can attain 5–10 m, with **Beinn Fhada** having the highest classic midslope antiscarps. **Druim Shionnach** is exceptional, with a 14 m antiscarp, but this may have developed as part of a graben structure opposite the source scarp.

Research is needed to understand why and how antiscarps develop. Their incidence and character may illuminate the extent to which deformation is either extensional in unsupported steep slopes, or compressional, driven by differential glacio-isostatic rebound stresses between valley floor and summit ridge. The factors governing antiscarp height are especially unclear. It could be an indicator of rebound stress intensity, but will also depend partly on rock-type and strength, and on length of exposure to weathering. Extant heights may be much reduced from their original levels, partly by crest degradation but mainly by trench infilling. It is rare to find datable bedrock exposures on an antiscarp, or a fault-like fracture in the few exposed cross-sections. Some antiscarp arrays may have been subdued by the Loch Lomond Stadial (LLS) glaciers, or re-emerged after them (**Beinn Fhada**; Beinn Odhar Bheag, Glenfinnan, NM 850 775).

A special case of apparent antiscarp occurs where the failed mass includes the summit ridge, and the fracture plane 'daylights' behind the crest. This creates the phenomenon known as a 'split ridge', common in the Alps as a 'doppelgrat' (Crosta, 1996). **Sgurr na Ciste Duibhe** displays aspects of this tendency, but a remarkably clear example extending intermittently for over 1.5 km and attaining a source scarp height of 10–15 m has recently been recognized on Aonach Sgoilte in Knoydart (Figure 2.12).

The spatial distribution and root causes of rock slope failure

Perhaps the most puzzling aspect of the rock slope failure phenomenon is its irregular spatial distribution. Even on mountain ranges most conducive to it, failure is far from endemic: it may be abundant, sparse, or absent on valley-sides of similar scale, steepness and geological character. Where rock slope failure is common, it is seldom obvious why one section of valley slope should have failed rather than adjacent sections; local factors are clearly important. Given that most failures appear to date from early or mid-Holocene times, this suggests that at periods of maximum rebound and climatic stress, extensive areas of valley-side were close to the limits of stability.

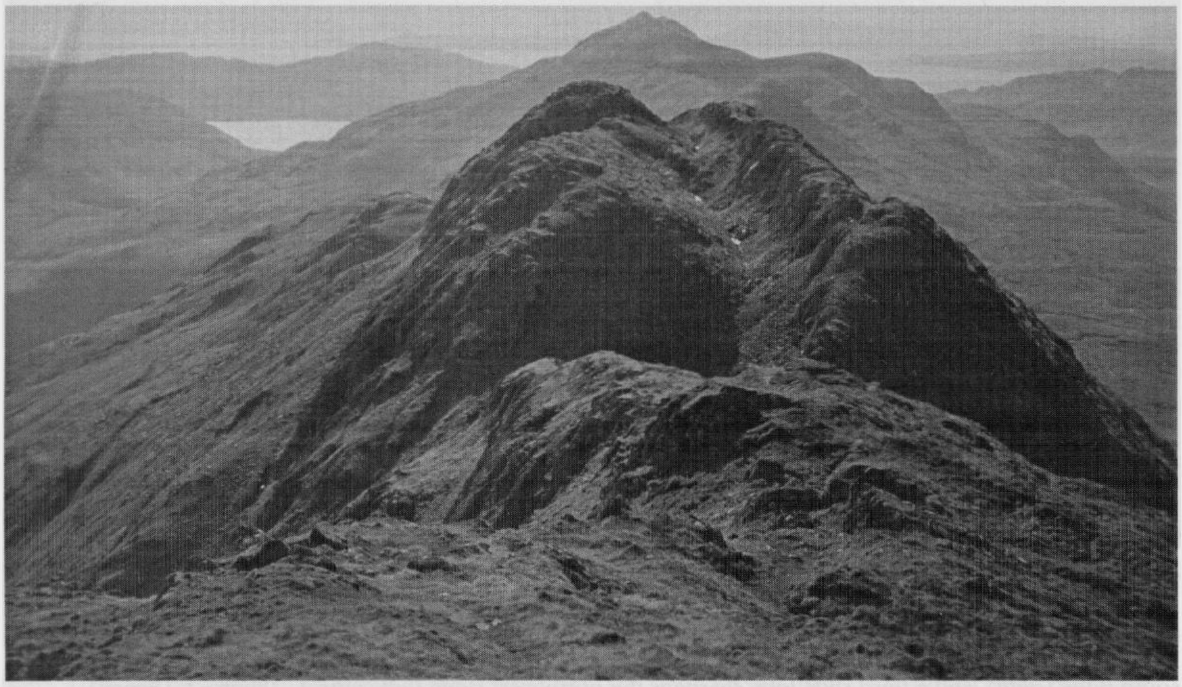
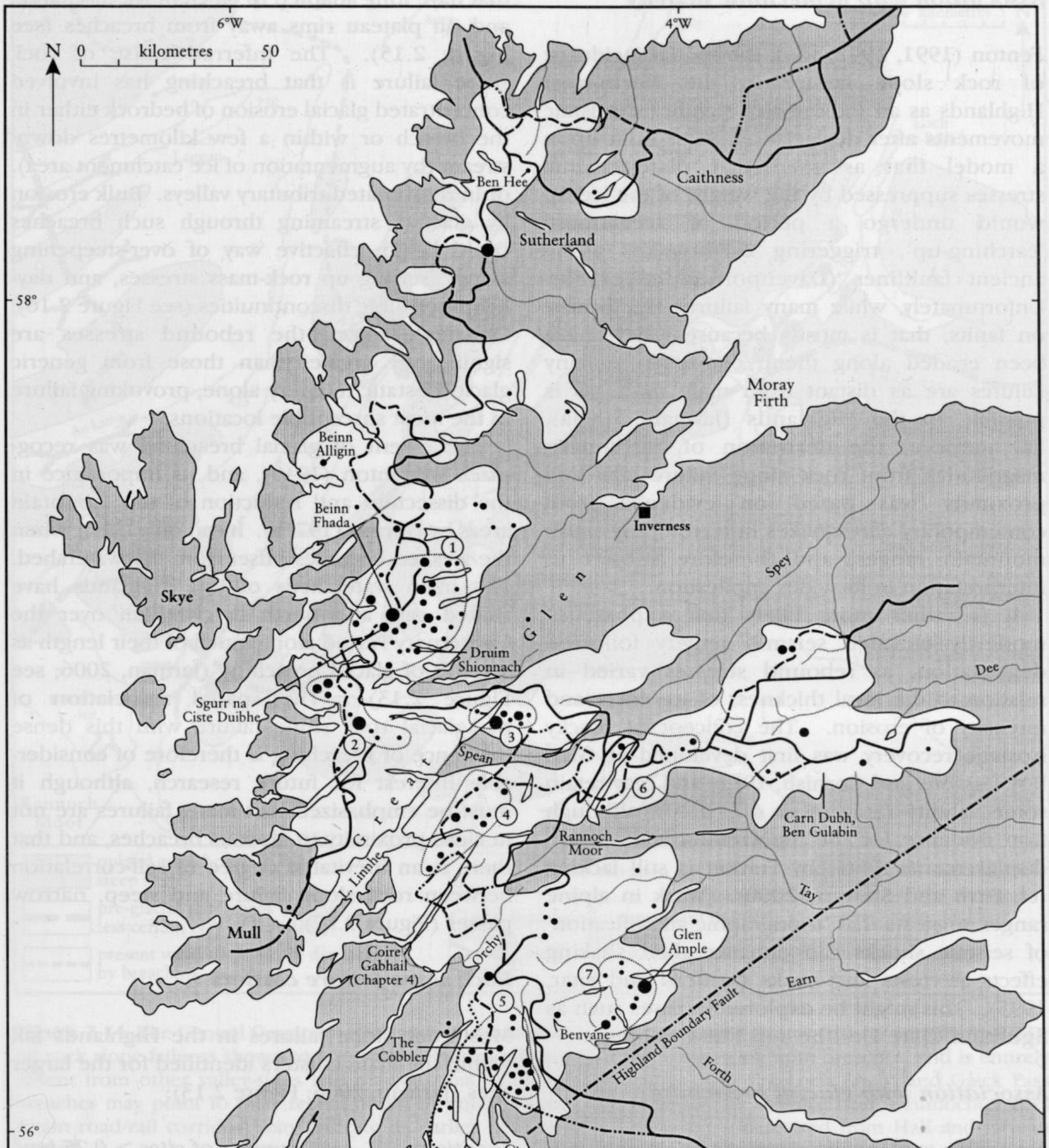


Figure 2.12 Aonach Sgoilte rock slope failure, Knoydart (NG 836 020). The ridge is split over 1.5 km by a source fracture daylighting behind the crest, often 30 m downslope on the north (right). The summit mass seen here has slipped south by 10–15 m. The gentler slope below is extensively antiscarped, one being 500 m long and reaching 7.5 m in height. A wedge slip has left the shadowed notch. The rounded headscarp crest (contrasting with **Sgurr na Ciste Duibhe**) could indicate relatively ancient inception. (Photo: D. Jarman.)

Association with ice limits

Two studies have addressed the wider distribution of rock slope failure, though regrettably neither has been published to expose the debate. Holmes (1984) found that in nearly all cases, some force, augmenting gravity, was required to mobilize translational sliding. He sought to demonstrate a close correlation between failure locations and the upper limits of the Loch Lomond Stadial (LLS) glaciers, as identified by Sissons and his school. He envisaged that excessive meltwater pressures at deglaciation would trigger a spate of failures. Unfortunately, where the LLS was a valley-full glaciation with nunatak ridges exposed, there is an inevitable co-incidence between steep valley-sides where rock slope failure is most likely to occur, and the upper limits of the glaciers. Where the LLS achieved near-icecap coverage at its centres, as is now thought likely (Golledge and Hubbard, 2005), such a correlation obviously cannot occur. In fact, failure can be found at all levels within any glaciated valley system, both within and well beyond the LLS outer limits. Furthermore, this model does not explain adequately the absence of rock slope failure from apparently suitable terrain well within the LLS outer limits such as Ardgour (see Figure 2.13). Nor does an engineering model developed for discrete, compact translational block-sliding account for the large proportion of diffuse and laterally extensive slope deformations. Finally, the model cannot account for the rock slope failures that have been dated (directly or inferentially) to several thousand years after deglaciation.

Figure 2.13▸ Spatial distribution and size of 140 larger rock slope failures (RSFs) (> 0.25 km²) in the mainland Scottish Highlands (distribution of all rock slope failures is similar). Rock slope failure is clustered on main watersheds that have been breached and displaced during Pleistocene times. It is scarce in ranges away from the watersheds, in the far north where ice cover was thinner, and in the eastern Grampians where glacial dissection is less intense. Sites reported in this chapter are shown. After Jarman (2006).


6°W
4°W
N
0 kilometres 50
58°
56°
Ben Hee
Caithness
Sutherland
Moray Firth
Beinn Alligin
Beinn Fhada
Inverness
Spey
Skye
Druim Shionnach
Dee
Sgurr na Ciste Duibhe
Spean
Rannoch Moor
Carn Dubh, Ben Gulabin
Tay
Linnhe
Mull
Glen Ample
Coire Gabhail (Chapter 4)
Orchy
Earn
The Cobbler
Benvane
Highland Boundary Fault
Forth
Clyde
Glasgow
present main watersheds
inferred pre-glacial watersheds where displaced by breaching
(alternatives or uncertain)
(possible east-flowing Clyde)
main mainland mountain areas
RSF sizes
0.25–0.49 km²
0.50–0.99 km²
1.00–1.99 km²
2.00–3.00 km²
Clusters of larger RSFs
1 Affric–Kintail–Glen Shiel
2 Knoydart
3 Glen Roy–Loch Lochy
4 Lochaber (Glencoe–Mamores–Grey Corries)
5 Arrochar Alps–Luss Hills
6 Ericht–Gaick
7 Trossachs–Lochearnhead
(RSFs in lowlands and on islands/coastal cliffs not shown)

Association with neotectonic activity

Fenton (1991, 1992) took the spatial incidence of rock slope failure in the North-west Highlands as an indicator of significant seismic movements after deglaciation. This built upon a model that assumed that plate-tectonic stresses suppressed by the weight of the icecap would undergo a period of accelerated 'catching-up', triggering earthquakes along ancient faultlines (Davenport *et al.*, 1989). Unfortunately, while many failures are located on faults, that is mostly because valleys have been eroded along them; conversely, many failures are as distant from main faults as is possible in the Highlands (Jarman, 2003a). Furthermore, the derivation of earthquake magnitudes from rock slope failure size and proximity was based on evidence from contemporary earthquakes in tectonically active mountain ranges, and therefore subject to interpretation in its wider application.

It is rather more likely that a phase of modestly elevated seismic activity followed deglaciation, as rebound stresses varied in relation to the local thickness of ice cover and intensity of erosion. The concept of blocky isostatic recovery was first developed at Glen Roy (Sissons and Cornish, 1982) and may retain some validity (Stewart *et al.*, 2000), although firm evidence for the 'neotectonic fault scarp' displacements found by Fenton is still lacking (cf. Firth and Stewart, 2000). Work in alpine ranges suggests that 'topographic amplification' of seismic shocks can enhance their shaking effects at crests and peaks (Ashford and Sitar, 1995). This might be explored in cases such as **Sgurr na Ciste Duibhe** and **The Cobbler**.

Association with glacial breaching

A possible explanation currently being explored views rock slope failure as a response to locally exceptional slope stresses, on top of those generically induced by glaciation/deglaciation. A spatial association can be observed in every failure cluster with glacial breaches of main and secondary watersheds (Jarman, 2003a,b; 2006; Tables 2.1 and 2.2). The Central Grampian cluster demonstrates a near-100% association between rock slope failure and the breaches of Loch Ericht, Garry, and Gaick (Hall and Jarman, 2004) (see Figure 2.14). Conversely, failure is sparse or absent in mature troughs and glens that have long adapted to efficient ice discharge, and on plateau rims away from breaches (see Figure 2.15). The inferred cause of rock slope failure is that breaching has involved concentrated glacial erosion of bedrock either in the breach or within a few kilometres downstream (by augmentation of ice catchment area), or in rejuvenated tributary valleys. Bulk erosion by glaciers streaming through such breaches could be an effective way of over-steepening slopes, setting up rock-mass stresses, and daylighting fallible discontinuities (see Figure 2.16). On deglaciation, the rebound stresses are significantly greater than those from generic glacio-isostatic recovery alone, provoking failure in the most susceptible locations.

The extent of glacial breaching was recognized by Linton (1949), and its importance in the dissection and reduction of the mountain areas by Haynes (1977a). It can only occur when the iceshed becomes offset from the watershed. The main watersheds of the Highlands have shifted east and north by 5–30 km over the Quaternary Period along much of their length as a result of glacial breaching (Jarman, 2006; see Figure 2.13). The spatial association of paraglacial rock slope failure with this dense incidence of breaching is therefore of considerable interest for future research, although it must be emphasized that many failures are not in close proximity to obvious breaches, and that there is an inevitable degree of self-correlation between rock slope failure and steep, narrow passes (Figure 2.17).

Rock slope failure clusters

Most rock slope failures in the Highlands fall within the main clusters identified for the larger sites (Jarman, 2006; Figure 2.13):

Location	*number of sites > 0.25 km²*
Affric–Kintail–Glen Shiel	29
Knoydart	8
Glen Roy–Loch Lochy	7
Glencoe–Mamores–Grey Corries	13
Arrochar Alps–Cowal–Luss Hills	20
Loch Ericht–Gaick	7
Trossachs–Lochearnhead	9
TOTAL (7 clusters with 5 sites or more) > 0.25 km²	*93*
Total (all larger RSFs)	140

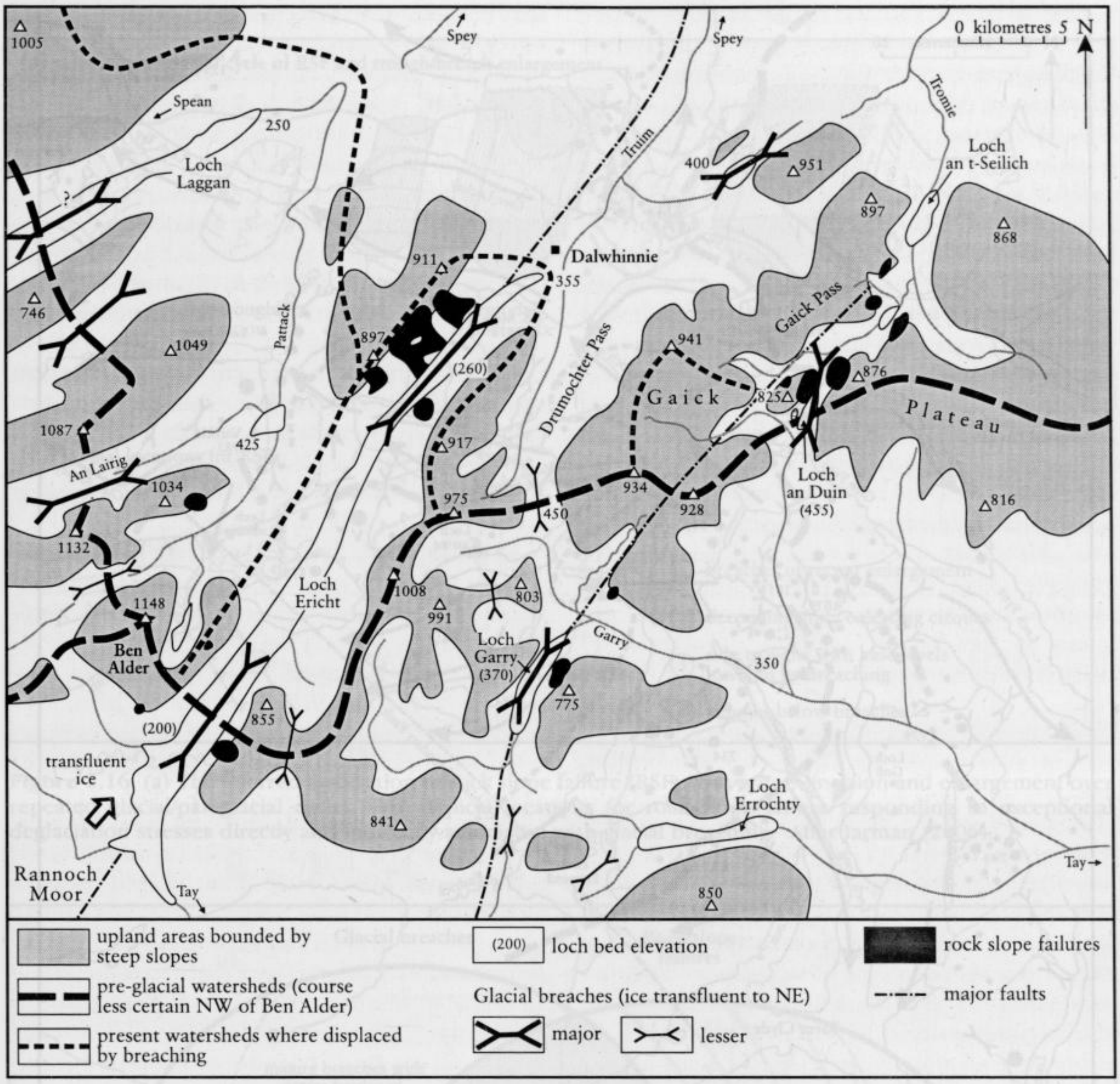


Figure 2.14 The Central Grampian Highlands, including the Loch Ericht–Gaick cluster (cluster 6 in Figure 2.13). All rock slope failures shown true to scale. Failure only occurs in or downvalley from breaches, and is entirely absent from other valley-sides and plateau rims. Failure concentrations in the Loch Ericht and Gaick Pass breaches may point to their recent origin or enlargement; rock slope failure absence from Drumochter Pass (main road/rail corridor) may indicate its earlier development. Adapted and revised from Hall and Jarman (2004).

It may be that these clusters indicate where glacial breaching and erosion have been most active in Devensian times, and thus where shifts in ice centres and/or dispersal patterns have been most marked. Work is required to scope and calibrate deglaciation slope stresses of all kinds, and to refine icecap models in light of rock slope failure information. The intensity of dissection by breaching increases dramatically from east to west across the Highlands, as in microcosm in the Lake District and North Wales (Clayton, 1974, after notes by D. Linton; Haynes, 1977a, 1995). Failure clusters may indicate where dissection is further intensifying, and where the 'Clayton Zones' of dissection intensity are migrating eastwards (see Gordon and Sutherland, 1993, fig. 2.1).

The sites selected here mostly fall within the two densest rock slope failure concentrations first recognized by Holmes (1984) – the

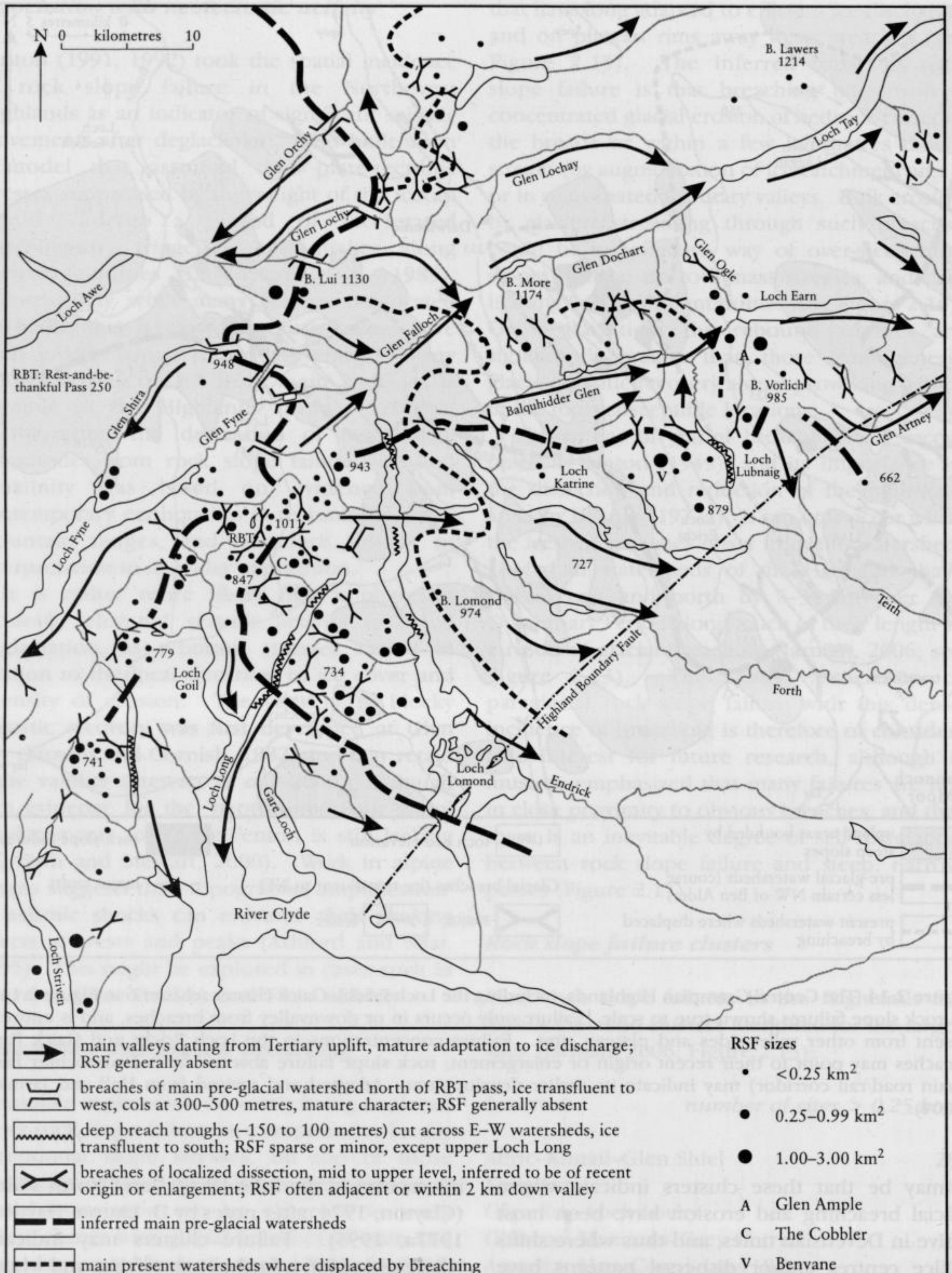


Figure 2.15 The Southern Highlands, an area of intense rock slope failure (RSF) activity, including the Arrochar–Cowal–Luss and Trossachs–Lochearnhead clusters (clusters 5 and 7 in Figure 2.13). Failure is scarce or absent in main pre-glacial valleys and some breaches of the main watershed, despite their slopes and geology being susceptible to it. Its paucity along the deep breach trench of Loch Lomond is surprising. Note mini-clusters top-centre and top-right, where locally intense breaching occurs across main and secondary watersheds. The locations of three sites (**Glen Ample**, **The Cobbler**, **Benvane**) are shown. Adapted and revised from Jarman (2003a).

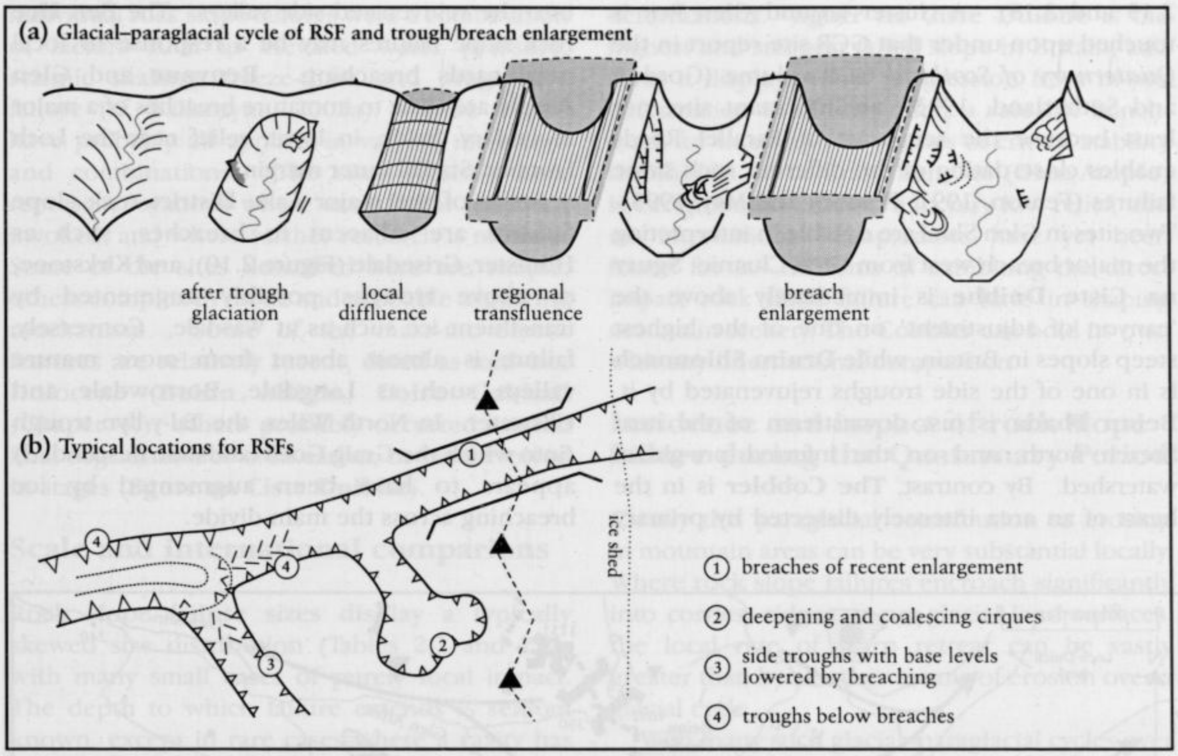


Figure 2.16 (a) The inferred association of rock slope failure (RSF) with breach incision and enlargement over repeated glacial/paraglacial cycles. (b) Typical locations for rock slope failure responding to exceptional deglaciation stresses directly and indirectly associated with glacial breaching. After Jarman (2006).

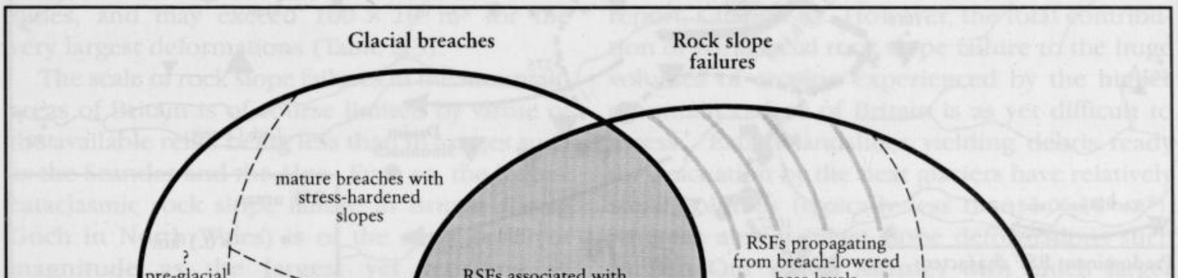


Figure 2.17 The nature of the association between paraglacial rock slope failure and glacial breaching. This suggests why many breaches may lack rock slope failure, and acknowledges that not all failures can be attributed to breaching. After Jarman (2006).

Southern Highlands, and Affric–Kintail (Figures 2.15 and 2.18). A cluster around Glen Roy is touched upon under that GCR site report in the *Quaternary of Scotland* GCR volume (Gordon and Sutherland, 1993), an important site, not least because the sequence of Parallel Roads enables close dating of the different rock slope failures (Fenton, 1991; Peacock and May, 1993). Two sites in Glen Shiel are notable in interpreting the major breach west from Glen Cluanie: **Sgurr na Ciste Duibhe** is immediately above the 'canyon of adjustment' on one of the highest steep slopes in Britain, while **Druim Shionnach** is in one of the side troughs rejuvenated by it. **Beinn Fhada** is just downstream of the next breach north, and on the inferred pre-glacial watershed. By contrast, **The Cobbler** is in the heart of an area intensely dissected by primary and secondary breaching, with failure ramifying into the rejuvenated side valleys. The **Ben Hee** rock slope failures may be a response to local northwards breaching. **Benvane** and **Glen Ample** are close to immature breaches of a major secondary divide, in lower relief near the Loch Lomond Stadial outer margin.

Some of the major Lake District rock slope failures are adjacent to breaches, such as Honister, Grisedale (Figure 2.10), and Kirkstone, or above troughs possibly augmented by transfluent ice such as at Wasdale. Conversely, failure is almost absent from more mature valleys such as Langdale, Borrowdale and Ullswater. In North Wales, the Tal-y-llyn trough (into which the Graig Goch landslide descended) appears to have been augmented by ice breaching across the main divide.

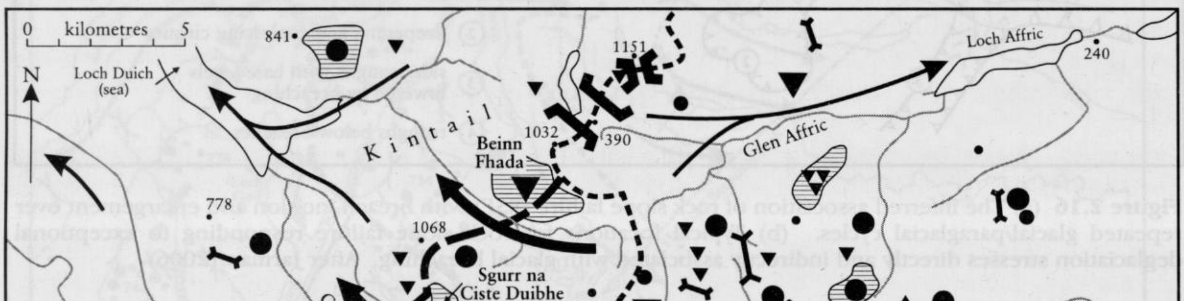


Figure 2.18 Part of the Affric–Kintail–Glen Shiel rock slope failure cluster (cluster 1 in Figure 2.13). Rock slope failures tend to be located near breaches of the inferred pre-glacial watershed, and in side troughs rejuvenated by breaching. Note the locations of three GCR sites – **Beinn Fhada**, **Druim Shionnach** and **Sgurr na Ciste Duibhe**. Adapted from Jarman (2003b).

It is probable that the actual triggers for individual rock slope failures were a combination of factors such as elevated water pressure, seismic shaking, freeze-thaw, and progressive failure (cf. Ballantyne, 2002a). These factors have probably all applied in varying intensities and combinations. The sites selected here represent locations where each factor has been invoked, and where further research is merited. Some of the sites described here are simple, others complex in mode and probable triggering mechanism. Some of the mass-movement features are relatively recent, dated as mid–late Holocene (**Beinn Alligin**; **Coire Gabhail** (Chaper 4)); others probably occurred around final deglaciation or even earlier, or have evolved in stages (**Sgurr na Ciste Duibhe**).

Scale and international comparions

Rock slope failure sizes display a typically skewed size distribution (Tables 2.1 and 2.2), with many small cases of purely local impact. The depth to which failure extends is seldom known, except in rare cases where a cavity has been largely evacuated, but is generally assumed to be in the order of tens of metres for smaller rock slope failures, rising to 100–150 m for larger cases (Holmes, 1984; Fenton, 1991). Inferred volumes reach 10×10^6 m^3 for translational slides, and may exceed 100×10^6 m^3 for the very largest deformations (Table 2.3).

The scale of rock slope failures in the mountain areas of Britain is of course limited by virtue of the available relief being less than in ranges such as the Scandes and the Alps. Even so, the largest cataclasmic rock slope failure in Britain (Graig Goch in North Wales) is of the same order of magnitude as the largest yet reported in Scandinavia at Kärkevagge (Jarman, 2002); albeit at approximately 50×10^6 m^3 these are an order of magnitude smaller than the ten largest in the Alps, let alone the extraordinary Flims failure which reaches $12\,000 \times 10^6$ m^3 (Abele, 1974).

With slope deformations, the typical scale in the Alps involves relief of 1000 m, a depth of 100 m, and a volume of 100×10^6 m^3 (Brückl and Parotidis, 2005). It is interesting that such dimensions are approached by the largest or highest rock slope failures in the Highlands (Table 2.3).

In a European context rock slope failures such as **Beinn Fhada** and Glen Pean (de Freitas and Watters, 1973) are of significant scale and bear instructive comparison as steep mountain deformations. **Sgurr na Ciste Duibhe** is the highest and steepest failed slope in Britain, and since it displays some progression from in-situ deformation to sliding, offers a valuable bench-mark for international studies of critical stability thresholds. By contrast, Ben Our (**Glen Ample**) is exceptionally extensive in very low relief, and no international comparators have yet been found for it. In terms of exhibiting the direct impact rock slope failure can have in shaping mountain scenery, **The Cobbler** can hold its own with any international comparison.

Incidence and impact of rock slope failure during the Quaternary Period

Clearly this paraglacial contribution to erosion in mountain areas can be very substantial locally. Where rock slope failures encroach significantly into corries, ridges or pre-glacial land surfaces, the local rate of scarp retreat can be vastly greater than by all other means of erosion over a glacial cycle.

With many such glacial–paraglacial cycles over the Quaternary Period, the cumulative impact of rock slope failure will have been very substantial, especially in the most geologically susceptible areas (Evans, 1997; Hall and Jarman, 2004; cf. **Trotternish Escarpment** GCR site report, Chapter 6). However, the total contribution of paraglacial rock slope failure to the huge volumes of erosion experienced by the higher mountain ranges of Britain is as yet difficult to assess. Extant landslides yielding debris ready for evacuation by the next glaciers have relatively small volumes (typically less than 1×10^6 m^3), whereas almost intact slope deformations such as Ben Our (**Glen Ample**) with much larger volumes may not be much more vulnerable to erosion than the surrounding terrain.

The incidence of rock slope failure may have changed as Quaternary landscape adaptation to ice progressed, and as glaciations increased in severity. It seems likely that paraglacial failure would have been fairly endemic in the relatively weak early Quaternary glacial–interglacial cycles, as fluvial valleys with interlocking spurs became adapted to efficient ice discharge as straightened and deepened troughs. In the great ice-sheet glaciations of mid-Quaternary times, transfluence across watersheds would have initiated the process of glacial breaching, provoking a fresh round of intensive but less widespread failure.

Table 2.3 Large rock slope failures (RSFs) in the Scottish Highlands for which data are available. After Jarman (2006). Sites are listed from the north, with the Great Glen separating the North-west Highlands from the Grampians. Note the disproportionate number of large RSFs studied north-west of the Great Glen, where foliation (F) is rarely as conducive to sliding as in the Southern Highlands. Most studies are of (sub-)cataclasmic RSFs or slope deformations, rather than conventional arrested slides. *Continued opposite.*

RSF	**Ref.**	**Mode**	**Area** km^2	**Vol.** $\times 10^6 m^3$	**Depth** m	**H/S** m	**A/S** m	**Slide plane**	**Comments**
Loch Vaich, Ross-shire	2	ext def	0.5		>50?		2	J low angle	Short-travel (50 m) slip, forward toppling on 60° F
Sgurr Bhreac, Fannich	2,3	ext def	0.82	36?	?	30	Sm	?	Sackung with lattice of fissures
Beinn Alligin, Torridon	1,2	cata	0.52	3.5	200 20 #1	60	–	42°	Acute faulted wedge in sub-horizontal sandstone
Glenuaig, Strathcarron	2	ext def	0.7		?	<5	<2	F 15°+	Short-travel sliding slump, incipient fissuring
Sgurr na Conbhaire, Monar	2,6	sub-cata	0.35		150		2	F 30–40°	Long-travel (150 m) slump onto lower slope
Sgurr na Feartaig, Strathcarron	2	ext def	0.9		100?	2	yes	F	Short-travel block slide
An Socach, Monar	2	comp def	1.0	–	20?	nil	sm	–	500 m long, linear A/S diffuse margins – rebound
Carn na Con Dhu, Mullardoch	2,3	slide	1.46	61?	120?	12 35?	2	not on F/J	Short-travel slide/slump, A/S <200 m long on strike of J1+J2
An Sornach, Affric	2,3,4	ext def	0.75	13?	30?	42	3	not F/J	Slip with A/S lattice > bulge > collapse. Rebound 5 m A/S
Mullach Fraoch-choire, Affric	3	sub-cata	0.2	0.73	20	10	–	J2,3 29°	Slide tongue within 1.1 km^2 slope deformation
Sgurr na Lapaich, Affric	2,3	comp def	0.3	7?	100?	10	–	–	Ridge crest failure, possibly seismic/rebound faulting
Beinn Fhada, Kintail	2,3, 4,6	comp def	3.0	112 #2	100?	none	10	–	~8 sub-horizontal A/S < 700 m long, main ones are 5–8 m high
Sgurr na Ciste Duibhe, Glenshiel	5	ext def	1.25	5–10 #3	80	15	(11) 5	not F/J	Summit lowered ~10 m > long-travel slide in deformation
Sgurr a' Bhealaich Dheirg, Glenshiel	2	comp def	0.7		100?		6		Bulging slide, rebound A/S < 200 m long

Footnotes:
'Ref.': reference sources are (1) Ballantyne, 2003; (2) Fenton, 1991; (3) Holmes, 1984; (4) Jarman, 2003c,d,e, 2004a, and present volume; (5) Jarman, 2003b; (6) Watters, 1972.
'Mode': cata = cataclasmic; sub-cata = sub-cataclasmic; ext def = extensional deformation (sag, creep); comp def = compressional deformation (rebound).
'Area': RSF size is here taken as the gross area including source cavity, since most cases are incompletely evacuated. British Geological Survey mapping of RSF is variable and incomplete, but recent sheets only map as 'landslips' disturbed ground, thus excluding both source areas and semi-intact slope deformations. The gross area best indicates the geomorphological impact of the RSF, but clearly requires adjustment when volumetric calculations are made.
'Vol.'(-ume) and maximum **'Depth'** should be seen as broad estimates, especially sites marked '?' where the depth cannot readily be assessed.
#1 depth figures are for cavity (ref. 2) and debris tongue (ref. 1);
#2 volume (ref. 3) assumes there is a failed mass with a boundary at ~100 m, no volume can be calculated if the failure partly dissipates at depth;
#3 volume and depth are for main cavity within larger deformation.
'H/S' = headscarp (rear scarp, source scarp) maximum height.
'A/S' = antiscarp (obsequent scarp, counterscarp, uphill-facing scarp) maximum height – figures in brackets are graben trenches or uphill faces of large slipped masses.
'Slide plane': F = foliation or schistosity surface;
J = joint-sets (in order of significance);
RFA = residual friction angle.

Table 2.3 – *continued*. For key see the footnotes on the previous page.

RSF	Ref.	Mode	Area km²	Vol. ×10⁶m³	Depth m	H/S m	A/S m	Slide plane	Comments
Ciste Dhubh, Affric	5	sub-cata	0.46	7	80	30	2	?	Corrie-floor source, toe reaches river in breach glen
Druim Shionnach, Cluanie	5	comp def	0.55	–	150?	25	(14) 3	–	Top A/S is outer half of graben > Cluanie bulge
Meall Buidhe, Knoydart	6	ext def	0.5		40?	30	7?	J1,2 < 44°	Broad slump zone
Mam na Cloiche Airde, Knoydart	6	sub-cata	0.26		40	20	–	35°	Semi-intact masses > slope debris > 5° flow slide
Glen Pean, Knoydart	6	comp def	2.5	–	60?		–	J1 28–48°	A/S array on strike of F/J2, cataclasmic slide to west
GREAT GLEN									
Streap, Glenfinnan	6	Slide	0.25		25	75	(10)	J1 36°	Long-travel arrested sub-cataclasmic summit has lost top ~15 m, seismic trigger?
Beinn an Lochain W, Arrochar	6	ext def	0.34		15?	<5	<2	F 20–30°	Thin, undeveloped slide, upper tier beside
The Cobbler SW, Arrochar	4	slide	0.62	8–10	30	28	(10) 6	not F	Four-panel, short-travel, disintegrated slip
Hell's Glen, Cowal	3,6	ext def	0.52	1.75 (+)	60	15	(15) 5	J2 40–50°	Topple block slips and collapses in broad slump
Mullach Coire a' Chuir, Cowal	3	slide	0.57	9.6?	20	50	(12) 2	F + J2	Part-collapsed sliding topple on stepped surface
Meallan Sidhein, Loch Striven	6	slide	0.75		70	40	–	F 25–32°	Slip in phyllite, effective F dip 20°, equals RFA
Tullich Hill West and East	4	slide	1.25 in total			40	8	not F	Short-travel, multi-phase, slump complex
Benvane, Trossachs	4	def/ slide	1.25	25	20–30	26	3	not F	Deformation progresses laterally to slide
Ben Our (**Glen Ample**), Lochearnhead	4	def	2.90	100–200?	150?	4	4		Platy deformation with basal slumps

Many of these breaches are now relatively mature. It is therefore likely that the incidence of failure has diminished into the last (Devensian) glaciation. The extant population of rock slope failures may thus be relatively modest, and its spatial distribution probably indicates where glacial erosion and other destabilizing factors were concentrated latterly.

Rock slope failure commonly occurs with a delayed reaction time of hundreds or even several thousands of years after deglaciation. Thus although many failures are within the boundaries of the Loch Lomond Stadial (LLS), this was short-lived (*c*. 12 900–11 500 years BP) and carried out little fresh erosion. These rock slope failures are probably responding to stresses induced during the Last Glacial Maximum, which peaked approximately 22 000 years BP and deglaciated approximately 15 000 years BP.

However, paraglacial responses as delayed as at **Beinn Alligin** (7000 years after deglaciation) and **Coire Gabhail** (9000 years after deglaciation) may be exceptional. No large rock slope failure movements are known within the mountain areas during recorded history, with even conspicuous cases such as Glen Kinglass (NN 190 096) of *c*. 1700 AD (Clough, 1897) only amounting to 70 000 m³ (Holmes, 1984). Progressive failure in one area of Norway is still leading to catastrophic collapses (Bjerrum and Jørstad, 1968) but this is unknown in Britain, the creeping failure in fjord-type cliffs affecting road and rail at Attadale, Loch Carron (NG 914 377; Watters, 1972) perhaps being the nearest approximation.

Significance of rock slope failure in the older mountain areas

Understanding mass movements in lowland Britain is of critical importance for civil engineering, geohazard awareness, and active geomorphological processes such as coastal retreat, but there are different reasons for studying paraglacial rock slope failure in the mountain areas, and for conserving key sites:

- It is a significant if overlooked contributor to glaciated landscape development, especially as an agent of selective linear erosion (notably breaching), where rates of valley incision and widening can be orders of magnitude more rapid than normal.
- It has played a remarkable role in shaping many mountain summits and ridges, and is a potential key component in Earth science and landscape interpretation and geotourism development (cf. Brown, 2003).
- It links with other nature conservation and environmental history interests, in that failed and deformed slopes greatly increase habitat niche availability, ameliorate microclimate, and thus enhance biodiversity. Because these slopes are typically drier and warmer, and more fertile and sheltered, they have played an important part in the colonization of the mountains by early man and in the survival of subsistence farming and contemporary land utilization in otherwise inhospitable terrain.
- Finally, the spatial distribution of rock slope failure has potential to inform and calibrate efforts to inform the analysis of shifting ice centres and dispersal patterns over the Devensian glacial period, with possible benefits for palaeoclimate change studies.

The sites selected here represent all of these aspects of rock slope failure to varying degrees, but by comparison with well-studied fields such as coastal landslips and glacial deposits, there is considerable scope to augment the site coverage as further failure research proceeds. In particular, sites in Lochaber, the Lake District, and North Wales would reflect local diversity of expression, while no sites have yet been subjected to state-of-the-art geotechnical investigation, or to slope-stress modelling in relation to underlying causes and trigger events.

BEINN FHADA (BEN ATTOW), HIGHLAND (NH 000 185–NH 021 185)

C.K. Ballantyne and D. Jarman

Introduction

The majority of large (> 0.25 km^2) rock slope failures in Scotland take the form of rock slope deformations that lack runout of debris. The largest area of rock slope deformation occurs on the south-west side of Beinn Fhada (Ben Attow), a 1032 m-high peak between the head of Loch Duich and upper Glen Affric. Slope deformation at this site involves the entire mountainside over an area of about 3 km^2, and was estimated by Holmes (1984) to involve the displacement of 112×10^6 m^3 (roughly 300 million tonnes) of rock. Although this estimate must be regarded as approximate in view of the uncertainty concerning the depth of deformation, it implies that the Beinn Fhada feature is probably the largest rock slope failure on the Scottish mainland. It is also significant as the site of the most impressive suite of antiscarps (uphill-facing scarps) in Britain.

The Beinn Fhada rock slope deformation was first interpreted by Watters (1972) as a translational landslide over a deep failure plane. Holmes (1984) and Holmes and Jarvis (1985) re-interpreted the site in terms of deep internal rock deformation, expressed at the surface by antiscarps produced by joint-guided block-flexural toppling. Fenton (1992) proposed that deformation reflected sliding failure triggered by a high-magnitude earthquake. Jarman and Ballantyne (2002) provided a more comprehensive description of the site, attributed rock slope deformation to paraglacial stress-release following deglacial unloading, and proposed two further possible models to explain the assemblage of associated landforms. Jarman (2003e) further reviewed the characteristics of the site, noting inconsistencies between the field evidence and a translational sliding model, and considered possible reasons for exceptionally large-scale rock slope deformation at this location.

Description

Setting

The southern slopes of Beinn Fhada rise 750–900 m above the adjacent valley floor of Gleann Lichd at average gradients of 30°–35°, forming one of the most extensive uninterrupted bedrock slopes developed in metamorphic rocks in the Scottish Highlands (Figures 2.19–2.21). Above the slope crest a remnant of pre-glacial surface forms an undulating plateau up to about 1 km wide. The mountain is underlain by psammites and semipelites of the Moine Supergroup of Neoproterozoic age (May *et al.*, 1993). The rocks have been deformed, folded and metamorphosed and the bedding now generally dips slightly eastwards. Much of the psammite is coarse-grained and gneissose. In the area of rock slope deformation, Holmes and Jarvis (1985) detected four main discontinuities: one parallel to foliation; one joint-set striking parallel to, and dipping steeply into, the slope (J1); and two sets that dip gently westwards (J2 and J3).

Glacially moulded rock outcrops occur up to 950 m on Beinn Fhada and 1050 m on the neighbouring summit of Sgurr nan Ceathreamhnan (Ballantyne *et al.*, 1998a) suggesting that during the last (Late Devensian) glacial maximum the summit plateau of Beinn Fhada lay under a thin cover of glacier ice, and that a westwards-moving icestream *c.* 1000 m thick occupied Gleann Lichd. During the subsequent Loch Lomond Stadial of *c.* 12.9–11.5 cal. ka BP a valley glacier moved westwards down Gleann Lichd. The surface of this glacier descended from about 600 m near the present-day watershed to about 300 m in lower Gleann Lichd (Tate, 1995).

The area of rock slope deformation

The area of rock slope deformation has been described by Jarman and Ballantyne (2002). It lacks distinct lateral margins and is defined by a remarkable array of antiscarps (Figures 2.19–2.22). On the upper half of the slope these achieve lengths of up to 800 m and heights of up to 10 m, but those above the slope crest and on the lower slope are 1–5 m high. All are composed of intact bedrock, with steep upslope faces and sharp crests, implying formation after deglaciation (Figure 2.22). The antiscarps are aligned parallel to the slope contours, though some descend gently westwards or south-eastwards across the slope and some converge (Figure 2.20). Small antiscarps occur within the area of renewed glacial occupation of Gleann Lichd during the Loch Lomond Stadial, descending to within 50 m of the valley floor.

The slope exhibits three large-scale bulges or convexities separated by intervening depres-

Figure 2.19 The Beinn Fhada rock slope failure seen from the west across Gleann Lichd. Unbroken antiscarps extend up to 800 m across the 30°–35° glacial trough side. Deformation extends for 3 km along the valley and onto the pre-glacial upland surface, reaching the south top (1000 m) in the background, and affecting 3.0 km^2. (Photo: D. Jarman.)

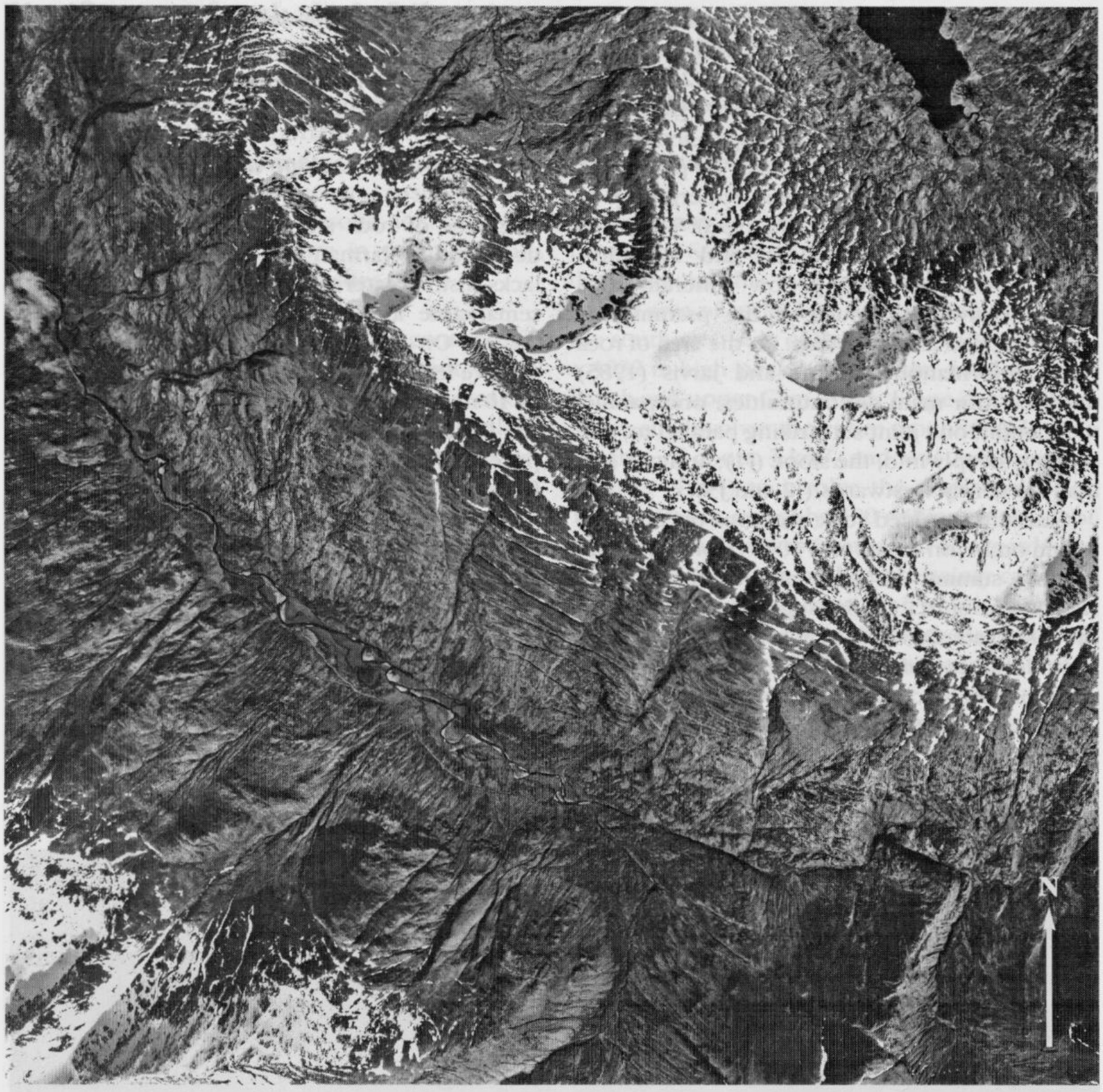


Figure 2.20 Vertical aerial photograph of the Beinn Fhada rock slope deformation. The three major slope convexities are highlighted by antiscarp arrays, as is the extent of the pre-glacial land surface with its structural lineaments. (Photo: Crown Copyright: RCAHMS (All Scotland Survey Collection).)

sions and highlighted by the convex-outward planform of associated antiscarps (Figure 2.21). Antiscarps also extend on to the adjacent plateau and across the depression between the western and central bulges, indicating that slope deformation was more extensive than the bulges alone suggest. According to Fenton (1991), the area of rock slope deformation appears to be generally under compression, though a minor area of shallow translational sliding failure occurs near the eastern margin of the major slope deformation (Figure 2.21). The toe of the slope is apparently intact, with no evidence for displacement towards the valley axis. Springs emerging near the foot of the area of deformation appear to be fed by groundwater movement through a sub-surface zone of fractured rock upslope.

The slope crest above the main area of deformation is marked by a degraded rock scarp up to 90 m high. Weathered rock crops out locally in the scarp face, which diminishes in height northwestwards above an oblique rock ramp (Figure 2.21) and merges eastwards with prominent

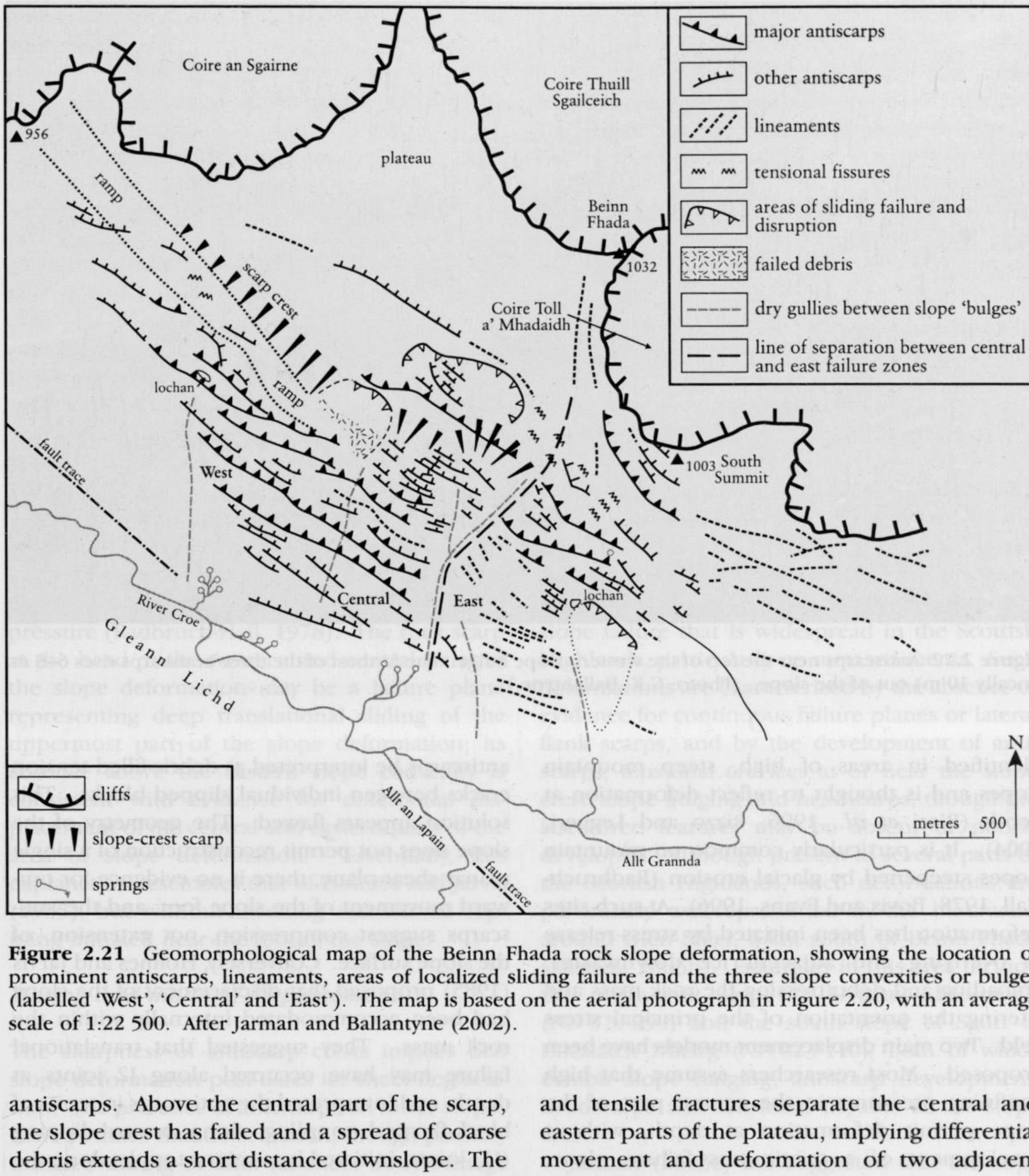


Figure 2.21 Geomorphological map of the Beinn Fhada rock slope deformation, showing the location of prominent antiscarps, lineaments, areas of localized sliding failure and the three slope convexities or bulges (labelled 'West', 'Central' and 'East'). The map is based on the aerial photograph in Figure 2.20, with an average scale of 1:22 500. After Jarman and Ballantyne (2002).

antiscarps. Above the central part of the scarp, the slope crest has failed and a spread of coarse debris extends a short distance downslope. The western and central convexities terminate upslope at the scarp foot, suggesting that the scarp represents a failure plane (Holmes and Jarvis, 1985). Above the slope crest, the plateau surface is crossed by structural lineaments, some of which have been re-activated by rock-mass deformation. Above the central slope bulge a shallow depression with a 10 m-high headscarp and internal antiscarps marks a site of incipient sliding failure (Figure 2.21). Above the eastern slope bulge, antiscarps up to 4 m high extend upslope to the summit ridge. Offset lineaments and tensile fractures separate the central and eastern parts of the plateau, implying differential movement and deformation of two adjacent rock masses.

Interpretation

Mechanics of deformation

The morphological characteristics of the Beinn Fhada failure zone are characteristic of those of deep-seated gravitational slope deformation (Chigira, 1992; Soldati, 2004), and in particular of *sackung*-type ('sagging') slope deformation (Hutchinson, 1988). The latter has been widely

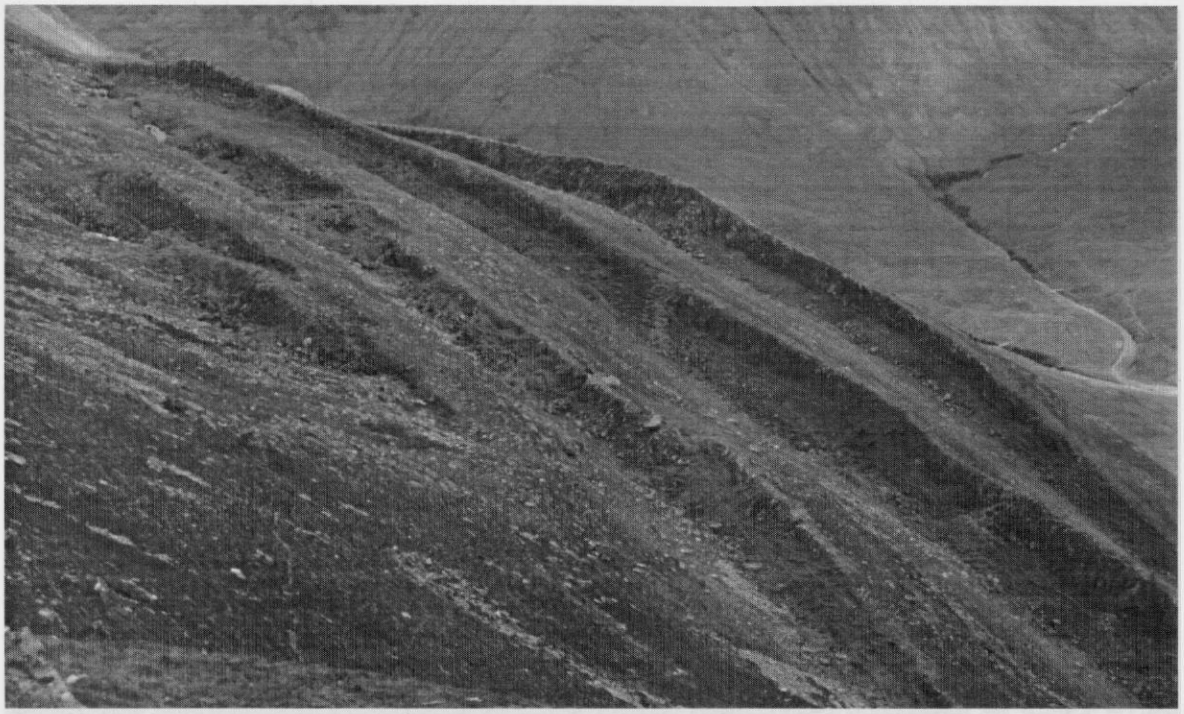


Figure 2.22 Antiscarps near the top of the western slope bulge. The farthest of the three antiscarps rises 6–8 m (locally 10 m) out of the slope. (Photo: C.K. Ballantyne.)

identified in areas of high, steep mountain slopes and is thought to reflect deformation at depth (Bisci *et al.*, 1996; Rizzo and Leggeri, 2004). It is particularly common on mountain slopes steepened by glacial erosion (Radbruch-Hall, 1978; Bovis and Evans, 1996). At such sites deformation has been initiated by stress-release as overlying and adjacent ice downwastes, unloading and debuttressing the rock mass and altering the orientation of the principal stress field. Two main displacement models have been proposed. Most researchers assume that high confining pressures in the central part of the slope permit deformation at depth, without development of a continuous failure plane, though shearing surfaces may be present at the top and/or base of the slope where confining pressures are lower (e.g. Mahr, 1977). Others have proposed that the zone of deformation is seated on a continuous shear surface (e.g. Savage and Varnes, 1987; Bovis and Evans, 1996).

Both models have been invoked for rock slope deformation at Beinn Fhada. Watters (1972) suggested translational sliding along a continuous deep failure-plane, with outward movement of the slope foot initiating sequential upslope separation of large slices of rock; the antiscarps he interpreted as debris-filled tension cracks between individual slipped blocks. This solution appears flawed. The geometry of the slope does not permit reconstruction of a single planar shear-plane, there is no evidence for outward movement of the slope foot, and the antiscarps suggest compression, not extension, of the slope surface. Conversely, Holmes and Jarvis (1985) proposed that displacement of the slope had been accommodated internally within the rock mass. They suggested that translational failure may have occurred along J2 joints at depth, and interpreted the antiscarps in terms of block-flexural toppling along inward-dipping (J1) joints, initiated by a minor topple along the lower slope. There is, however, no evidence for the latter. Jarman and Ballantyne (2002) suggested two further explanations. The first involves movement along a deep failure-plane or shear zone, with associated antiscarp formation by compressional block-flexural toppling. The second involves glacio-isostatic rebound of the valley floor and lower slope with the development of compressional (reverse) fault-swarms across the slope, forming antiscarps.

Jarman (2003e) has outlined arguments against development of a continuous failure-plane under the zone of slope deformation. The main points are:

(1) the apparent absence of suitably aligned joint-sets;
(2) the slope configuration precludes development of a single planar surface connecting the headscarp and toe slope;
(3) the absence of a headscarp above the eastern part of the area of deformation;
(4) the absence of lateral flank scarps or rupture zones;
(5) the absence of evidence for toe slope displacement, or of a failure plane at the slide toe.

These considerations appear to favour an alternative visco-plastic explanation of slope deformation. In terms of this explanation, the antiscarps represent fracture and toppling of near-surface rock masses over a region of deep deformation caused by micro-fracturing of rock under high pressure (Radbruch-Hall, 1978). The rock scarp at the head of the western and central parts of the slope deformation may be a failure plane representing deep translational sliding of the uppermost part of the slope deformation; its absence above the eastern slope convexity is consistent with evidence for differential displacement of the central and eastern parts of the area of slope deformation. Essentially, this explanation resembles that of Holmes and Jarvis (1985), but without invoking extensional toppling initiated near the foot of the slope.

Timing and mode of displacement

The sharpness of antiscarp crests implies that slope deformation post-dates ice-sheet deglaciation. The presence of antiscarps on lower slopes demonstrates that deformation, though possibly initiated during or after ice-sheet downwastage (*c.* 17–15 cal. ka BP), continued after deglaciation at the end of the Loch Lomond Stadial (*c.* 12.9–11.5 cal. ka BP). Both Watters (1972) and Holmes and Jarvis (1985) suggested that high water-pressures during deglaciation may have aided slope deformation by decreasing the interlayer strength of the rock mass. Although elevated joint-water pressures have been identified elsewhere as instrumental in gravitational deformation of slopes (Bovis and Evans, 1996), the presence of antiscarps within the area re-occupied by ice during the Loch Lomond Stadial suggests that deformation continued after final deglaciation. Fenton (1992) has suggested that slope deformation was triggered by a high-magnitude seismic shock due to fault re-activation by differential glacio-isostatic unloading, but this explanation appears to rest solely on the proximity of the Gleann Lichd and Strathconon faults. Deep-seated gravitational slope deformation is widely considered to be a gradual phenomenon (Bisci *et al.*, 1996; Bovis and Evans, 1996) extending over centuries or millennia until post-deglaciation strength-equilibrium conditions are regained. At Beinn Fhada, the lack of runout debris, the essentially intact nature of displaced blocks and the continuity of antiscarp crests are consistent with gradual rather than abrupt displacement.

Wider significance

The Beinn Fhada rock slope deformation represents a type of paraglacial (glacially conditioned) slope failure that is widespread in the Scottish Highlands, particularly on metasediments. Such deformations are characterized by the absence of evidence for continuous failure planes or lateral flank scarps, and by the development of antiscarps, tensional crevices at or near the slope crest, slope bulging and headscarps, though the last three features may be absent or poorly developed. Although present in several parts of the Scottish Highlands, such deformations are particularly well-represented in the mountains around Glen Shiel, 6 km south of Beinn Fhada (Jarman, 2003b). Examples in this area include the north-west slope of **Druim Shionnach** (NN 070 090) and the south slope of Sgurr a' Bhealaich Dheirg (NH 023 140), both of which exhibit slope bulging, antiscarp development, headscarps and tensional fissures at the slope crest.

Jarman (2003e) has suggested that the large extent of rock slope deformation at Beinn Fhada may reflect the exceptional width of the plateau at this site, as stresses may be higher within slopes below broad mountain ridges (Beck, 1968; Gerber and Scheidegger, 1969). Alternatively, the exceptional size of the Beinn Fhada failure may simply reflect the occurrence of two or three contiguous areas of slope deformation on an uninterrupted slope of unusually high and steep relief. Jarman (2003c,e) also suggested an association between the location of rock slope failures and breaches mainly attributable to glacial erosion (Linton, 1949). In the case of the Beinn Fhada rock slope deformation, enhanced slope steepening may have resulted from accelerated glacial sliding velocities as the icestream occupying Gleann Lichd at the last glacial maximum descended westwards from or across the watershed to the valley floor (see Figure 2.18).

Conclusions

The Beinn Fhada rock mass deformation is the best documented example of *sackung*-type deep gravitational slope deformation in Great Britain. It is important for several reasons. The site exemplifies all of the principal characteristics of such slope deformations, namely the development of slope convexities (bulges), the formation of widespread antiscarp arrays, a possible exposed failure plane at the crest of part of the deformed rock mass, diffuse lateral margins without flank scarps, and the absence of footslope deformation or evidence for a continuous failure plane. In terms of surface area and estimated volume it is not only the largest such slope deformation in Great Britain, but also the most extensive rock slope failure on the Scottish mainland. The height (6–10 m) and length (600–800 m) of the most conspicuous antiscarps are almost without parallel in Scotland, and the overall area of deformation is unusual in exhibiting evidence for complex deformation in the form of three distinct large-scale slope bulges, one of which has moved differentially relative to the other two.

Like many major rock slope failures in the Scottish Highlands, the development of the Beinn Fhada rock slope deformation can be attributed to slope steepening by glacial erosion and rock-mass weakening associated with deglacial unloading and paraglacial stress-release. Displacement was probably gradual and aided by high joint-water pressures. In common with similar slope deformations in Scotland and elsewhere, the absence of a continuous failure plane makes analysis of failure geometry and progression speculative. Though there is widespread acceptance that *sackung*-type gravitational slope deformation reflects a combination of deep-seated sliding, formation of antiscarps by joint-guided toppling and deep-seated deformation under high confining pressures, the validity of this explanation in the context of the Beinn Fhada rock slope deformation remains conjectural.

SGURR NA CISTE DUIBHE, HIGHLAND (NG 988 143)

D. Jarman

Introduction

Sgurr na Ciste Duibhe (1027 m) is one of the Five Sisters of Kintail in the Western Highlands. It is the clearest case of rock slope failure controlled by a basement fault. It has been advanced – with insufficient justification – as evidence for high-magnitude seismic events following the last deglaciation (Fenton, 1992). Its summit area has been lowered by about 10 m as a result of creep or slippage, and is the most striking example in Britain of this kind of paraglacial landscape modification. It also demonstrates classic rock slope failure features including ridge-top depressions and arêtes. The deformation progresses downslope into a sliding failure of unusual geometry, which probably reaches the floor of Glen Shiel; if so, this is the greatest vertical extent of rock slope failure in Britain at almost 1000 m, approaching alpine scale.

This is one of the 20 largest rock slope failures in the Highlands, and is within one of the densest clusters situated in the Glen Shiel–Affric area (Figure 2.18). While this cluster may have neotectonic associations, it is also within an area of anomalously low valley interconnectivity (Haynes, 1977a) and may point to relatively recent breaching of the main watershed by transfluent ice (Jarman, 2003b). Sgurr na Ciste Duibhe stands directly above the gorge of the River Shiel at the probable locus of the breach (Linton, 1949).

Description

The mountain ridge on the north side of Glen Shiel is continuous above 725 m OD for 13 km, one of the longest in Scotland, and matched by that on the south side. For 1 km, the ridge is dislocated by the intersection of the Glen Shiel Fault-swarm with the crest of Sgurr na Ciste Duibhe (Figures 2.23–2.25). The main fault passes 100 m behind the summit, where a 10 m red rock step on the north-east spur is prominent on the skyline (Point 985). The fault then crosses the ridge 300 m east of the summit, interrupting it with a 15 m crag (Point 935). Between these incidents, the fault is expressed as an arête across a small corrie head, partly

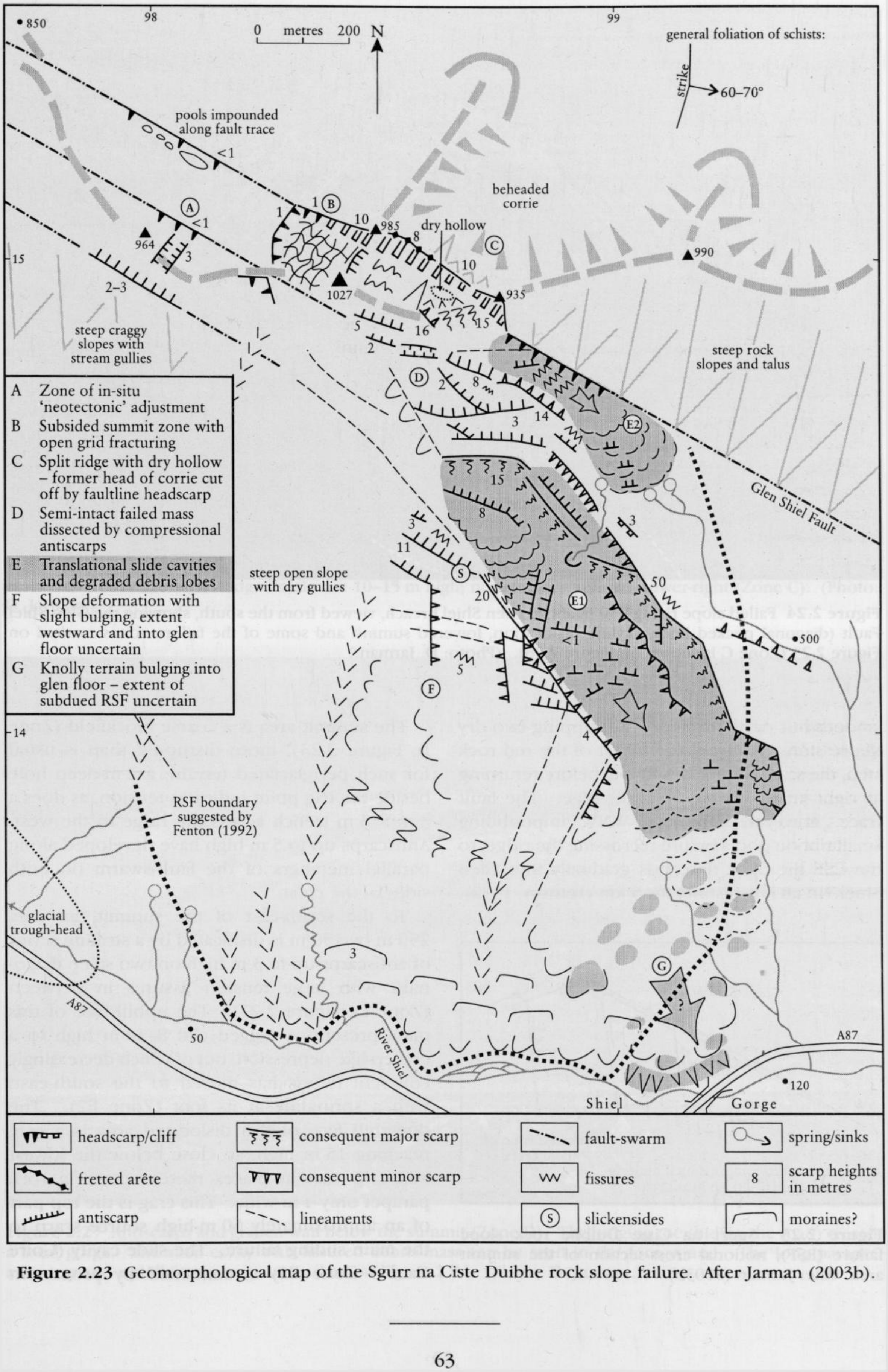


Figure 2.23 Geomorphological map of the Sgurr na Ciste Duibhe rock slope failure. After Jarman (2003b).

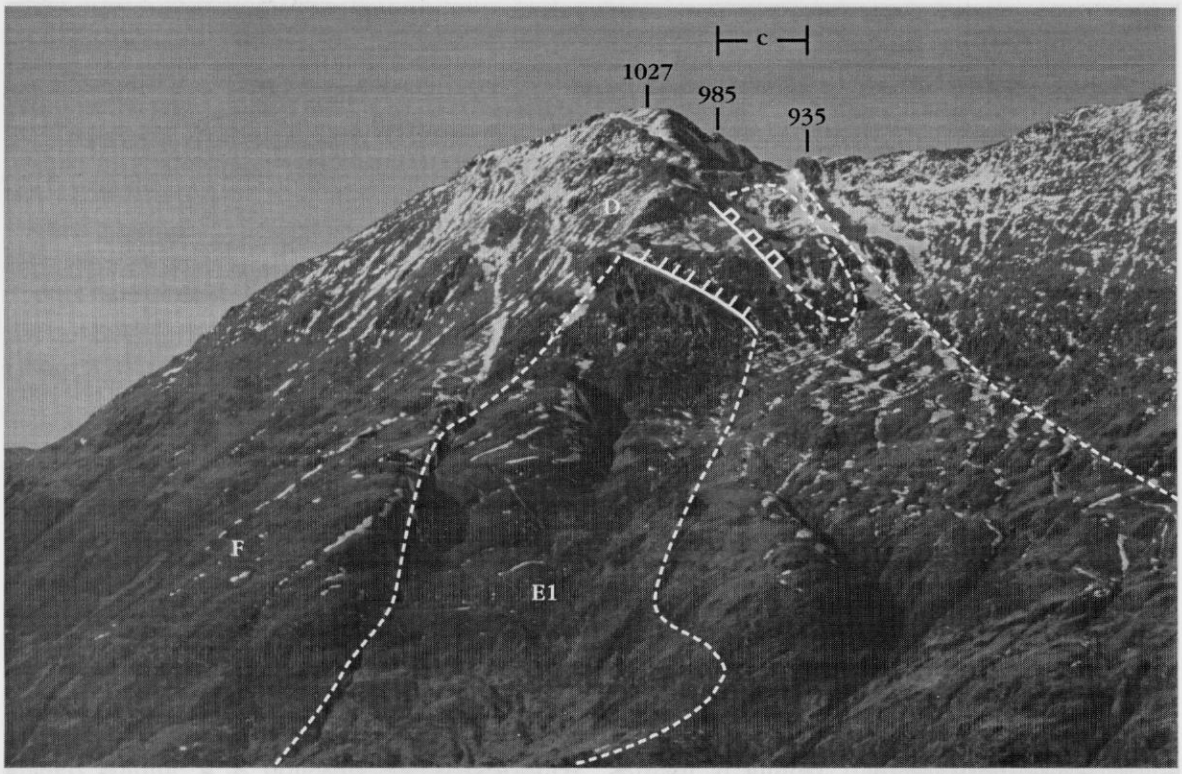


Figure 2.24 Failed slope rising 950 m above Glen Shiel breach, viewed from the south, showing the Glen Shiel Fault (diagonal pecked line), skyline dislocation, lowered summit and some of the failure zones marked on Figure 2.23 (Zone C is shown on Figure 2.26). (Photo: D. Jarman.)

smooth but partly fretted, and trapping two dry depressions (Figure 2.26). West of the red rock step, the scarp diminishes to 1 m before returning at right angles to the summit ridge. The fault trace, however, continues WNW, impounding small ribbon pools before recrossing the ridge; to the ESE the trace descends gradually into Glen Shiel. In all it is distinct for 5 km (Fenton, 1992).

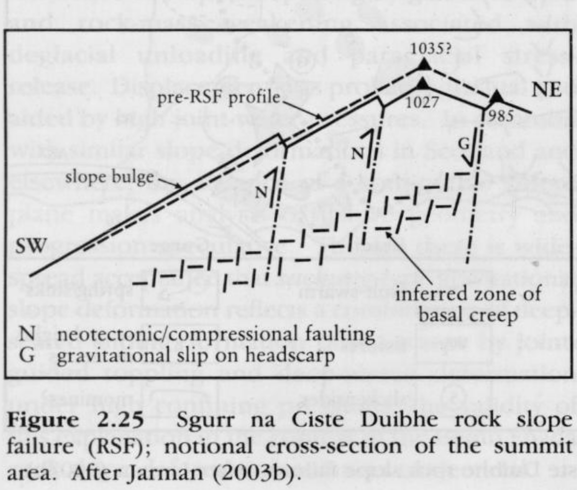


Figure 2.25 Sgurr na Ciste Duibhe rock slope failure (RSF); notional cross-section of the summit area. After Jarman (2003b).

The summit area is a coarse blockfield (Zone B, Figure 2.23), more disrupted than is usual for such periglaciated terrain; a 2 m-deep hole beside the trig point indicates tension, as does a 3 m × 3 m trench across the ridge to the west. Antiscarps up to 5 m high have developed along parallel members of the fault-swarm on both sides of the crest.

To the south-east of the summit, an area 250 m by 150 m is dislocated by a striking series of antiscarps up to 3 m high on two steep diagonals, with large tension fissures in between (Zone D, Figure 2.27). The uphill face of this mass presents a ragged cliff 8–14 m high to a graben-like depression, out of which decreasingly coherent debris has moved to the south-east, with a springline at its foot (Zone E2). The downhill face of this dislocated area is a crag reaching 15 m high, so close below the lowest antiscarp that in places there remains a rock parapet only 4 m wide. This crag is the top part of an approximately 60 m-high source scarp to the main sliding failure. The slide cavity (Coire Caol – Zone E1) is contained by prominent

Figure 2.26 Five Sisters summit ridge dislocated by subsidence along the Glen Shiel Fault. View looking south-eastwards from Point 985. Ridge breaks are 10–15 m high; note the dry hollows, lower-right (Zone C). (Photo: D. Jarman.)

Figure 2.27 Antiscarps and graben wall below the summit (Zone D). The bulging toe (hiding the road) creates a local gorge. The slide cavity with fissured debris-mass can be seen in the foreground. The long parapet/ antiscarp and uphill-facing crag are marked on Figure 2.24. (Photo: D. Jarman.)

sub-parallel scarps 300 m apart, orientated NNW–SSE at 45° to the fall-line. The cavity reaches 50–80 m deep by contour extrapolation, with the scarp on its east being considerably higher than that on the west, and stepped and embayed with signs of incipient retreat above. In the head of the cavity a large monolithic failed mass remains, presenting an antiscarp up to 8 m high to its source; its surface is convex and subdued, with distinct decimetric antiscarplets and furrows. Below this, the main cavity is not fully evacuated: its floor also has antiscarplets, and a substantial stream sinks beneath it. Beyond the confines of the cavity, a very degraded debris-lobe descends at least to springs at 300 m OD, and probably to 200 m OD.

On the west side of this slide cavity, a broad midslope convexity has distinct indicators of tensional failure in its upper parts, including a 5 m-deep fissure, and some minor antiscarps (zone F). At its head at 650 m OD, the cavity scarp breaks back as an 11 m-high rockface with slickensiding on its smooth surfaces (Gordon, pers. comm.). The lowest part of this convexity forms a bluff protruding into Glen Shiel to form a local gorge with anomalous local topography; it has an absence of rock outcrops or surface wetness, but displays no positive indicators of failure. In its lee to the west, a broad embayment beneath the convexity has a series of debris ridges with pronounced uphill faces, reaching 3 m high, which however are not typical antiscarps. To the west again, a steep open slope extends almost unbroken from summit to valley floor, lacking surface-water drainage and the broken crags typical of the lower glen. Several springs rise near the slope foot, but when observed with the River Shiel in spate, their flows were modest and adjacent gullies remained dry.

Fenton (1992) includes all of these areas within the rock slope failure boundary, giving a possible maximum area of 1.9 km^2. Holmes (1984) identified only a limited area of 0.14 km^2 near the summit, as does the 1:50 000 geological map. The failure certainly extends over at least 0.95 km^2 including the in-situ summit ridge deformation, and probably over at least 1.25 km^2 (Jarman, 2003b). The volume of the main cavity is of the order of 5–10 × 10^6 m^3. Efforts to assess the overall volume of the rock slope failure would be very difficult; suffice it to say that it appears deep-seated, with Fenton (1991) estimating a depth in excess of 50 m.

The bedrock consists of Neoproterozoic age Moine psammites and subsidiary semipelites of the Morar Group; the bedding and main foliation in the rocks dips at 50°–75° to the east or south-east. It is probably co-incidental that this rock slope failure is developed in stratigraphically equivalent rocks to those underlying the **Beinn Fhada** failure. No detailed structural analysis has been made, but Fenton (1991) suggests fractures dipping south more steeply than the slope at about 45°. Fluid alteration has occurred along the near-vertical Glen Shiel Fault, giving rise to a weak band of oxidized and degraded rock: this is visible as an eroded trench and may have aided mass slippage.

Interpretation

This complex rock slope failure demonstrates a clear progression from in-situ deformation along the ridge west of the summit, through spreading, creep, and embryonic sliding failure in the summit area and upper slopes, to sub-cataclasmic failure of a large segment of the midslope.

The configuration of the whole complex is unusual in being orientated up to 90° away from the fall-line trend of the glen wall. This suggests, as at **Beinn Fhada** nearby, that joint-sets conducive to translational sliding are not well developed here. Indeed, analyses of 12 sites north-west of the Great Glen by Watters (1972) and Holmes (1984) suggest that both schistosity surface and principal joint planes are commonly inclined above 60°, by contrast with the South-west Highlands (e.g. **The Cobbler**).

Here four structural components can be identified. The Glen Shiel Fault is clearly the backing scarp for the whole rock slope failure; Fenton (1992) describes it as the 'headscarp', but movement is as much along it as down it. Secondly, the schistosity strikes orthogonally to the fault, and provides the return scarp and internal step-down scarps to the failed summit mass. Thirdly, the parallel members of the fault-swarm have allowed graben-type spreading and subsidence of the summit mass and short-travel sliding to the south-east. Some elements of these parallel faults appear to have been displaced south as part of a broader slope spreading. Fourthly, the main slide cavity is controlled by a north-west–south-east joint-set that may be cognate with the main joint-set identified at **Beinn Fhada**.

It is inferred from the 10 m height of the red rock step on the north-east spur that the summit of Sgurr na Ciste Duibhe has been lowered by 8–10 m (Figure 2.25). Although the return scarp to the north-west is only 1 m high, the step scarps within the disrupted blockfield make up the difference. Such lowering of a major summit by paraglacial rock slope failure would be unique in Scotland: close parallels occur at Carn na Con Dhu near Glen Affric (NH 07 24) and Beinn Bhreac by Loch Lomond (NN 32 00) where large sections of summit plateau have subsided. The area affected by lowering here extends 100 m north-east and north-west of the summit, and 200 m to the south-east, one of the most substantial encroachments into a mountain ridge by rock slope failure in Britain.

Equally remarkable is the failed mass south-east of the summit, which is semi-intact rather than disrupted, but is carved up by curving antiscarps on alignments discordant with the general structure (Figure 2.27). These suggest that the mass has begun to move by basal creep plus forward toppling, with both compressional antiscarps (Fenton, 1991) and tension fissures. Poised above the main rock slope failure cavity and with only limited lateral restraint, this mass may be only marginally stable. Analogous failed masses occur at Ben Lawers (NN 63 41) and Ben Vorlich by Loch Lomond (NN 29 12). Their survival may indicate a long-term lack of significant seismic shaking, for which precariously balanced rocks are a recognized indicator.

Although the main rock slope failure cavity is unusual in its slantwise orientation, the residual mass in the neck is a common feature of such slides (e.g. Meall Cala, Figure 2.39), as is the low-key disturbance of the floor (e.g. Beinn an Lochain west, Argyll, NN 215 076). The latter feature may indicate post-slide decompressive recovery, though the underground watercourse suggests incomplete removal (compare with Beinn Each, **Glen Ample**). The considerable volume of the cavity is not readily accounted for by debris below, implying partial evacuation by the last glacier. Very few rock slope failures within the Loch Lomond Stadial limits have been identified as pre-dating the Loch Lomond deglaciation (cf. **Beinn Fhada**). Sgurr na Ciste Duibhe provides a good opportunity to test this issue, by investigating the integrity of the knolls in Zone G (which could be a glacially over-ridden slipped mass), and the provenance of the atypically substantial lateral-moraine type mounds to its west.

To the west of the slide cavity, the broad midslope convexity has definite indicators of failure in its upper and eastern margins, but minimal indications of downhill displacement. As a hybrid between in-situ deformation and translational sliding, it fits the model identified in this area of the Cluanie-hybrid type failure exemplified at **Druim Shionnach**. In a context of high-angle schistosity planes and joint-sets in steep relief, decompressive forces are envisaged as conducive to slope bulging, with formation of grabens and antiscarp arrays, but no development of a sliding surface or debris lobe. Indeed, the Sgurr na Ciste Duibhe rock slope failure could have evolved initially as a Cluanie-hybrid failure affecting much of the glen slopes, with the more disrupted upper half then slicing off diagonally by progressive creep and sub-cataclasmic sliding. Lack of surface drainage and the powerful basal springs confirm deep-seated failure.

It is unclear whether the translational slide has at some stage reached the narrow glen floor and temporarily blocked it. Major landslide dams are rare in the British mountains, although common in other ranges, the dams impounding Llyn Tal-y-llyn being a good exemplar (Hutchinson and Millar, 2001). The rock slope failure toe below the knolls is exceptionally steep without being a rock gorge, and the River Shiel immediately downstream is atypically braided through coarse angular debris. This could be a result of fluvial breaching of a small dam, without re-activating the slide lobe.

One of the most widely recognized indicators of rock slope failure in mountain ranges is the split ridge or *doppelgrat* (Radbruch-Hall *et al.*, 1976; Crosta, 1996). This occurs where the source scarp daylights behind the crest, creating an uphill-facing scarp often confused with anti-scarps. Sgurr na Ciste Duibhe exemplifies the ridge-top depression in Britain, other instances being found on Ben Challum (NN 38 31) and Helm Crag, Lake District (NY 325 090) and most strikingly Aonach Sgoilte (Figure 2.12). The sharpening of a crest into an arête by rock slope failure is also seen locally here, but is better-developed farther east along the ridge between Saileag and Sgurr a' Bhealaich Dheirg (Figure 2.28), and on Aonach Meadhoin.

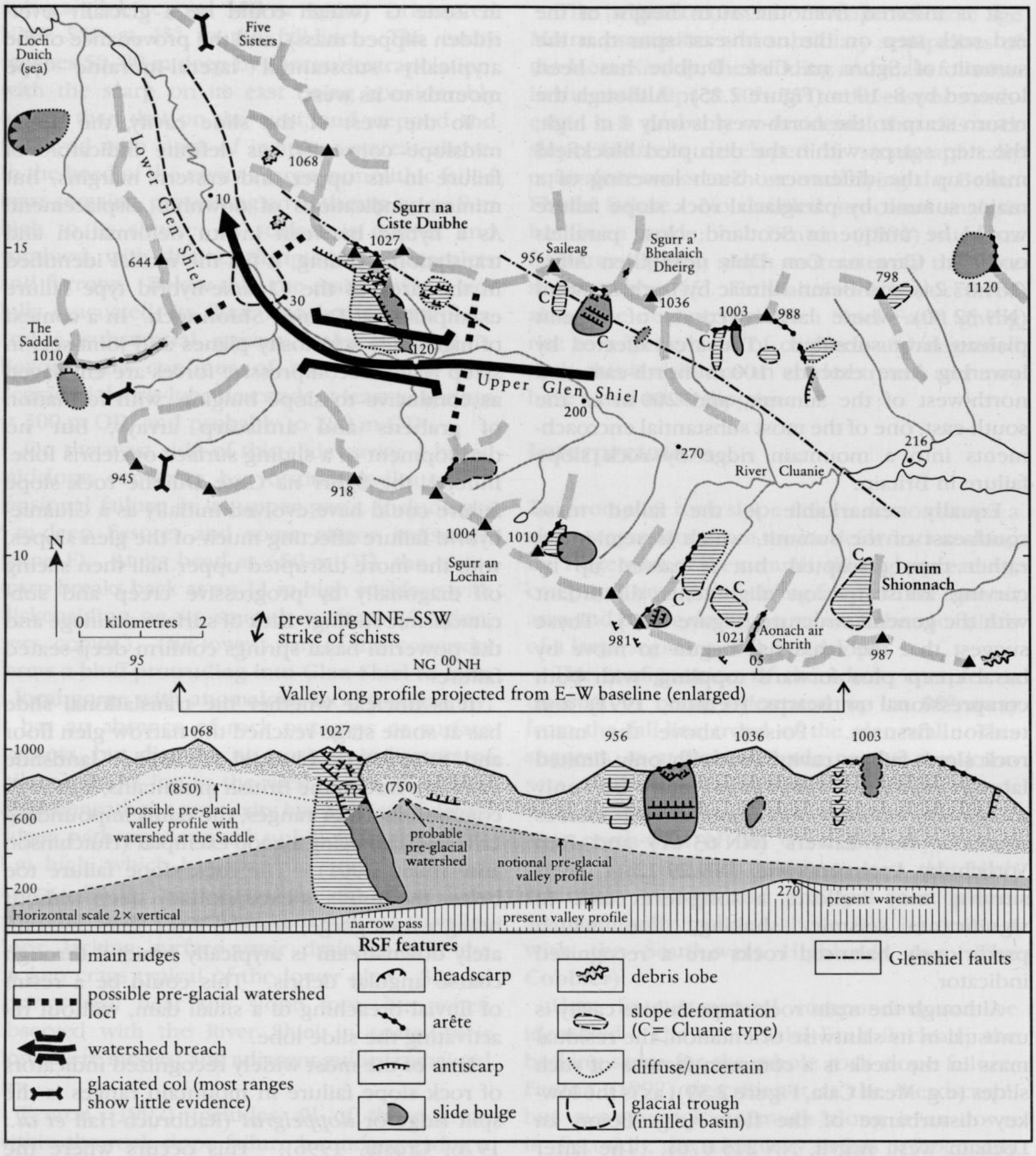


Figure 2.28 Map and long-section of the Glen Shiel breach with reconstructed pre-glacial watershed and associated rock slope failures on the north side of the main valley and in the trough corries of the south Cluanie ridge (e.g. **Druim Shionnach**). After Jarman (2003b).

Neotectonic activity

Fenton (1991, 1992) identified Sgurr na Ciste Duibhe as a prime example of a rock slope failure controlled by basement faulting, and triggered by neotectonic activity along it in response to post-glacial stress-release. From fault dimensions, he estimated a paleoseismic event here of magnitude 6.0–6.6 M_s, and from the incidence of rock slope failure and sediment liquefaction, magnitudes of 4.5–5.9 M_s. The implausibility of this model has been noted in the 'Introduction' to the present chapter, and the polyphase nature of the complex rock slope failure here further militates against it. In particular, the midslope slide cavity is markedly more subdued than either the lowest side slip into it or the sharply etched antiscarps and arête above. Fenton (1992) further proposed that the ridge crest has been offset by approximately 15 m in a sinistral sense, as a result of post-glacial intra-plate shearing, and attributed the ridge-crest hollow to this movement. The model for this was the proposed 160 m lateral displacement along the Kinlochhourn Fault nearby (Ringrose, 1989), which has been refuted by Firth and Stewart (2000). Here, there is no lateral offset to the north-east spur or the adjacent corrie-head gullies: an apparent offset of this scale where the fault cuts the east ridge is attributable to sliding out of the 'graben' section of the rock slope failure (Zone E2).

However, it remains possible that this and other rock slope failures have been partly triggered by seismic shocks of local origin, as the terrain recovered from differential ice loadings of 700–1000 m between ridge and glen, and from concentrated slope-foot erosion. Kintail is currently a focus of minor seismicity, and there is a marked cluster of rock slope failures here (Jarman, 2006). The high available relief, the existence of a sizeable basement fault crossing a narrow ridge, and the evidence of slickensiding all make Sgurr na Ciste Duibhe one of the prime sites in Britain for detailed examination of paleoseismicity.

Glacial breaching

Since the precise trigger mechanisms for the rock slope failure may prove difficult to determine, it is more fruitful to consider why this major failure complex has occurred here, within a dense cluster of such failures. Glen Shiel is a short west-flowing valley typical of the Western Highlands where the main watershed lies close to the coast, with a major glacial breach at its head (270 m OD) through to Glen Cluanie (Figures 2.18 and 2.28). Sgurr na Ciste Duibhe stands above the foot of its steep descent at the point where it becomes a glacial trough only 50 m above OD. However, Linton (1949) places the pre-glacial watershed at this point, implying that possibly 500–750 m of erosion has occurred here over the Quaternary Period, by a combination of vigorous trough-head excavation by the west-flowing valley glacier, and glacial breaching at times when the iceshed lay to the east of the watershed. Haynes (1977a) observes anomalously low valley interconnectivity in Kintail, and the breaches of the main watershed are at their highest elevations here. Haynes attributes this to a subtle combination of resistant geology, a high mountain axis aligned north-east–south-west, and an ice dome centred on the range deflecting other icestreams around it. In this context, the Glen Shiel breach may be relatively young, and bulk erosion may have been concentrated at the foot of Sgurr na Ciste Duibhe. This will have provoked rock slope failure partly by exposing potential failure planes, but primarily by generating rock mass stresses sufficient to propagate deep fracturing and compensatory outward movement.

In identifying a strong association between possible recent breaches and the incidence of rock slope failure in this area, in contrast to an absence of rock slope failure along mature glen sides, Jarman (2003b) suggests that this may indicate a shift or intensification of ice dispersal patterns in Devensian times. In this analysis, Sgurr na Ciste Duibhe is the most significant rock slope failure in this area.

Conclusions

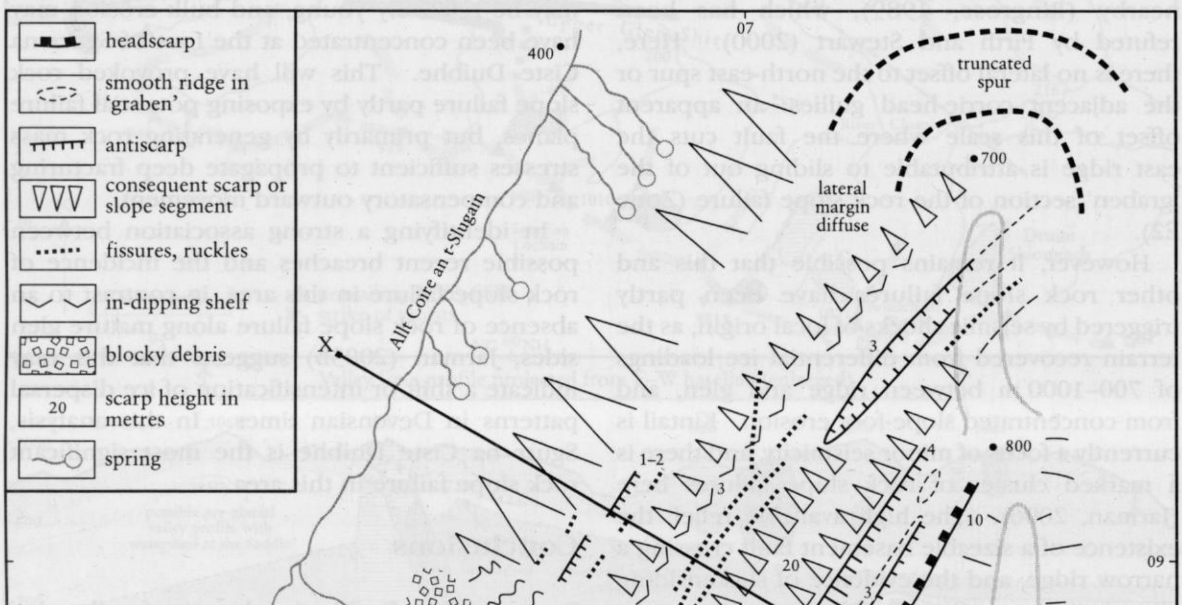
Sgurr na Ciste Duibhe is a key site for showing structural controls on rock slope failure, and paraglacial mountain summit shaping. The failure complex demonstrates vertical progression from in-situ deformation to long-runout sliding over almost 1000 m of valley-side. It is clearly associated with a basement fault zone, and is the best site on which to test theories of elevated seismic activity around deglaciation. The mountain top owes much of its present shape to rock slope failure, with fine examples of arêtes, ridge-top depressions, and antiscarps; its fractured and lowered summit may be unique in Britain. The failure stands above one of the most deeply excavated glacial breaches in Britain, and is the most significant member of the Kintail cluster in exploring the association between recent bulk erosion, generation of deep-seated rock-mass stresses, and their release in various modes of slope failure.

DRUIM SHIONNACH, HIGHLAND (NH 070 090)

D. Jarman

Introduction

Druim Shionnach is the type example of the 'Cluanie-hybrid' mode of rock slope failure identified by Jarman (2003b) and associated with steeply inclined and highly indurated metasediments in the Cluanie–Glen Shiel area and elsewhere. It has the essential characteristics of the compressional semi-intact slope deformation, with no signs of disintegration or debris mass, but it also has the pronounced headscarp and extensional spreading features found in translational slides. Such transitional character is valuable in understanding the mechanics of rock slope failure initiation and development. This failure also shows unusually clear-cut geological controls, and has produced a remarkably steep, smooth slope bulge (Figures 2.29–2.31).



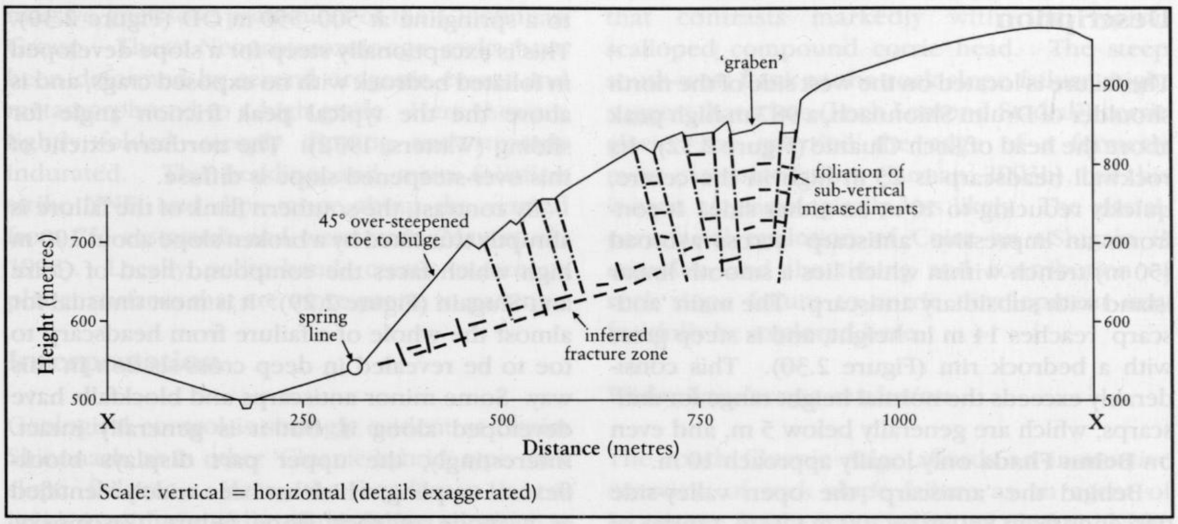


Figure 2.30 Section X–X on Figure 2.29, showing over-steepened bulge and graben progressively tilting failed slices away from source. After Jarman (2003b).

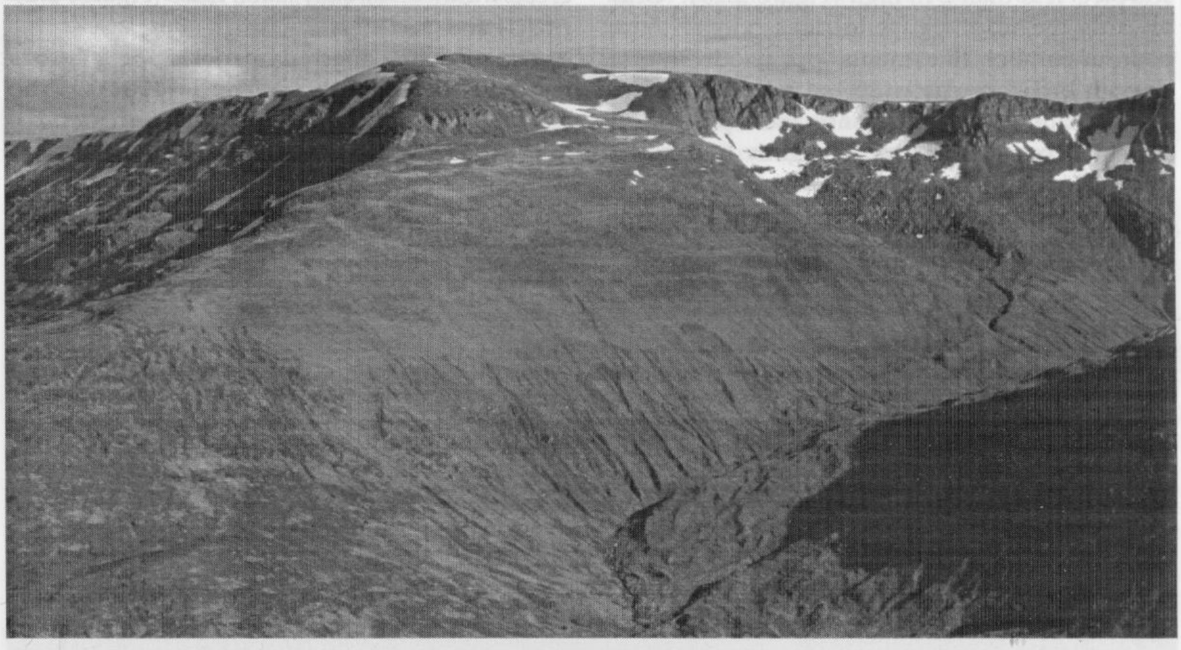


Figure 2.31 The Druim Shionnach rock slope failure is on the flank of a side trough off the main Cluanie preglacial valley. The smooth and bulging failed slope is wider than the apparent source scarp and notably lacks surface drainage and a clear lateral margin. (Photo: D. Jarman.)

The ridge on the south side of the Cluanie–Glen Shiel breach valley is notable for its succession of compound corries. Most of these have rock slope failures on their flanks (Figure 2.28), but not on their headwalls (as at **Ben Hee**); generally these failures are of Cluanie-hybrid type. The role of failure in lateral enlargement of corries is evident at Druim Shionnach, and westwards along the ridge the process has progressed further, with interfluves first being narrowed to arêtes and then reduced to rounded rumps.

◂**Figure 2.29** Geomorphological interpretation of the Druim Shionnach rock slope failure based on OS 1:25 000 mapping. After Jarman (2003b).

Description

The failure is located on the west side of the north shoulder of Druim Shionnach, a 987 m-high peak above the head of Loch Cluanie (Figure 2.32). Its rockwall headscarp is 25 m high in the centre, quickly reducing to 10 m on either side. It confronts an impressive 'antiscarp' across a broad (50 m) trench within which lies a smooth linear island with subsidiary antiscarp. The main 'antiscarp' reaches 14 m in height, and is steep grass with a bedrock rim (Figure 2.30). This considerably exceeds the normal height range for antiscarps, which are generally below 5 m, and even on **Beinn Fhada** only locally approach 10 m.

Behind the 'antiscarp' the open valley-side descends from 850 m to 700 m OD in a series of smooth slope facets and broad benches. These are level or slightly in-dipping, and incidented with abundant minor ruckles, fissures, and antiscarplets less than 2 m high (Figure 2.29). Only towards the north-east end does one of these contour-parallel lineaments open out into a smooth broad trench with 3 m outer antiscarp. These features fade out onto the open north shoulder, but can be traced slightly beyond its brow. Below 700 m OD, the main valley-side steepens to an angle of approximately 45° down to a springline at 500–550 m OD (Figure 2.30). This is exceptionally steep for a slope developed in foliated bedrock with no exposed crags, and is above the the typical peak friction angle for sliding (Watters, 1972). The northern extent of this over-steepened slope is diffuse.

By contrast, the southern flank of the failure is abruptly truncated by a broken slope about 100 m high which faces the compound head of Coire an t-Slugain (Figure 2.29). It is most unusual for almost the whole of a failure from headscarp to toe to be revealed in deep cross-section in this way. Some minor antiscarps and blockfalls have developed along it, but it is generally intact. Interestingly, the upper part displays block-flexural toppling, which has been widely identified as a mode of rock slope failure (Zischinsky, 1966; de Freitas and Watters, 1973; Holmes, 1984; Hutchinson, 1988), but is here only a few metres deep, and merely a process of superficial creep within an already failed mass (Figures 2.29 (inset) and 2.32).

The total area affected by rock slope failure is given as 0.33 km^2 by Holmes (1984). The 1:50 000 geological map indicates an extent of approximately 0.4 km^2, and including in-situ deformation of the north shoulder the area may reach 0.55 km^2. The failure has formed within

Figure 2.32 The Druim Shionnach rock slope failure top surface, seen in close-up from the summit ridge to the south-west. The prominent peak is the 14 m-high antiscarp facing the source scarp across a half-graben. Note the block-flexural toppling in the near-vertical metasediments, revealed in section in the foreground (see inset, Figure 2.29). (Photo: D. Jarman.)

massive gneissose psammites of the Glenfinnan Group. These Neoproterozoic-age rocks have been deformed by several orogenic events and metamorphosed to a high grade. Here they are tightly folded, steeply dipping and strongly indurated. The bedding and main foliation strike NNE, and dips range about the vertical from 75° eastwards and westwards (May *et al.*, 1993). Locally, pelite bands create micaceous planer surfaces that are more prone to parting.

Interpretation

Geological control is strongly evident at Druim Shionnach, as in other 'Cluanie-hybrid' type rock slope failures. Here, the headscarp is co-incident with the strike of the foliation, which is sub-vertical at the crest and dips 80° glenwards near the toe. Although no geotechnical analysis has been conducted, it may be inferred from the steep, intact bulge and in particular its lack of lateral restraint that joint-sets inclined valley-wards at angles conducive to sliding are not present; the main structural controls here are orientated north-west–south-east.

The major feature at Druim Shionnach is therefore interpreted as a kind of 'graben' (Jarman, 2003b), where the failed mass has moved outwards in response to decompression. The 'anti-scarp' is thus not a typical adjustment feature within a deforming mass, as at **Beinn Fhada**, but the face of an unusually broad tension trench, hence its exceptional height. A comparable case occurs on the Arrochar Ben Vorlich above Loch Sloy (NN 29 11). The subsidiary feature within the 'graben' has probably not literally subsided as in a rift valley, but reflects the stepping or doubling of the trench.

Within the failed mass, a progression can be seen from tensional features in the upper half to compression in the bulge. There is no evidence of downslope sliding movement, unless the toe has been glacially trimmed, and the scale of displacement evident in the source zone has presumably been accommodated by internal deformation and creep. A schematic cross-section (Figure 2.30) suggests that such deformation may be at least 100 m deep, consistent with the assumptions of Holmes (1984) and Fenton (1991).

A peculiarity of Druim Shionnach is its discordance with the pre-failure topography. Not only do the tension features transgress onto the north shoulder, they also continue south-west across the mouth of a smooth open bowl that contrasts markedly with the typical scalloped compound corrie head. The steep south-west flank to the rock slope failure might suggest that a late (Loch Lomond Stadial?) corrie glacier has quarried the edge of a formerly more extensive failure (Jarman, 2003b), but this is seen as glaciologically less likely. The glacial/paraglacial evolution of Coire an t-Slugain is complex, and the timing and contribution of rock slope failure to corrie development may fruitfully be explored here.

Wider landscape evolution

The south Cluanie ridge affords an instructive overview of rock slope failure as an agent of mountain landscape evolution (Figure 2.28). This is one of the longest high-level ridges in Scotland, continuously above 700 m for 15 km. The main ridge has become asymmetrical as a result of glacial trough–corrie development exploiting the strike of the schists, with its centre-line offset by up to 2 km to the south from an original median between Glen Quoich and Glen Shiel, and by up to 500 m between the extant summits, which typically lie off the main ridge out on the projecting spurs. However, failure has probably contributed less to this headward corrie erosion (by contrast with **Ben Hee**) than to their lateral expansion. All the extant failures are on the corrie flanks, or in their headwall angles, and display Cluanie-hybrid character, notably north-west of Aonach air Chrith. Those north-east of Sgurr Beag and Sgurr an Doire Leathain have shaped the spur crests into arêtes, the latter having progressed into a large sliding slump. Rock slope failure has therefore contributed to corrie amalgamation, creating the compound corries typical of the Moine Supergroup (Gordon, 1977), and to the reduction of the intervening ridges to a level where they have become subject to glacial scour. By contrast, there is minimal failure on the long steep south flank of the main ridge above Glen Quoich, implying that that valley has long since adjusted to ice discharge; unlike Glen Shiel its head has not become breached.

Other nearby examples of the Cluanie-hybrid type rock slope failure type occur in similar geological and topographical contexts on the northern arêtes of Sgurr a' Bhealaich Dheirg, while on its south-west flank a notable failure in the breached valley of Glen Shiel has affinities despite being orthogonal to the strike of the schists. This failure has 7 m antiscarps noted by Fenton (1991) as 'pop-ups' co-inciding with the Glen Shiel Fault-swarm. 'Cluanie-hybrid' type character can also be observed in some of the failures in the Mamores–Grey Corries cluster, again on steeply dipping schists and quartzites.

Conclusions

Druim Shionnach is a well-defined rock slope failure that illustrates transitional character between the slope deformation and the sliding mass, with both compressional and extensional elements. It has several exceptional features, notably a 14 m-high 'antiscarp' and graben structure, and a rare exposure in cross-section of block-flexural toppling. While in itself its mountain-shaping role is limited to trough–corrie widening, other rock slope failures of this 'Cluanie-hybrid' type in the vicinity clearly contribute to the evolution of the whole ridge and to arête development on its spurs.

BENVANE (BEINN BHÀN), STIRLING (NN 533 122)

D. Jarman

Introduction

Benvane is a major reference site for the diversity of rock slope failure modes and features in the old hard rocks of Britain (Figures 2.33–2.35). It displays a lateral progression from in-situ slope deformation to translational sliding. It is located on some of the lowest relief to give rise to extensive failure in the Scottish Highlands. Its boundaries are notably distinct, and it displays one of the finest and most extensive lattice antiscarp arrays in Britain, here, unusually, exhibiting three distinct orientations. The failure extends up to 120 m behind the brow of the broad ridge over a distance of 1 km, and is a telling indicator of the effect failure can have in wholesale reduction of relief in mountainous

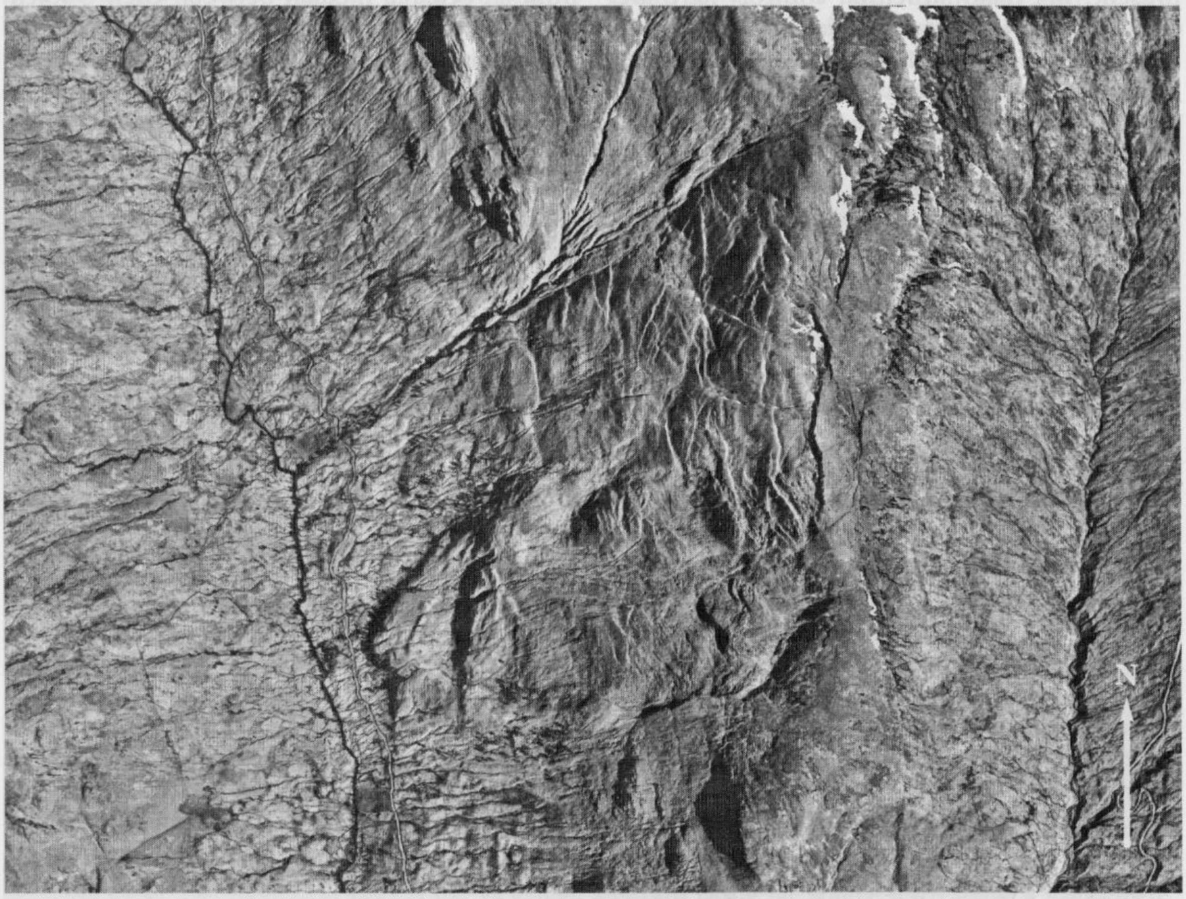


Figure 2.33 Vertical aerial photograph (1989) of Benvane, with sun from the east accentuating the array of antiscarps, scarplets and benches. (Photo: Crown Copyright: RCAHMS (All Scotland Survey Collection).)

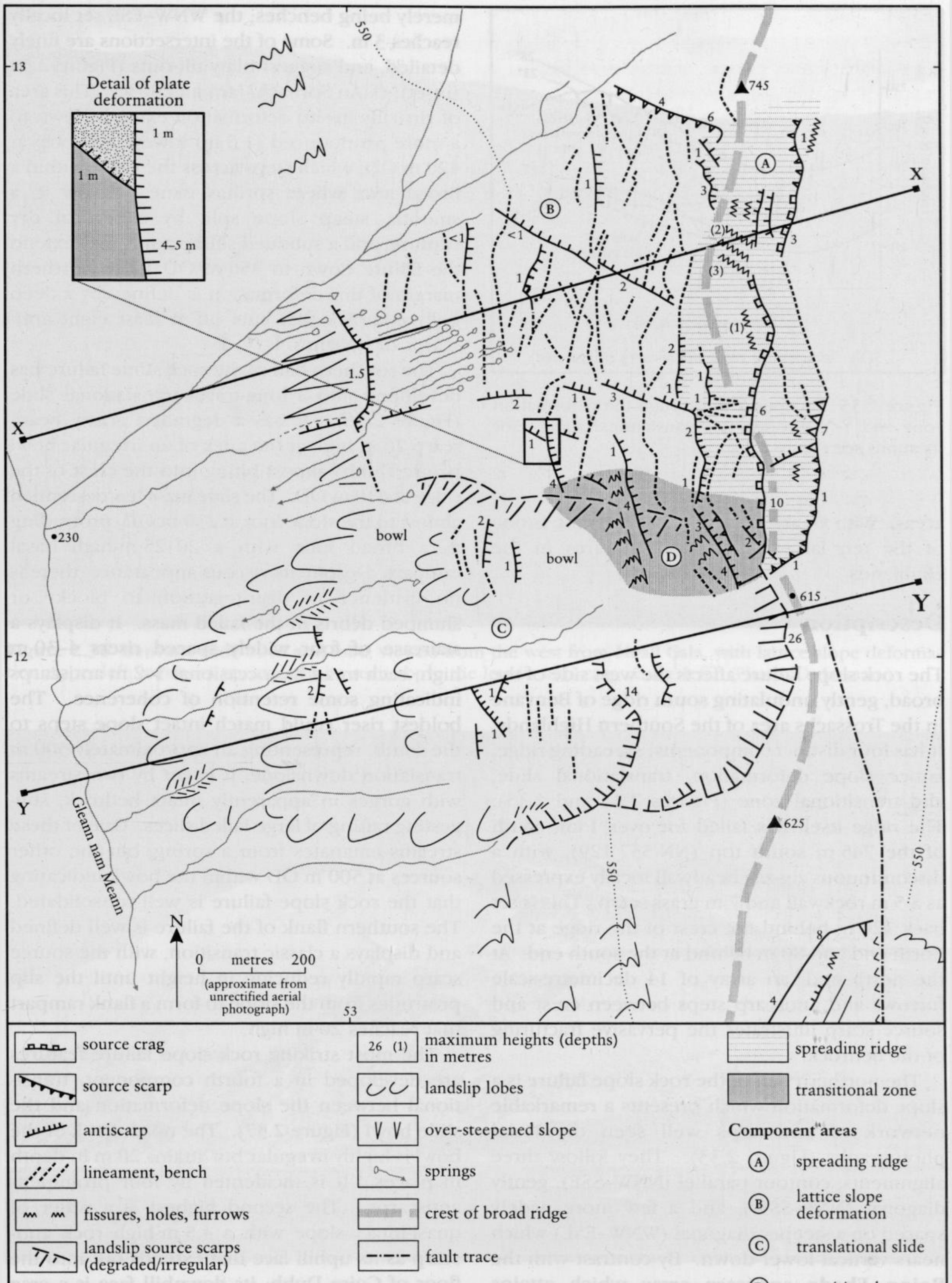


Figure 2.34 Geomorphological interpretation of the Benvane rock slope failure complex. Based on unrectified aerial photograph with field verification.

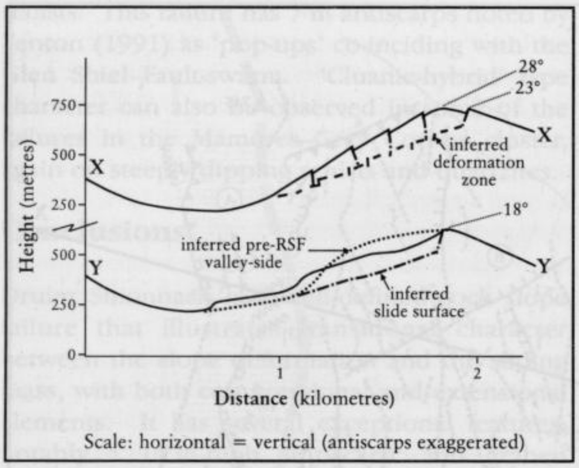


Figure 2.35 Sections X–X through the deformation zone and Y–Y through the translational slide. For locations see Figure 2.34.

areas. With an area of 1.25 km^2, Benvane is one of the ten largest rock slope failures in the Highlands.

Description

The rock slope failure affects the west side of the broad, gently undulating south ridge of Benvane in the Trossachs area of the Southern Highlands. It has four distinct components: spreading ridge, lattice slope deformation, translational slide, and transitional zone (Figures 2.34 and 2.35). The ridge itself has failed for over 1 km south of the 745 m south top (NN 537 129), with a discontinuous zig-zag headwall locally expressed as a 5 m rockwall and 7 m grass scarp. This is set back 120 m behind the crest of the ridge at the north end and 80 m behind at the south end. At the north end, an array of 14 decimetre-scale furrows and antiscarp steps between crest and source scarp illustrates the pervasive fracturing of the bedrock.

The northern half of the rock slope failure is a slope deformation which presents a remarkable network of antiscarps well seen on aerial photographs (Figure 2.33). They follow three alignments; contour parallel (NNW–SSE), gently diagonal (NNE–SSW), and a few more widely spaced on a steeper diagonal (WNW–ESE) which nears vertical lower down. By contrast with the **Beinn Fhada** antiscarp array which attains heights of 5–10 m, this array generally attains less than 1 m in height, with many elements merely being benches; the WNW–ESE set locally reaches 3 m. Some of the intersections are finely detailed, and suggest platy tilt-outs (Figure 2.34 (inset); cf. An Sornach, Jarman 2003c). This area of virtually in-situ deformation extends down to a more pronounced (1.5 m) lowest antiscarp at 420 m OD, which steps across the slope within a broad area where springs issue. Below it, a smooth, steep slope split by a vertical dry rupture, and a subdued slump zone, may extend the failure down to 350 m OD. The northern margin of this deformation is defined by a deep gully complex that cuts off at least eight antiscarps or benches.

The southern half of the rock slope failure has developed into a long-travel translational slide (Figure 2.36). It has a degraded grassy headscarp 26 m high at the apex of an irregular bowl (Coire Dubh) almost biting into the crest of the ridge at 610 m OD. The slide mass has descended almost to the slope foot at 230 m OD, protruding as a broad lobe with a 20–25 m-high basal rampart. Despite its viscous appearance, there is no evidence of disintegration to blocky or slumped debris in the failed mass. It displays a staircase of four widely spaced risers 4–30 m high; each tread has occasional 1–2 m antiscarps indicating some retention of coherence. The boldest riser could match intact slope steps to the south, representing an approximately 300 m translation downslope; it is cut by two streams with gorges in apparently intact bedrock, suggesting rafting of large failed slices. One of these streams emanates from a spring, but the other sources at 500 m OD within the bowl, indicating that the rock slope failure is well-consolidated. The southern flank of the failure is well defined and displays a classic transition, with the source scarp rapidly reducing in height until the slip protrudes from the slope to form a flank rampart that reaches 20 m high.

The most striking rock slope failure features are developed in a fourth component, transitional between the slope deformation and the slide bowl (Figure 2.37). The north flank of the bowl is highly irregular but attains 20 m in depth in places. It is incidented by four prominent antiscarps. The second highest is a wafer of quasi-intact slope with a 4.5 m-high rock antiscarp as its uphill face that extends out into the floor of Coire Dubh; its downhill face is a crag above a zone of slippage with tensional antiscarps. Adjacent to the headscarp of Coire

Figure 2.36 Benvane slide bowl and lobe, viewed from the west from Meall Cala, with lattice slope deformation upper-left; extensive springs can be seen above the lowest antiscarp centre-left. (Photo: D. Jarman.)

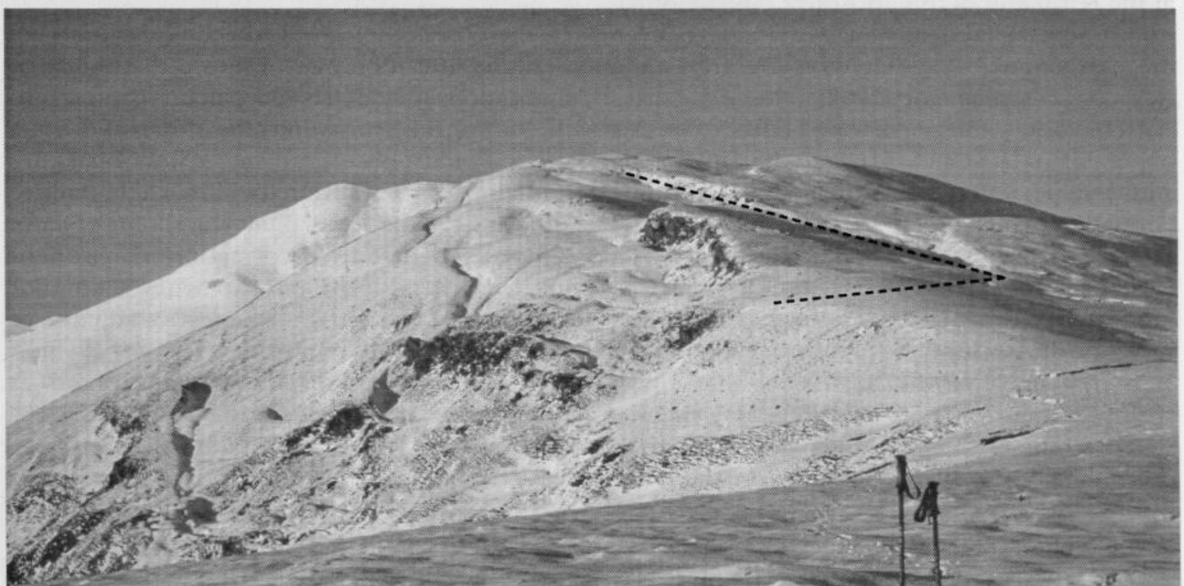


Figure 2.37 View north across the degraded headscarp of the slide bowl (Coire Dubh) to the fresher crags of the transitional zone. The extent of incipient encroachment into the broad ridge is indicated with a broken line. (Photo: D. Jarman.)

Dubh, another wafer with a fretted crest has slipped down approximately 10 m, opening a 4 m-deep tension trench. At the neck where it still attaches to the deformed slope, it transmutes into trifurcating antiscarps 0.5–2 m high. At the head of this transitional sector, a short 10 m rock crag is the most pronounced feature of the rock slope failure. It breaks back to become an obtuse wedge source scarp to a subsided section of the spreading ridge, which is some 400 m long and extends 80 m in from the ridge crest (Figure 2.38). A series of tension trenches up to 2 m wide and deep occur above the north side of this subsided wedge, and in its floor, on the WNW–ESE orientation, with the sense of movement being southwards down-ridge as much as valley-wards (cf. **Sgurr na Ciste Duibhe**).

Deranged drainage is a standard indicator of rock slope failure (Holmes, 1984) and here the pattern may provide pointers to the structure and sequence. It is unusual to have substantial streams flowing over a large slide lobe and incising its risers. It is also unusual to have extensive springs above the lowest antiscarp in the slope deformation zone, with the main source on a remarkable 50 m-wide front, although more conventional springs also occur at the north end of this antiscarp. The deformation otherwise lacks any surface drainage, even dry fluvial gullies as seen on **Beinn Fhada** (Jarman and Ballantyne, 2002).

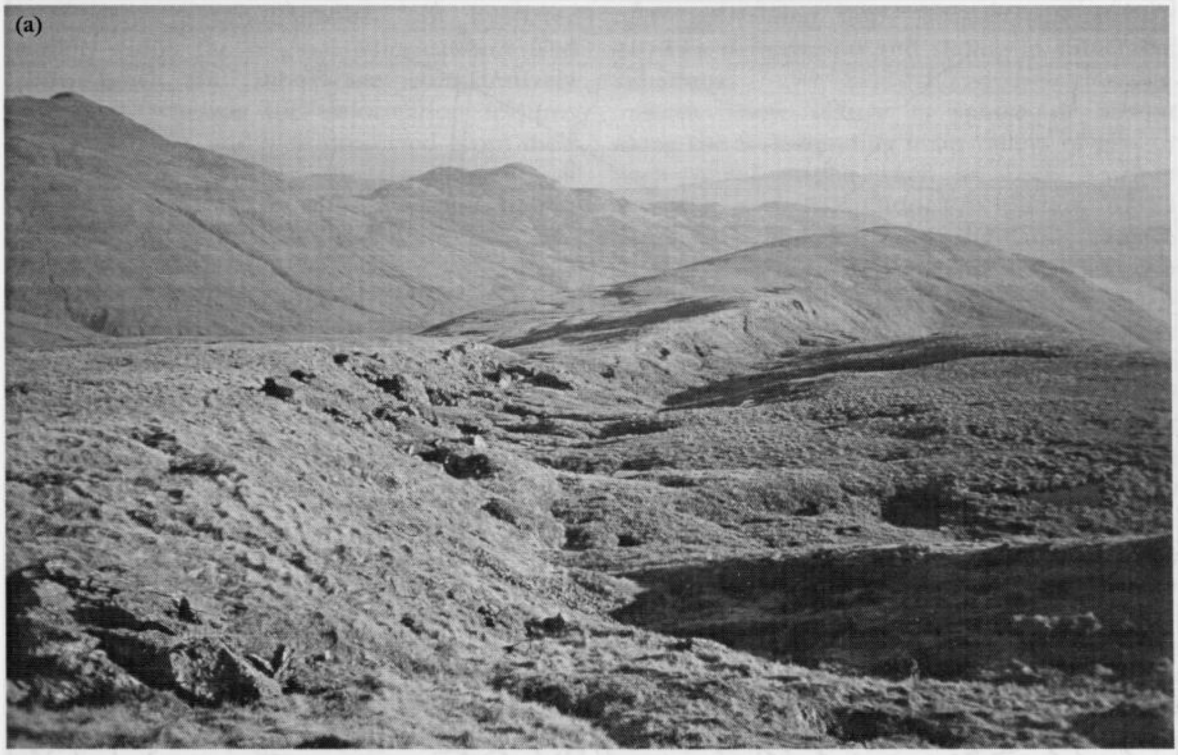
Geologically, the underlying bedrock consists of Dalradian (late Cambrian–Precambrian) arenite and semipelite of the Ardnandave Sandstone Formation, which dip at 30°–55° south-east into the slope. The rock slope failure lies just north-west of a broad, large-scale monoformal fold hinge, termed the 'Downbend', which separates rocks to the south-east that dip steeply south-east from those to the north-west that dip at shallower angles. The 1:50 000 geological map shows a minor NE-trending fault across the north part of the site. It only marks the Coire Dubh area (0.55 km^2) as a 'landslip', whereas Holmes (1984) identified 0.91 km^2 from aerial photographs, and the full extent is 1.5 km^2. It is difficult to assess the volume of the translated debris in the southern half, since the cavities are only partially evacuated, and the slide plane is unknown. At a conservative depth of 20 m as expressed in the bounding features, the order of magnitude is approximately 10×10^6 m^3. There is even less evidence for the volume affected by deformation in the northern half. A plane exposed at source scarp and slope foot would slice 50–60 m off the ridge, and at an average depth of 25–30 m the failed, but still quasi-in-situ, mass could amount to an additional 15–18×10^6 m^3. The total failure volume is thus very substantial in Scottish Highland and north European terms (cf. Table 2.3).

Benvane lies within a structurally related cluster of rock slope failures (Figure 2.39). The aerial photographs show its NNW–SSE ridge-splitting component continuing as an erosional lineament, which then controls a shallow, arrested 0.24 km^2 landslip on the east side of the ridge in Gleann Casaig. To the north of the deformation, the geological map shows similar features recurring sporadically for 2 km along the midslopes almost to the col above Glen Buckie. On the opposite side of Gleann nam Meann, the south ridge of Meall Cala is nicked by a small but striking failure which well represents the classic acute wedge form of rock slope failure. It has a 20–30 m-high source plane on the dip of the schists, and a 12 m detachment scarp crag on the south flank.

Interpretation

In the absence of any geotechnical studies of Benvane, it can only be observed that the large translational slide has developed contrary to the dip of the schists into the slope, and has a generalized surface gradient of less than 20°, implying an exceptionally low-angle failure surface near the lower limit for sliding (Figure 2.35). The slope deformation component may have failed to progress to actual sliding for the same reasons: its steepest gradients of 28°–35° are well above the residual friction angle for schists, but the plane exposed at source scarp and slope foot is approximately 23° (Figure 2.35). This deformation is of a platy character, with the strong but widely spaced WNW–ESE and north–south joint-sets guiding the rupturing of the main plates, and the contour benches and scarplets relaxing the stresses. The whole slope is in compression, with no open fissures. By contrast, the broad ridge above is in tension, with numerous furrows and trenches; their comparatively innocuous state suggests long inactivity.

No dates are available for Benvane, and it is not obvious whether the two main components



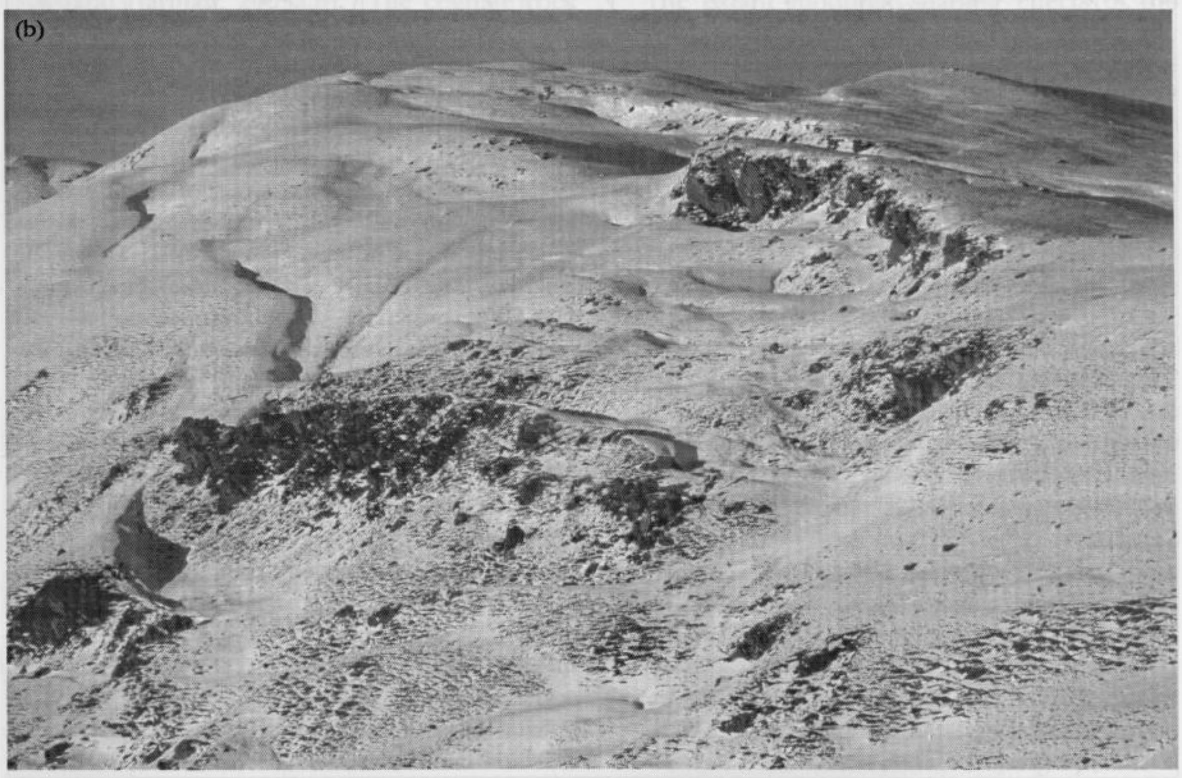


Figure 2.38 (a) View south down the spreading ridge to the slide bowl. The 6 m-high source scarp to the subsidence graben is not the limit of encroachment in to the ridge, the true headscarp being just visible on the left edge. (b) A close-up view across the slide bowl of the transitional zone extending into the spreading ridge. (Photos: D. Jarman.)

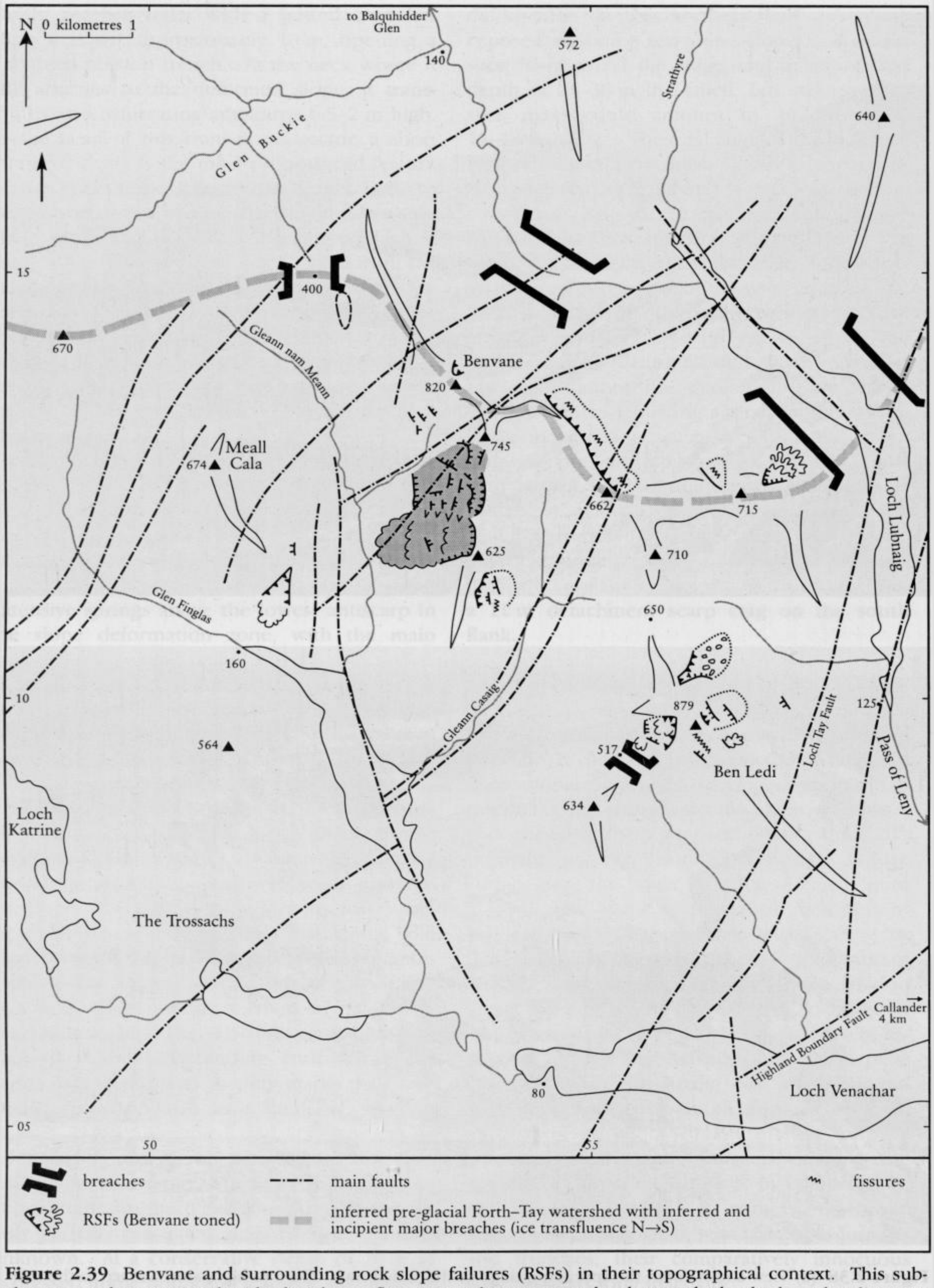


Figure 2.39 Benvane and surrounding rock slope failures (RSFs) in their topographical context. This sub-cluster may be associated with glacial transfluence south-east across local watersheds, the breaches being at varying stages of development. Unlike the **Glen Ample** sub-cluster immediately to the north-east, there is no specific association with main faults.

have evolved simultaneously, or by later sliding within the original deformation. The slide bowl and lobes are comparatively degraded, whereas the deformation features are fairly sharp and well preserved given their small scale. However, the transitional area between them has much larger and bolder features, and represents progressive encroachment of the slide into the deformed slope and ridge, with two substantial secondary slips into the bowl at midslope, and incipient encroachment into the ridge above. Indeed the trench fissures around the obtuse wedge bite suggest that the zone of actual translational failure has migrated up-ridge northwards as well as headwards.

It is not obvious why extensive and deep-seated rock slope failure should occur in such an area of relatively low relief, well removed from the main mountain cores, and from channels of intensive selective glacial erosion such as Loch Lubnaig (Linton, 1940). Yet there are 10 failure complexes affecting 2.9 km^2 of the 43 km^2 around Benvane (Figure 2.39), a density of 7% which compares with some of the highest in Scotland (Jarman, 2003a,b). The cognate rock slope failure cluster at **Glen Ample** 8 km to the north-east records an exceptional density of over 16%.

Benvane therefore provides an excellent locus for research into the mechanics of rock slope failure, and the reasons for its occurrence. Of the two triggers commonly invoked, elevated water pressures at deglaciation seem irrelevant to a compressional slope deformation and gently spreading ridge. Benvane and Ben Ledi appear to have been nunataks during the Loch Lomond Stadial (Holmes, 1984), but most of the site was probably ice covered, and hence the delicate deformation antiscarps and low-level slide lobe must post-date it. A high-magnitude seismic trigger is at odds with the presence of large erratic boulders on the steep sides of some antiscarp trenches, and the slide is far from cataclasmic. There is no major fault crossing the site, although a branch of the Loch Tay Fault passes down Gleann Casaig. However this cluster of rock slope failures, and the Glen Ample cluster nearby, are close to the outer limits of the Loch Lomond ice, and probably at a point where the Devensian icecap gradient was in steep transition from highland to lowland terrain. Differential glacio-isostatic recovery may have been most acute here, generating slope stresses sufficient to provoke deformation and sliding in vulnerable situations.

Rock slope failure is sparse or absent along the W–E-trending main valleys of pre- or early-glacial origin, such as Loch Katrine/Venachar and Balquhidder, a pattern found throughout the Southern Highlands (Figure 2.15). The concentration of rock slope failure in N–S-orientated side-valleys may indicate an early stage in their enlargement by transfluent ice from the north. Glen Finglas and its two tributaries are a relict of the pre-glacial dendritic Forth drainage system (Linton and Moisley, 1960). Their heads show signs of glacial over-riding, and the 400 m OD col west of Benvane is an incipient glacial breach of the pre-glacial Forth–Tay divide (Linton, 1940). It is possible that glacial downcutting even in this lower-relief area has been sufficient during the Devensian glacial to destabilize the slopes of Benvane and its neighbours. Similar lattice antiscarp arrays occur close to developing breaches in Glen Luss (NS 28 95) and near Tyndrum on Beinn Chaorach (NN 35 32).

The extant mountain-shaping effects of the Benvane rock slope failure are modest, but the scale of incipient encroachment is so great as to render the whole south ridge vulnerable to reduction and eventual 'divide elimination' (Linton, 1967).

Conclusions

The Benvane rock slope failure complex is an outstanding example of quasi in-situ slope deformation, with one of the finest and most extensive lattice antiscarp arrays in Britain. It displays lateral progression to a deep but degraded, long-travelled but coherent translational slide. The interface between these two zones is made conspicuous by rock slope failure features of much fresher character. Deformation encroaches into the broad summit ridge scale, and demonstrates the past and potential contribution of failure to large-scale erosion. Benvane also affords instructive comparison with the **Glen Ample** failure cluster as a platy deformation on steeper valley slopes, as compared to more gently sloping upland. It provides an excellent basis for research into the mechanisms, triggers, and underlying causes of rock slope failure in mountain areas of relatively lower relief.

GLEN AMPLE, STIRLING (NN 596 160–NN 610 215)

D. Jarman

Introduction

The area south of Lochearnhead, Perthshire is of exceptional significance as having the highest known density of rock slope failure in the Highlands, with seven failures affecting 16% of the 26 km² Glen Ample area (Figure 2.40). Core areas of other failure clusters studied do not exceed 8% (Table 2.2). It is also one of the most pronounced concentrations of significant failures along the line of a major basement fault, the Loch Tay Fault. The two principal failures, at Ben Our and Beinn Each, are essentially in-situ slope deformations with marked structural expression. Their extensive, but often delicate, ground rupture features are possible indicators of neotectonic activity: high-magnitude seismic shocks following deglaciation have been proposed but not yet confirmed in the Highlands (Stewart *et al.*, 2000). These structures provide unusually clear evidence of how deep-seated deformation can develop in some of the gentlest relief known to be affected by paraglacial rock slope failure. Ben Our is of exceptional significance for its extent and its unique platy structure.

Description

Glen Ample is a short (8 km) side-valley off of Loch Earn, with rather open slopes and less than 500 m relief to its immediate rims. It narrows at its head into a minor glacial breach of the main Forth–Tay divide south to the major breach of Loch Lubnaig (Figure 2.39). There are several lesser rock slumps and slides on its flanks, and just south of the pass is a more extensive anti-scarped zone. Directly above the pass stands the impressive Beinn Each rock slope failure. At the foot of the glen, one of the three largest rock slope failures in the Highlands occupies most of the low rounded hill of Ben Our. Being located at the junction of Glen Ample with the trough of Loch Earn, it is unusual in responding to slope stresses in directions almost 90° apart.

On the opposite side of Loch Earn, a small but striking rock slope failure has a deep, narrow wedge cavity and a slide lobe exhibiting creep in the last century. The west side of Glen Ogle has a chain of crag collapses across which a railway was engineered without re-activating them. Its rounded nose has signs of deformation, progressing to sliding slumps, complementary to Ben Our. Together with some rock slope failures on the south-west side of Loch Lubnaig, this dense cluster stands apart from the general concentration along the main Highlands watershed close to the west coast (Figure 2.13), and it occurs in some of the lowest relief in the Highlands to support rock slope failure.

Geologically, Glen Ample comprises Dalradian metasedimentary rocks (late Precambrian–early Cambrian in age). These are mainly arenites, semipelites, and pelites, with a distinctive intercalation of 'Green Beds' (which include reworked volcanic detritus) on the south-west slope of Ben Our. The rocks of Ben Our contain a higher proportion of schistose pelites and semipelites. The rocks are of greenschist to lower amphibolite metamorphic grade, typified by biotite and garnet growth. Structurally, Glen Ample lies close to the Highland Boundary Fault, where the relatively flat-lying Dalradian rocks become downfolded into a large monoformal structure called the 'Downbend', whose axis trends north-east. Thus while the beds dip gently on Ben Our, they are steeply inclined on Beinn Each. Glen Ample has formed by enhanced erosion along the line of the Loch Tay Fault, a sub-vertical NNE-trending structure. There is no recorded information on joint-sets, but there appear to be no obvious bedding or cleavage dips that can easily account for the incidence of rock slope failure in this area (J. Mendum, British Geological Survey, pers. comm.)

Ben Our (Beinn Odhar)

When seen on an aerial photograph, or in ideal snow or light conditions, the pervasive platy deformation of Ben Our is very unusual for a hill of relatively unassuming height and character (Figure 2.41). The summit area is almost flat, with tops at 730 m and 740 m OD separated by a shallow graben-like saddle. A swarm of scarplets runs behind the summit above the col to the south and below the broken crags on its east. To the west, these scarplets converge into a major scarp reaching 4 m in height, which runs for 600 m above the fluvial cleft of Coire Mheobhith. Since this scarp faces uphill (north) it appears to be an antiscarp, but together with the scarplet

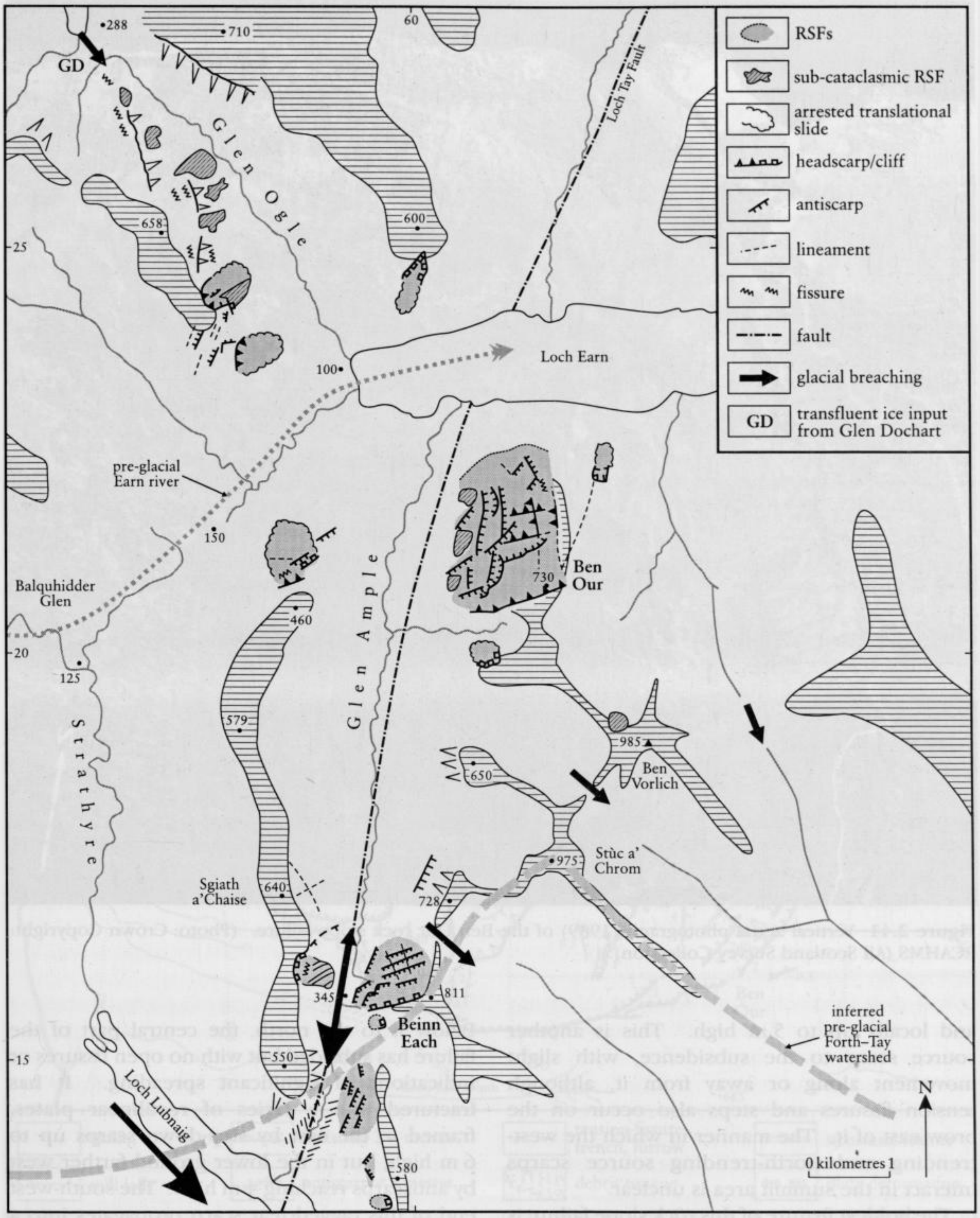


Figure 2.40 The Glen Ample rock slope failure (RSF) cluster in relation to the Loch Tay Fault and immature glacial breaches.

swarm girdling the summit, it is in fact the source fracture from which the whole mass of the hill has slipped slightly away (Figure 2.42).

The broad shoulder north from the summit is split by a fracture 1.2 km long, in places a mere furrow, but generally a sharp step typically 1–2 m

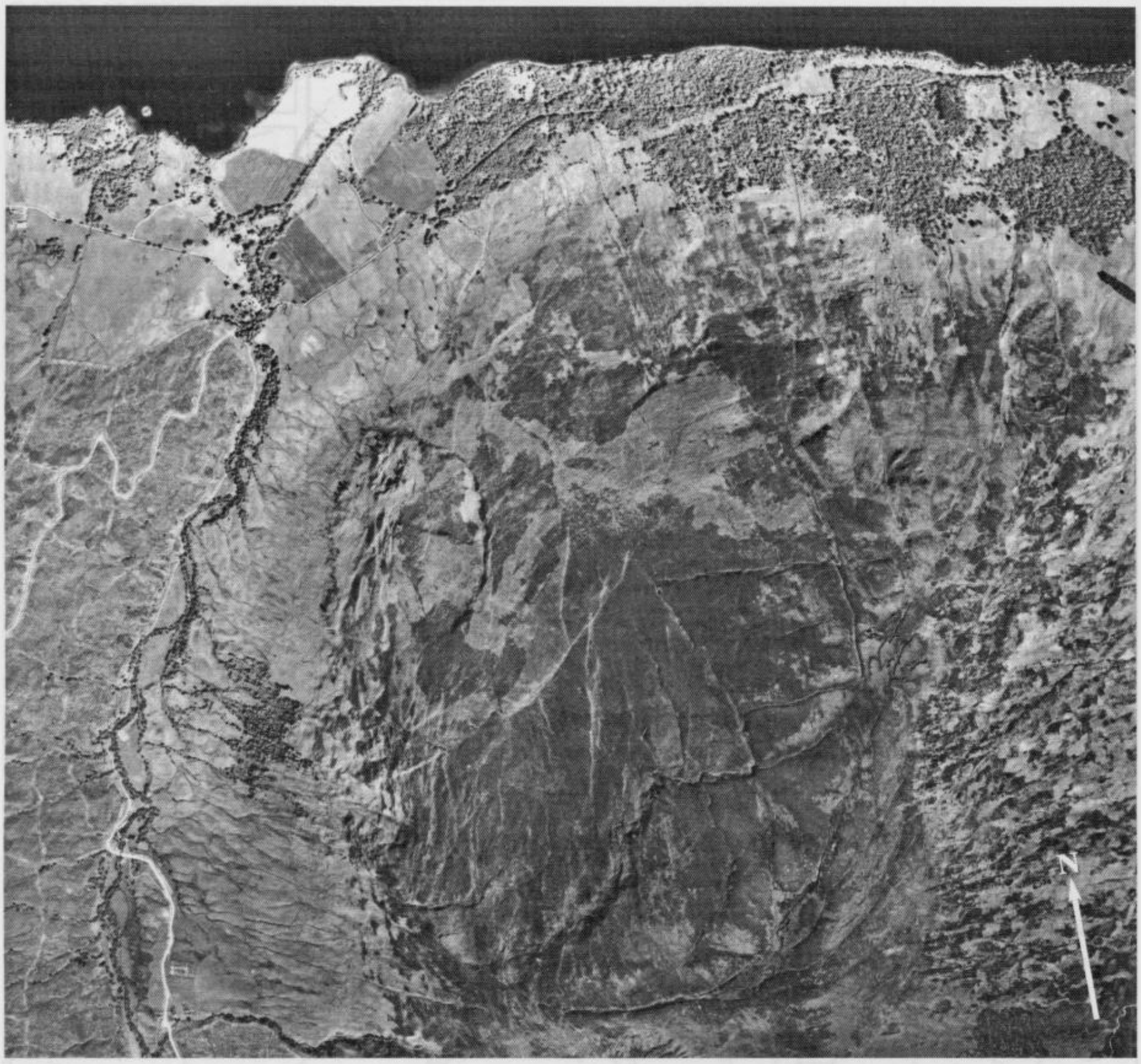


Figure 2.41 Vertical aerial photograph (1989) of the Ben Our rock slope failure. (Photo: Crown Copyright: RCAHMS (All Scotland Survey Collection).)

and locally up to 5 m high. This is another source scarp to the subsidence, with slight movement along or away from it, although tension fissures and steps also occur on the brow east of it. The manner in which the west-trending and north-trending source scarps interact in the summit area is unclear.

The boldest feature of this rock slope failure is a ragged tear scarp which scythes across the whole site in two arcuate sweeps, reaching 18 m high (Figures 2.41 and 2.42). Above this feature the gentle upper slopes are split by a tension scarp and furrow, and have minor antiscarps. Below it to the north, the central part of the failure has subsided but with no open fissures or indications of significant spreading. It has fractured into a series of rectilinear plates, framed in the east by step-down scarps up to 6 m high, but in the lower ground farther west by antiscarps reaching 4 m high. The south-west end of this ragged tear scarp propagates into a series of nested slip hollows, culminating in a conspicuous promontory that has crept out into Glen Ample. This pattern of short-travel upward-propagating movement has been described at Tullich Hill (Jarman, 2003d).

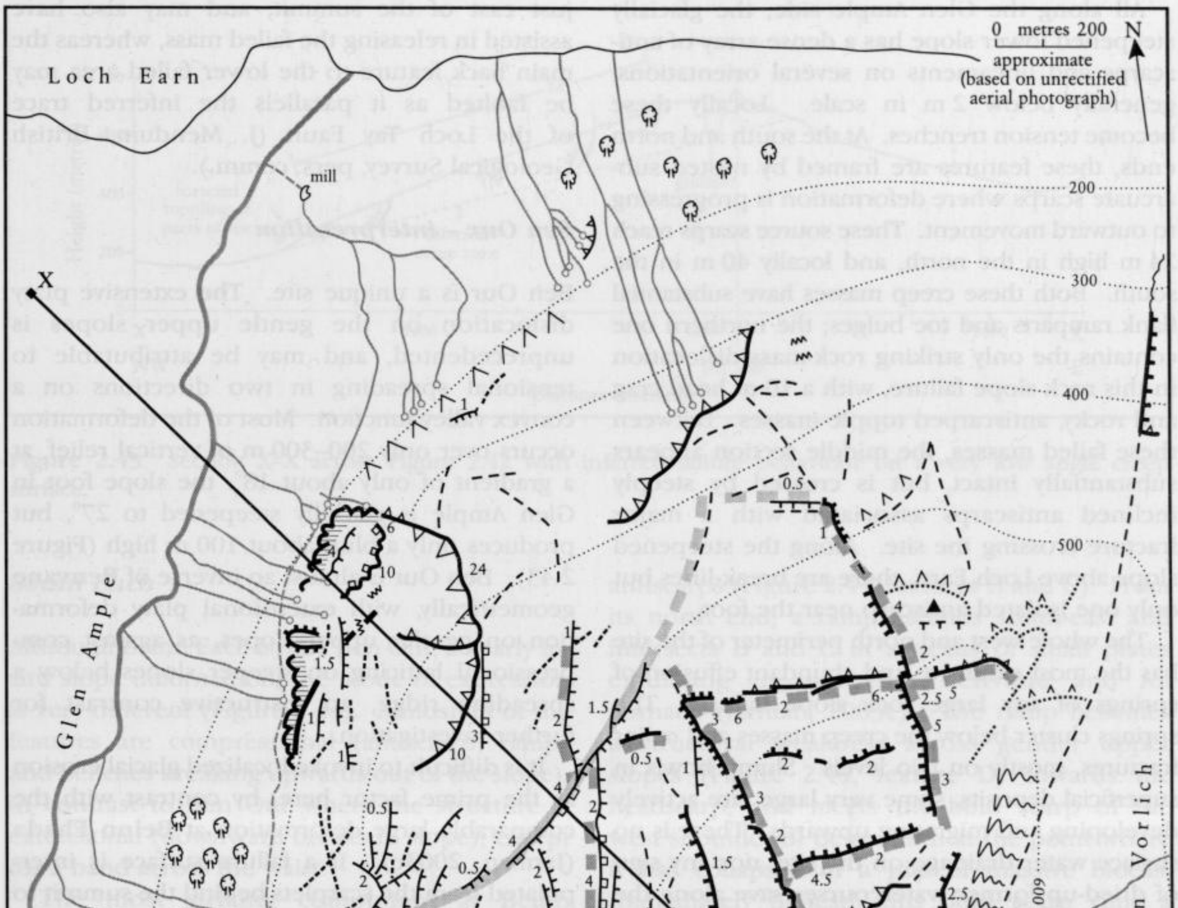


Figure 2.42 Geomorphological interpretation of the Ben Our rock slope failure, based on the unrectified aerial photograph with field verification.

All along the Glen Ample side, the glacially steepened lower slope has a dense array of antiscarps and lineaments on several orientations, generally below 2 m in scale. Locally these become tension trenches. At the south and north ends, these features are framed by nested subarcuate scarps where deformation is progressing to outward movement. These source scarps reach 24 m high in the north, and locally 40 m in the south. Both these creep masses have substantial flank ramparts and toe bulges; the northern one contains the only striking rock-mass dislocation in this rock slope failure, with a 10 m head crag and rocky, antiscarped topple masses. Between these failed masses, the middle section appears substantially intact, but is crossed by steeply inclined antiscarps associated with a major fracture crossing the site. Along the steepened slope above Loch Earn, there are break-lines but only one isolated antiscarp near the foot.

The whole west and north perimeter of the site has the most extensive and abundant effusion of springs of any large rock slope failure. The springs cluster below the creep masses and major fractures, mostly on two levels. Slump bowls in superficial deposits, some very large, are actively developing and migrating upwards. There is no surface water drainage on the site, nor any sign of dried-up former watercourses save along the southern boundary, indicating the pervasiveness of fracturing.

The extent of failure is reasonably clear except on the north shoulder and east slope, where irregular terrain continues down towards Loch Earn and into Glen Vorlich. A separate, rectilinear rock slope failure sourcing at midslope close to the angle of these valleys has a long debris-lobe; its west flank scarp is an extension of a distinct furrow lineament. The total extent is at least 2.9 km^2. Holmes (1984) only identified the most conventional slope failure areas above Glen Ample, totalling 0.17 km^2.

Possible contributory geological controls include bedding and foliation surfaces dipping NNW at approximately 45° along the southern boundary and shallowing northwards to as low as 5°: in combination with suitable joints, these could facilitate the translational sliding along the west flank, and extensional creep within the core of the deformation. Massive rock 'Green Bed' units on the lower slopes and more schistose lithologies near the summit within an interlayered structure may also have assisted mass translation. A NNE-trending fault passes just east of the summit, and may also have assisted in releasing the failed mass, whereas the main back feature to the lower failed area may be faulted as it parallels the inferred trace of the Loch Tay Fault (J. Mendum, British Geological Survey, pers. comm.).

Ben Our – interpretation

Ben Our is a unique site. The extensive platy dislocation on the gentle upper slopes is unprecedented, and may be attributable to tensional spreading in two directions on a convex valley junction. Most of the deformation occurs over only 200–300 m of vertical relief, at a gradient of only about 18°: the slope foot in Glen Ample is glacially steepened to 27°, but produces only a bluff about 100 m high (Figure 2.43). Ben Our is almost an inverse of **Benvane** geometrically, with extensional platy deformation on gentler upper slopes, as against compressional latticing on steeper slopes below a spreading ridge, an instructive contrast for further investigation.

It is difficult to invoke localized glacial erosion as the prime factor here, by contrast with the comparably large deformation at **Beinn Fhada** (Jarman, 2003e). If a failure surface is interpolated from the scarplets behind the summit to the slope foot springline in the north-west corner, then at 14° this is too low for conventional translational sliding (Figure 2.43). Such a surface is unlikely to exist as a planar throughgoing discontinuity: the component blocks are more likely to have their own 'floors', whether clear-cut or transitional, staircasing down the slope as joint-sets intersect above the NNW-inclined foliation surface. This would favour tensional spreading (as along the ragged tear) and assist translational movement on the outer slopes, but its concave nature may have restrained mass creep. The interpolated 'failure plane' would simplistically give a general depth of failure in excess of 150 m, which is comparable with the maxima proposed for major rock slope failures in high relief in the North-west Highlands (Fenton, 1991). Such a depth would give a very large total failed volume of the order of 100–200 × 10^6 m^3, comparable with **Beinn Fhada**. The actual extent to which the rock mass has lost structural integrity remains somewhat conjectural until geophysical surveys are conducted, but may well be considerably less.

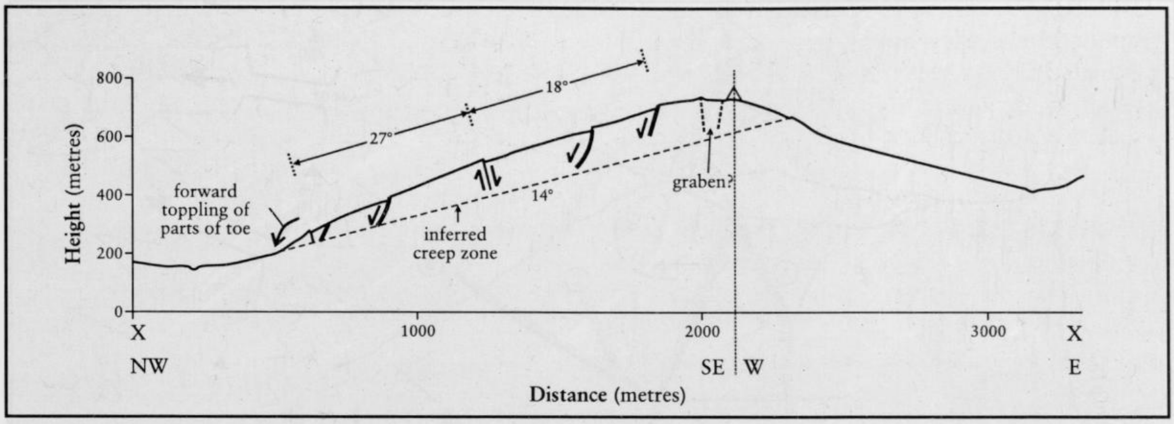


Figure 2.43 Section X–X across Figure 2.42 with inferred failure behaviour on a very low angle creep surface.

Beinn Each

Although Beinn Each is, like Ben Our, a nearly in-situ slope deformation, the mode of expression is very different (Figure 2.44). Almost all of the features are compressional (antiscarps, ramps and benches breaking upwards out of the slope), in contrast to Ben Our where the structure is extensional (downward breaks in slope), except for a band across the waist.

The most striking component at Beinn Each is a smooth dome, only about 200 m square, tilting out from the approximately 30° valley-side to an angle of approximately 40°. It is fractured by 'noughts-and-crosses' antiscarps typically 3–5 m high but reaching 9 m at one intersection, unusually high for sites south of the Great Glen. Visual impressions suggest that sinistral displacement of about 30 m may have occurred along the lower contour-parallel antiscarp. This extrusion has been likened to 'egg-box architecture' and 'celtic knotwork' (Figure 2.45).

This intense, but localized, deformation is at the lowest corner of the rock slope failure, only 150 m above the col at the head of Glen Ample. From it a sub-horizontal lineament extends north for 800 m, the whole width of the slope failure, below the steeper part of the valley-side. It snakes in the manner of an uncoiled rope, as do the lowest antiscarps on **Beinn Fhada**, but is generally no more than a broad bench (Figure 2.44, feature A). Midway, it is intersected by two pronounced lineaments trending diagonally south-west–north-east across the deformation and emerging in places as sharp, but modest, antiscarps (Figure 2.44, features B and C). From its north end, a ramp ascends south-east and intersects B and C in a nexus of small plates emulating in miniature **Benvane** and An Sornach (Jarman, 2003c). The ramp becomes a structural weakness across gentler upper slopes (Figure 2.44, feature D) towards the headscarp, and meets the bold scarp of the west shoulder of Beinn Each at the point where it has collapsed in a pile of massive blocks. Immediately beneath this bold scarp runs a final lineament (Figure 2.44, feature E). This starts from the extruded dome, extends uphill for 600 m as a well-defined, if discontinuous, antiscarp 2–6 m high, and continues as a trace onto the skyline. In places, it is the axis of a swarm of closely spaced lesser antiscarps; it resembles similar cliff-foot locations in the Mamores (e.g. Stob Ban, NN 147 648). Other features run parallel to these main lineaments and help to confirm the extent of deformation as about 0.5 km^2.

There are few obvious geological controls here (J. Mendum, British Geological Survey, pers. comm.), with the bedding and cleavage in the schists dipping too steeply to the NNW for translational sliding. The strike of the structure is however roughly parallel to lineaments B and C. A fault trace extending north-east from near Beinn Each summit may continue south-west to form the prominent southern 'headwall' to the rock slope failure, with an east–west fault causing an additional 'break up weakness' within the failure. Note that E and B correspond to fault traces mapped on the eastern side of Beinn Each.

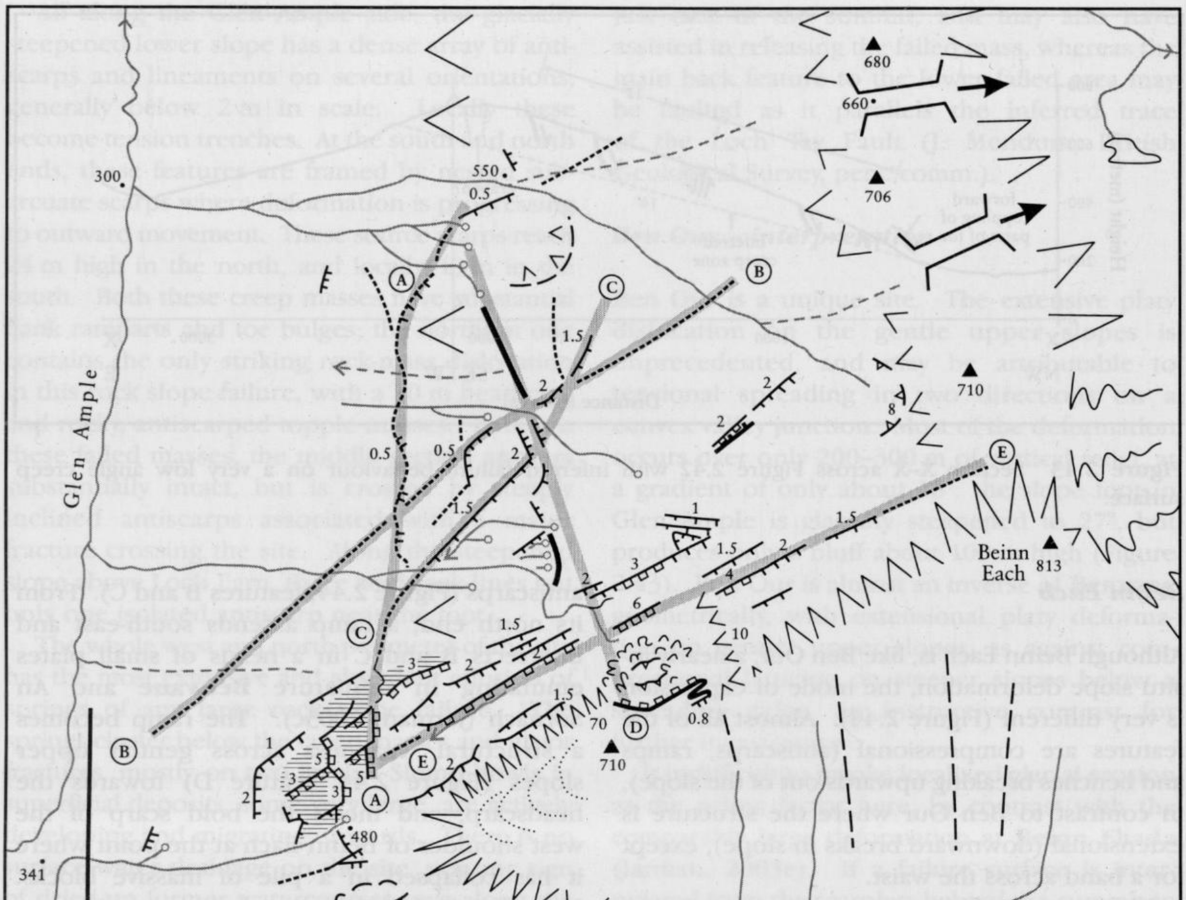


Figure 2.44 Geomorphological interpretation of the Beinn Each rock slope failure. Features A, B, C, D and E are described in the text.

Figure 2.45 Close-up of the Beinn Each rock slope failure nexus, suggesting extrusion of a component of the failed mass with fracturing along two joint-sets. (Photo: D. Jarman.)

Beinn Each – interpretation

Unlike Ben Our and **Benvane**, it is not at all clear where the Beinn Each rock slope failure originates. The bold scarp of the west shoulder cannot be interpreted as a 70 m headscarp since there is no sign that the failed mass has subsided or bulged out into the glen to any great extent. The collapsed section of this scarp, with its incipient encroachments into the ridge, is in effect a separate failure, as is that on the south-west flank of its nose (Figure 2.44). Nor is there any evidence of a source configuration along the heavily scoured north ridge. Nevertheless, this failure does occupy a broad wedge-shaped depression of subdued relief between steeper rockier bluffs.

A further sharp contrast with Ben Our, and with most deformations including Benvane, is the drainage pattern. Rather than a springline along the slope foot, there are major effusion zones at the upper and lower ends of lineament D, several springs associated with lineaments B and C, and streams following irregular courses over the rock slope failure. This could indicate that deformation is unusually shallow or partial, or alternatively that it is of such antiquity that it is reconsolidating. Examples such as Beinn an Lochain West and Beinn an Fhidleir in the Arrochar Alps (NN 215 076), and Na Gruagaichean in the Mamores (NN 227 105; Figure 2.11), suggest that removal of a previous failed layer might unload the surface sufficiently to re-activate deep-seated weaknesses. The 70 m-high scarp at Beinn Each is not the source cavity for the extant slope failure, but in this analysis it could represent the thickness of a previous failed layer now removed. The source of earlier failure could have been on the present north ridge, lowering it to enable over-riding by ice. Evacuation of such a failed layer could have been partly by landslipping *en masse*, since the present overall slope angle of approximately 26° is just feasible for translational sliding; selective quarrying of a weakened slope may also have played a part.

The present col at the head of Glen Ample may have been lowered by 100–200 m from its pre-glacial position. Although relatively modest, this localized erosion could have augmented the rebound stresses, especially if it has occurred mainly in Late Devensian times.

The most intense deformation occurs along the foot of the bold scarp, and at its nose. This is where the greatest thickness of material will have been removed in earlier glacial–paraglacial cycles, and closest above the breach where the valley-side is over-steepened along the 500 m contour. The 'eggbox' extrusions (or forward topples) must be close to the point of shearing or collapse, and their survival suggests vertical slices pinned at depth by the intersecting lineaments.

Interpretation

Remarkably, these major rock slope failures have not previously been published or commented upon. Holmes (1984) identified small sites along the Glen Ample slope foot at Ben Our, but nothing at Beinn Each. The British Geological Survey has yet to publish revised mapping of this area, although officers are aware of these sites.

The ages of these rock slope failures have not been investigated. The features are generally sharp but not unusually fresh except in the lowest collapse at Ben Our, indicating an earlier Holocene date. Their relatively low elevation has encouraged vegetation, and possibly protected them from periglaciation during the Loch Lomond Stadial. It seems more probable that such large deformations are a response primarily to the Last Glacial Maximum and its deglaciation: the main dislocations possibly occurred during the Windermere Interstadial, with the finer details emerging after final deglaciation.

Explaining the Glen Ample cluster is problematic. The association with glacial breaching and hence rapid erosion is initially attractive, since the Beinn Each rock slope failure and the sub-cataclasmic failure opposite stand directly above the Ample–Lubnaig breach. If Loch Lubnaig is accepted as a major breach of the former Forth–Tay divide (Linton, 1957), then Glen Ample is a subsidiary and possibly later-formed breach. The pass is of modest capacity, and may only be accommodating local ice displaced from flowing out north by transfluent ice down Glen Ogle (Figure 2.40). It does not appear to have been enlarging vigorously, and indeed lies almost transverse to regional ice outflow.

If glacial erosion has done no more than activate local slumping or forward toppling along the rock slope failure toes, then other causes must be sought. High-magnitude seismic shocks have been inferred from rock slope failure clustering and other indicators, especially where they co-incide with major faults (Fenton, 1991), although the evidence is weak (see 'Introduction', this chapter). The Loch Tay Fault runs along Glen Ample, and is one of the main Caledonian (NE–SW-trending) faults, with 7 km of strike-slip movement and up to 1 km of vertical displacement (Treagus, 2003); however there is no recorded present seismic activity along it. Some of the antiscarps run broadly parallel to this fault, but most interesting is the lineament which extends for over 1 km from near the summit of Ben Our, linking but essentially outwith it main and north-east failures (Figure 2.40. Any neotectonic origins for this feature, or for the rock slope failures themselves, must remain speculative at present. While Glen Ample is one of the best candidates for a rock slope failure cluster to be associated with post-glacial fault re-activation, it is nevertheless more likely to be a co-incidence of selective valley erosion along a suitable line of weakness.

This rock slope failure cluster is unusual in being located well to the east of the main watershed and former ice divide of the Highlands (Figure 2.15). Other easterly failures are associated with deep transectional breaches of the Grampian watershed (Hall and Jarman, 2004) or with vigorously enlarging trough heads such as Glen Clova. It may be that the location of this cluster in relation to the Pleistocene ice-sheets is significant. It lies close to the outer limit of the Loch Lomond Stadial (Holmes, 1984, after Sissons). It also lies close to the Highland–Lowland boundary at Callander, where the Devensian and earlier icecaps were in transition from high mountain-based domes to icestreams, possibly with relatively steep surface gradients and reductions in average thickness. On deglaciation, the regional glacio-isostatic rebound stresses may have diminished rapidly over relatively short distances, including from west to east across Glen Ample. Generally, such differentials are resolved by gradual deformation, or remain locked in. Where local rock structure is conducive, they may conceivably provoke ground rupturing, perhaps where additional local factors such as valley erosion apply.

Both Ben Our and Beinn Each have one unusually long and relatively continuous lineament running diagonally across the terrain in a north-east orientation. These are not parallel with the Loch Tay Fault, but may be with the strike of the foliation surface or a major joint-set (no geotechnical survey has yet been conducted) and do correspond to secondary fault orientation. They are expressed as antiscarps for much of their lengths. One hypothesis worthy of exploration is that initial ruptures occurred along these lineaments, which may roughly parallel the regional ice contours at their steepest. These ruptures would not necessarily involve high-magnitude seismic shocks, nor occur at the same time. They would trigger, or co-incide with, delamination of the surface to a depth of tens of metres, along another joint or quasi-bedding plane, or along a more irregular self-creating surface. The failed layer would fracture into slices or plates depending on terrain and geology, and would be freed to resettle in such a way as to minimize residual rock-mass stresses. Here, they have not developed into translational slides, but have progressed by creep and subsidence. As a result, surface water is channelled along the main fractures to emerge in springs.

A similar interpretation has been developed for the An Sornach rock slope failure in Glen Affric (Jarman, 2003c), which was previously advanced as neotectonically triggered (Fenton, 1991). Other small clusters of significant slope failures in apparently marginal, lower-erosion locations, which might be accounted for by regional glacio-isostatic rebound gradients, include Loch Striven and Glen Shira (see Jarman, 2003a), Strathfarrar (see Jarman and Reid, 2003), and west Knoydart.

The landshaping effects of these rock slope failures are relatively subtle. Despite its low profile, Ben Our is still the bulkiest of the promontories encircling the head of Loch Earn. Removal of all of the failed material would lower the whole hill by possibly as much as a hundred metres; alternatively, removal of the material below the ragged tear would widen the glen and accentuate the promontory for an interim period, as on the Sgiath a' Chaise ridge opposite. The Beinn Each rock slope failure is similarly tending to isolate the resistant summit core, which may originally have been an extended shoulder of Stuc a' Chroin rather than a separate peak; it is also helping to enlarge the Ample–Lubnaig breach.

Conclusions

Glen Ample is of considerable interest for its anomalously high density of rock slope failure, in a relatively isolated and low-relief location. Ben Our is one of the three largest rock slope failures in the Highlands, and its extensive platy deformation is unique in Britain. It is unusual and instructive in being located on a valley junction corner, exposing the hill to slope stresses in several directions. Beinn Each has a remarkably bold and intricate antiscarp array, on intersecting alignments, in marked contrast with the parallel array on **Beinn Fhada** and the filigree lattice on **Benvane**. Both Ben Our and Beinn Each clearly exhibit slope deformation with only limited progression into downslope separation. Their extraordinary expression, extent, and enigmatic origins have attracted international attention. This is a locality where it is worth investigating whether neotectonic seismic movements have acted as a trigger for rock slope failure, but even then they may be no more than ancillary. Other hypotheses such as differential (glacio-)isostatic rebound stresses are necessarily more speculative, but the sites are ripe for detailed geotechnical examination. The cluster offers great scope for exploring the fundamental causes and spatial distribution of rock slope failure in glaciated ancient mountain areas.

THE COBBLER (BEINN ARTAIR), ARGYLL AND BUTE (NN 260 058)

D. Jarman

Introduction

The Cobbler is a distinctive triple peak in the Arrochar Alps, in the South-west Highlands of Scotland. It is the most striking case in Britain of a mountain shaped by rock slope failure. Although limited failure has been recorded here its full extent and topographical impact has only recently been recognized (Jarman, 2004b). The main slope failure extends over the whole upper south flank of the mountain, and its source arête includes the Summit 'tor' and the spectacular horn of the South Peak. The North Peak is deeply fissured and overhanging, with indications of previous failure below. The well-known profile of three peaks closely grouped around a small corrie is therefore attributable to pervasive paraglacial rock slope failure (Figure 2.46).

The Cobbler is at the heart of the largest rock slope failure cluster in the Scottish Highlands (Figures 2.13 and 2.15). Several different modes of failure are evident on The Cobbler, ranging from in-situ fracturing through coherent translational slides with varying degrees of arrestment to a fully disintegrated rockslide. These kinds of rock slope failure are widely distributed in the 'old hard rock' uplands of Britain, and those on The Cobbler are particularly characteristic of the massive schists of the Arrochar Alps–Cowal area (Clough, 1897).

Description

There are four distinct zones of rock slope failure on The Cobbler, affecting 0.84 km^2 or 10% of the area of the mountain (22% of the area above 500 m OD), a remarkable intensity (Figure 2.47).

The main rock slope failure on the south face of The Cobbler is one of the 50 largest in the Scottish Highlands at 0.62 km^2, and is a translational slide complex in various stages of disintegration and arrestment. The 1901 geological map marks 'landslip' across the slope, but the current inset map only indicates two small slips. Holmes (1984) identified only the west part (0.20 km^2) from aerial photographs. The slide has four components or 'panels' over its 1200 m width, which emerge onto a broad midslope bench or 'alp' at 450–600 m OD (Figures 2.48 and 2.49).

Panel 1 (westmost) has the appearance of a chaotic pile of blocks several metres across. Its flank rampart is 5–15 m high, while its exceptionally steep (40°) toe rampart – which barely reaches the 'alp' – is at least 30 m high, suggesting the order of depth of the failed debris. However, the extent of disintegration is deceptive: the upper half is semi-intact, with only local fissuring, blocky dislocation, and short antiscarps in a grassy sheepwalk. The steeper lower half is extensively disrupted, but the aerial photograph shows organization into quasi-antiscarps, which are up to 6 m high and 150 m long. The antiscarps are much broken up, and appear to have emerged by forward rotation of contour-parallel rock slices on a convex slope. This indicates a considerable degree of coherence, given that the failed mass has spread fanwise from an 8 m-wide and 8 m-deep tension trench along the ridge west of the summit.

Panel 2 is separated from Panel 1 by an open gully on the general alignment of the NNE–SSW faults common in this area. The failed mass has descended appreciably further, despite appearing less disrupted, apart from some very large masses that protrude irregularly. One frac-

Figure 2.46 The distinctive profile of The Cobbler from the ESE, with the main rock slope failure on its left flank and a small rockslide into the breach col on the right. Both North Peak and South Peak may be the remnants of former corrie arms truncated by rock slope failure. The wide skyline nick may also result from a headwall collapse, but only small debris-lobes remain in the corrie. (Photo: D. Jarman.)

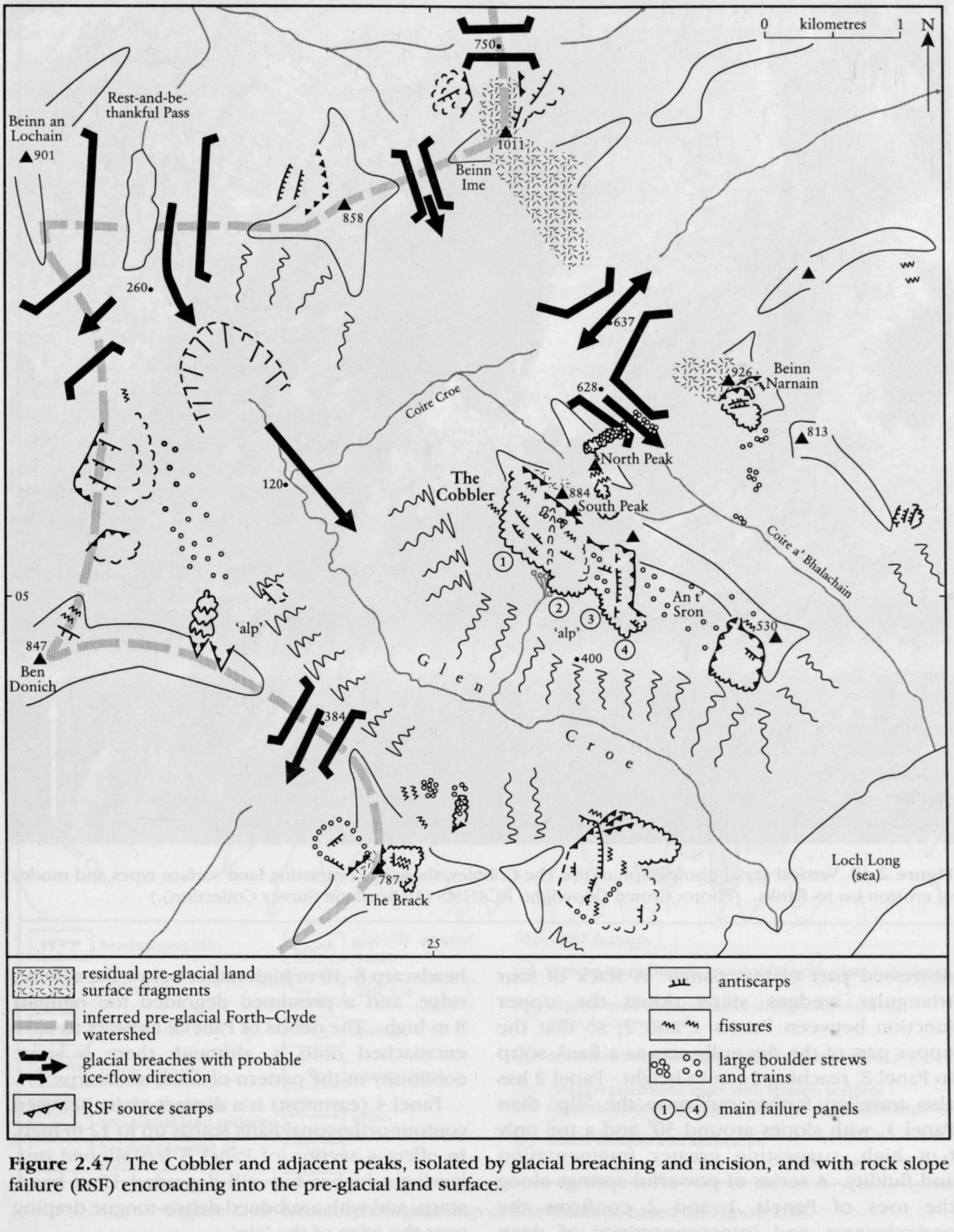


Figure 2.47 The Cobbler and adjacent peaks, isolated by glacial breaching and incision, and with rock slope failure (RSF) encroaching into the pre-glacial land surface.

tured slice on the west side is 25 m long and 8 m deep, and projects by 6–10 m. To the east, these protrusions resemble intact bedrock, but occasional deep fissures and basal springs confirm that most if not all are failed. Unlike Panel 1, a high but irregular headscarp is present, reaching 28 m west of the summit, and 12 m at the arête south-east of the summit above a tract of impenetrably jumbled megablocks, while the South Peak presents a 60 m rockface to the least

Figure 2.48 Vertical aerial photograph of the The Cobbler, showing contrasting land surface types and modes of erosion on its flanks. (Photo: Crown Copyright: RCAHMS (All Scotland Survey Collection).)

distressed part of this panel. A stack of four triangular wedges steps down the upper junction between Panels 1 and 2, so that the upper part of the dry gully acts as a flank scarp to Panel 2, reaching 14 m in height. Panel 2 has also travelled farther out onto the 'alp' than Panel 1, with slopes around 30° and a toe only 6 m high, suggesting greater fragmentation and fluidity. A series of powerful springs along the toes of Panels 1 and 2 confirms the pervasiveness and interconnectivity of deep fracturing.

Panel 3 by contrast is grassy and fully consolidated, with a probably thinner failed mass only betrayed by decimetre-scale furrow swarms and a small array of < 1 m antiscarps. It has a weak headscarp 8–10 m high rather below the summit ridge, and a presumed degraded toe rampart 8 m high. The debris of Panel 2 appears to have encroached onto it, although there is some continuity in the pattern of small antiscarps.

Panel 4 (eastmost) is a distinct cavity between contour-orthogonal flank scarps up to 12 m high. In effect a section of Panel 3 has slipped out, leaving a higher but still degraded 15 m headscarp, and with a subdued debris-tongue draping over the edge of the 'alp'.

The boundaries of the main rock slope failure are clearly defined, by comparison with many that have diffuse margins. The head and east flank scarps are almost continuous, and there is no spray fan below the toe ramparts. There is no

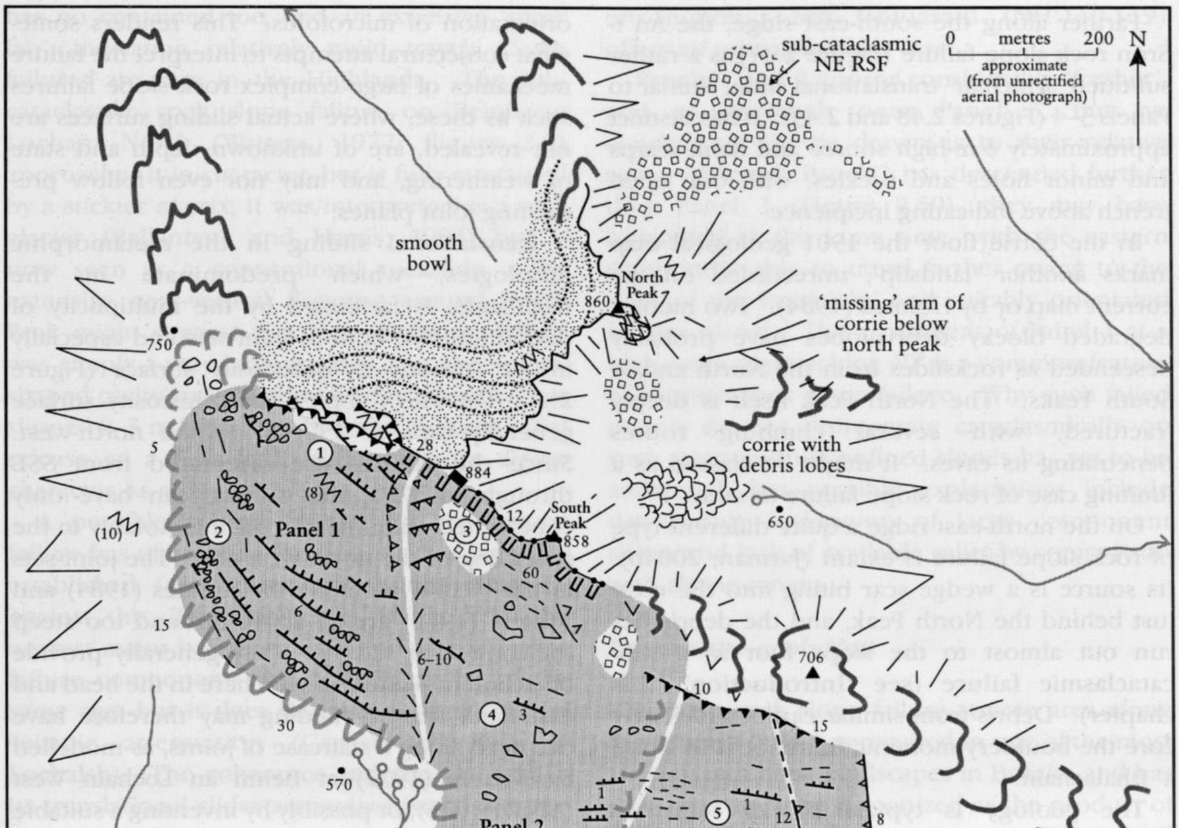


Figure 2.49 Geomorphological map of The Cobbler, based on Figure 2.48.

west flank scarp, unusually, since the outer end of the summit ridge has collapsed laterally. It is impossible to give an accurate volume for this rock slope failure, in view of its short travel and unknown failure surface, but applying conservative estimates for average depths of 20/15/5/10 m to the four panels yields an order of magnitude of 8–10 × 10^6 m^3.

Farther along the south-east ridge, the An t-Sron rock slope failure (Figure 2.47) is a rather subdued 'armchair' translational slide, similar to Panels 3–4 (Figures 2.48 and 2.49). It has distinct approximately 6 m-high source and flank scarps and minor holes and ruckles, with one open trench above indicating incipience.

In the corrie floor the 1901 geological map marks another 'landslip', unrecorded on the current map or by Holmes (1984). Two modest degraded blocky debris-lobes have probably descended as rockslides from the North and/or South Peaks. The North Peak itself is deeply fractured, with several climbing routes penetrating its caves. It might be classed as a limiting case of rock slope failure *in situ*.

On the north-east ridge a quite different type of rock slope failure is extant (Jarman, 2004b). Its source is a wedge scar biting into the crest just behind the North Peak, and the debris has run out almost to the slope foot as a sub-cataclasmic failure (see 'Introduction', this chapter). Debris from similar earlier slides may core the bouldery morainic hummocks in Coire a' Bhalachain.

The geology is typical blocky schistose arenite, semipelite and pelite of the Beinn Bheula Schist Formation within the Dalradian Supergroup (late Precambrian–early Cambrian). This unit is laterally equivalent to the Ben Ledi Grit Formation but has a greater proportion of pelite and semipelite, and was metamorphosed under upper greenschist facies conditions. The regional bedding and foliation vary from sub-horizontal to moderately north-west dipping (J. Mendum, British Geological Survey, pers. comm.).

Interpretation

The prevalent mode of rock slope failure in the Dalradian schists of the Southern Highlands is the short-travel arrested translational slide (Jarman, 2003a). On The Cobbler, the main and An t-Sron failures fall within this category. A geotechnical analysis of The Cobbler is not available, but Watters (1972) and Holmes (1984) back-analysed 14 rock slope failures in the Beinn Bheula Schist Formation in this area. They found peak friction angles ranging from 34°–50° and residual friction angles around 24°, increased by *i* values typically of 1°–5°, depending on coarseness of asperities and orientation of microfolds. This renders somewhat conjectural attempts to interpret the failure mechanics of large complex rock slope failures such as these, where actual sliding surfaces are not revealed, are of unknown depth and state of weathering, and may not even follow pre-existing joint planes.

Translational sliding in the metamorphic lithologies, which predominate in the Highlands, is facilitated by the multiplicity of discontinuities, both in joint-sets and especially in the foliation or schistosity surface (Figure 2.4). On The Cobbler, the schistosity surface generally dips at 25°–40° to the north-west. Since the failures are orientated from SSE through to WSW, this surface can have only contributed marginally to sliding, notably in the spreading of the north-west end. The joint-sets in this vicinity identified by Holmes (1984) and Watters (1972) are all above 50° and too steep for controlled sliding. They generally provide detachment planes, as seen here in the head and east flank scarps. Sliding may therefore have occurred along a staircase of joints, as modelled by Watters (1972) at Beinn an Lochain West (NN 215 076), or possibly by inventing a suitable plane where none pre-existed, as a series of small shear facets (Jarman, 2003c).

Holmes (1984) and Watters (1972) concluded that the translational slides in this area probably required a small additional force augmenting gravity in order to trigger shearing failure. Watters identified a toppling component (de Freitas and Watters, 1973), and both invoked elevated cleft water pressures; chemical weathering of abundant chlorite and muscovite may also have played a role in lubricating slide surfaces. Separation of large rock units by low-angle block gliding is common in this area, notably at Ben Donich (NN 22 05), Carnach Mor (NS 13 99), Hell's Glen (NN 18 05), and The Steeple (NN 20 00), and may account for the tensional spreading seen at The Cobbler (Panels 1–2, Figures 2.48 and 2.49). However, the source area is almost certainly above the Loch Lomond Stadial limit which Holmes (1984) identified as the likely locale of abundant meltwater to pressurise clefts, the Arrochar peaks having formed nunataks at this stage (cf. 'Introduction', this chapter).

The north-east rock slope failure is sub-cataclasmic in having fully disintegrated but not travelled bodily to the slope foot or beyond. It has no contained toe, and an extensive 'spray fan', indicating relatively rapid travel. Such failures are rare in the Highlands. The sub-cataclasmic rock slope failure on Beinn an Lochain North (Watters, 1972; Figure 2.9) approaches it in character, but is fully contained by a stickier matrix; it was interpreted as a rock glacier (Ballantyne and Harris, 1994) but is now seen as a conventional rockslide. The extensive near-vertical fissuring around North Peak might suggest that this north-east failure was simply a very large rockfall, but the wedge-shaped cavity and a retained cubic mass that has slipped 2–3 m from the rim could indicate initial release as a high-angle slide of more alpine character, as at **Beinn Alligin**.

A possible seismic trigger for rock slope failure has often been invoked but has yet to be established (see 'Introduction', this chapter). Against this, The Cobbler is 10 km from the nearest major basement fault and its rock slope failure components are unlikely to be of the same age, but it does lie on a current zone of seismic attenuation (Carlisle to Kyle of Lochalsh). The coherence and containment of its translational slides are suggestive of progressive creep. However, an unusually large fissure 75 m long and 10 m deep just beyond the toe of Panel 1 (NN 255 056) has affinities with tear or impact fractures beside large failures in Scandinavia (cf. Dawson *et al.*, 1986; Jarman, 2002).

No dates are available for The Cobbler rock slope failures. It is most probable that the translational failures here developed soon after final deglaciation, but since they extend to the summit, they owe their inception to the much greater stresses induced by the Late Devensian glaciation. In the main rock slope failure, Panels 3 and 4 are subdued, with degraded source and toe areas, and may be earlier than Panels 1 and 2; they may even be the rump of similar events since removed by glaciers, and here resemble the two-tier rock slope failure at Beinn an Lochain West (Watters, 1972; cf. Beinn Each (**Glen Ample**)). Erratic boulders are strewn over the upper parts of Panels 3 and 4 and across much of the upper south-east ridge (Figure 2.47) and may be ice transported following earlier rock slope failure episodes, as they occur up to 600 m OD, rather above the toe of Panels 1 and 2 (Figure 2.49). Boulder trains from probable failure sources are surprisingly uncommon: Carn Ghluasaid (NH 140 119) offers an unusually clear case

Panels 1 and 2 appear considerably 'fresher', and to encroach onto Panel 3, but no conclusions can be drawn as to their relative ages. Although Panel 2 has descended further than Panel 1 (Figure 2.50), they may have originated at the same time, with the eastern component able to travel farther owing to the slant of the basal 'alp' and suitably orientated release planes. The arrestment of Panel 1 at a high angle approaching 40° is a common feature of Scottish rock slope failure. Why such failed masses do not disintegrate cataclasmically on such steep and unconfined slopes has yet to be addressed, but possible explanations include dewatering, locking-up of large component slices, and lack of available relief by comparison with alpine ranges.

Landscape evolution

The main rock slope failure source area along the summit ridge has resulted in one of the most striking mountain landscapes in Britain, and has only recently been recognized as the product of paraglacial failure intersecting a corrie headwall (Jarman, 2004b). Prior to failure, the corrie rim would have cut into a level or gently south-west dipping smooth ridge, as it still does between the Summit and North Peak. This can be demonstrated if the flatter elements of the upper rock slope failure are re-instated to their source scarps. The exceptional rock tower of the South Peak may have been exaggerated by a small wedge slide yielding a blocky debris-pile a short way to the south-east. The North Peak may also have been reduced to a fractured stump by failure of a former north-east arm to the corrie during earlier interglacials: the prominent schistosity surfaces dip back into the corrie at angles (20°–30°) highly conducive to sliding and toppling.

The shaping of mountain summits by rock slope failure into arêtes and horns is also seen in this area at Ben Lomond and Beinn an Lochain (Figure 2.9). It is attributable to failure planes daylighting behind the crest, leaving a sharp edge that has not suffered rounding by glacial over-riding or periglacial weathering, as have most summit ridges in the schists.

If the west summit ridge of The Cobbler is re-assembled to pre-rock slope failure condition, a small fragment (approximately 0.05 km^2) of pre-

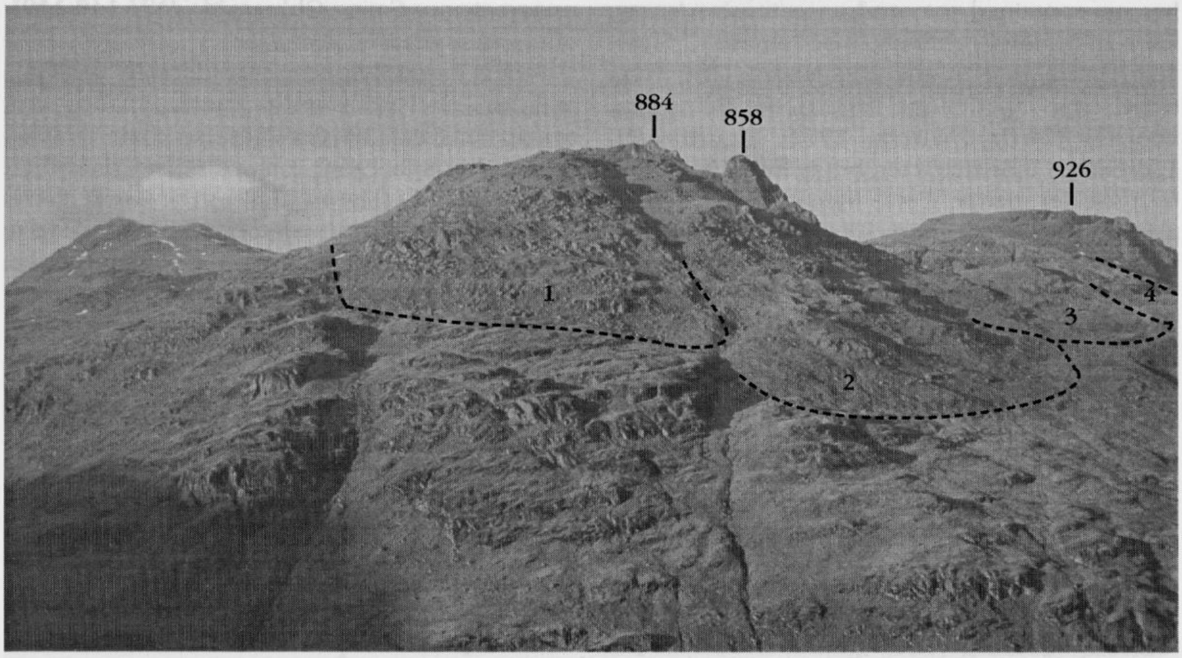


Figure 2.50 The main rock slope failure complex seen from the south-west across Glen Croe, showing the panels mapped in Figure 2.49. Panel 2 (on the right) has travelled further than Panel 1 to expose the arête culminating in the South Peak (Point 858). The level pre-glacial summit surface of Beinn Narnain (Point 926, right background) suggests the character of The Cobbler before it underwent more intense paraglacial rock slope failure. The summit tor (Point 884) stands out from the vestigial pre-glacial skyline. (Photo: D. Jarman.)

glacial upland surface can be identified. Behind the main headscarp and ridge-splitting trench, a small (< 2 m) dogleg depression and fissures indicate incipient extension of the rock slope failure by up to 25 m into the residual pre-glacial surface. The remarkable summit 'tor' may be a corestone left from stripping of a deep-weathering regolith (cf. Hall, 1991). The next peak to the east, Beinn Narnain, has a more extensive plateau surface of approximately 0.5 km^2 (Figures 2.47 and 2.50), and likewise has lost a quadrant of it to failure, leaving a projecting fractured arête. Other surrounding peaks show similar traces of an undulating pre-glacial upland surface, and encroaching rock slope failures.

In the core mountain area of 87 km^2 around The Cobbler, 7% of the total land surface is affected by rock slope failure, one of the highest densities so far identified in Scotland (Table 2.2); the figure could in fact be higher with many small failures. This rises to 10% for The Cobbler itself, to its bounding waters. This concentration lies within the largest cluster of rock slope failures in Scotland, with over 100 significant (> 0.02 km^2) cases in 500 km^2 west of Loch Lomond. No reasons were advanced for the existence of this cluster by Holmes (1984), nor following its publication by Ballantyne (1986a). Explanations related to Loch Lomond Stadial limits or high-magnitude seismic shocks are inadequate, although suitably inclined foliation and bedding, and the style of metamorphic grade, increase the incidence of rock slope failure (see 'Introduction', this chapter).

The tentative association between rock slope failure incidence and glacial breaches of possibly recent origin or active enlargement can be investigated here (Jarman, 2003a), if less straightforwardly than in the Kintail cluster (see **Sgurr na Ciste Duibhe**). The Arrochar Alps and surrounding hills are intensely dissected to such a degree that most are isolated, and few high-level linking ridges survive (Haynes, 1977a). This reflects their location at the junction of the catchments of the Clyde estuary, Loch Fyne, and the River Forth prior to its beheading by the cutting of Loch Lomond (Linton and Moisley, 1960) (Figure 2.13). These pre-glacial radiating valley systems have been over-run by ice centred at various times to the west, east, and particularly north of the triple watersheds, although probably not from as far as the Rannoch Moor ice centre, as suggested by Linton (1957) and Boulton *et al.* (1991). As a result, almost all of the peaks in this area are separated by glacially breached cols, some relatively narrow or deep.

The Cobbler is isolated by high-level breaches at 630 m OD and by the deep trough of Glen Croe, which descends from the Rest-and-be-thankful Pass (260 m OD) to sea level at Loch Long (Figures 2.15 and 2.47). Linton and Moisley (1960) show Glen Croe as a probable breach of the main pre-glacial Clyde–Forth watershed; it has certainly been incised in response to over-deepening of the Loch Long fjord. However, while the sub-cataclasmic north-east rock slope failure is directly above the breach into Coire a' Bhalachain, the main and An t-Sron failures are separated from the Glen Croe trough by an 'alp'. If recent breaching through the Rest-and-be-thankful Pass from the north has created high, local, slope stresses, then the rock slope failure incidence might suggest this has been more by widening at upper levels than by trough deepening. A similar incidence at higher levels is found on Ben Donich and The Brack opposite (Figure 2.47); this is not always the case, as rock slope failure is concentrated at lower levels along Loch Long and in Glen Kinglas, and extends from crest to foot of the deep Loch Sloy breach (Figure 2.15).

Conclusions

The Cobbler clearly demonstrates the effects of large-scale rock slope failure in creating mountain landforms such as arêtes and horns. The contribution of paraglacial slope failure to bulk erosion, valley widening, dissection of mountain massifs, and progressive elimination of ridges and summit areas has been given little consideration, but in susceptible areas its cumulative impact over the Quaternary Period is likely to be very considerable. The Cobbler and the surrounding Arrochar Alps and Cowal hills provide an important opportunity to understand this process, and to seek to quantify and date it. Containing the densest large cluster of rock slope failures in Scotland, they provide an exceptional locus for research into its causes and its possible significance as an indicator of shifting ice centres and dispersal patterns. Relicts of the pre-glacial land surface on The Cobbler and its neighbours provide scope for landscape reconstruction, in one of the upland areas of Britain most intensely dissected by glacial breaching.

The Cobbler itself has a variety of types of rock slope failure representative of the Dalradian rocks of the South-west Highlands. As one of the best-known and most idiosyncratically shaped mountains in Britain, in a conspicuous and accessible location in the Loch Lomond and The Trossachs National Park, The Cobbler is also well suited for research into geomorphological education, for geotourism, and for widening public awareness of landscape origins.

BEN HEE, HIGHLAND (NC 430 343)

D. Jarman and S. Lukas

Introduction

Ben Hee provides one of the best examples in Britain of Holocene rock slope failure activity within a corrie, and is one of the largest such cases. It also clearly represents the arrested translational slide mode of failure which predominates in the Scottish mountains. The failure complex has several components of rock slope failure arrested at different stages of development, which suggest progression of activity both downslope and laterally along the corrie headwall. Unusually extensive deposits in the corrie floor below may represent material reworked from failure in a previous interglacial period. The concept of rock slope failure as a major factor in glacial/paraglacial erosion over repeated cycles is in its infancy (Evans, 1997; Ballantyne, 2002a; Jarman, 2002), and Ben Hee offers a testbed for research into its scale and mode of operation.

The rock slope failure has encroached substantially into the headwall of the corrie, and further activity will lead to breaching into the adjacent corrie and dissection of the mountain block. Viewed in conjunction with neighbouring slope failures, Ben Hee affords an excellent illustration of the role of large-scale mass movement in initiating, enlarging, and then eliminating corrie-type landforms.

Description

Ben Hee (873 m) is a large mountain in northern Scotland separated from the Reay Forest massif by a glacial breach, and standing above the glacially modelled Caithness–Sutherland intermediate surface (Figure 2.51). An Gorm-choire is a large corrie that has operated, latterly at least, as a true glacial 'cirque', its sub-parallel sides reflecting structural controls rather than evolution as a glacial trough head. The corrie is approximately 1 km wide and 2 km long, and faces ESE. Its south flank is a 200 m-high crag, its north flank is a gullied and embayed scree-slope, and below its low headwall (2–15 m high) is a large landslip complex (Figure 2.52). This has three components laterally, unified by a continuous source trench that splits the smooth, broad ridge between the two summits. At the south corner, a small shallow wedge has dropped in several slices by 6 m, and encroaches into the broad ridge by 30 m; below it, a small disintegrated debris-mass clings to the headwall. At the north end, a similar small segment lowers the skyline by virtue of daylighting behind the crest, leaving a 5 m-deep hollow. The flanking rock buttress is crazed with tension fractures, and coarse, unstable, rockfall deposits below may have formed relatively recently.

In between, the main failed mass itself has three distinct tiers (1, 2 and 3 on Figure 2.52) below an obtuse wedge source. This fracture

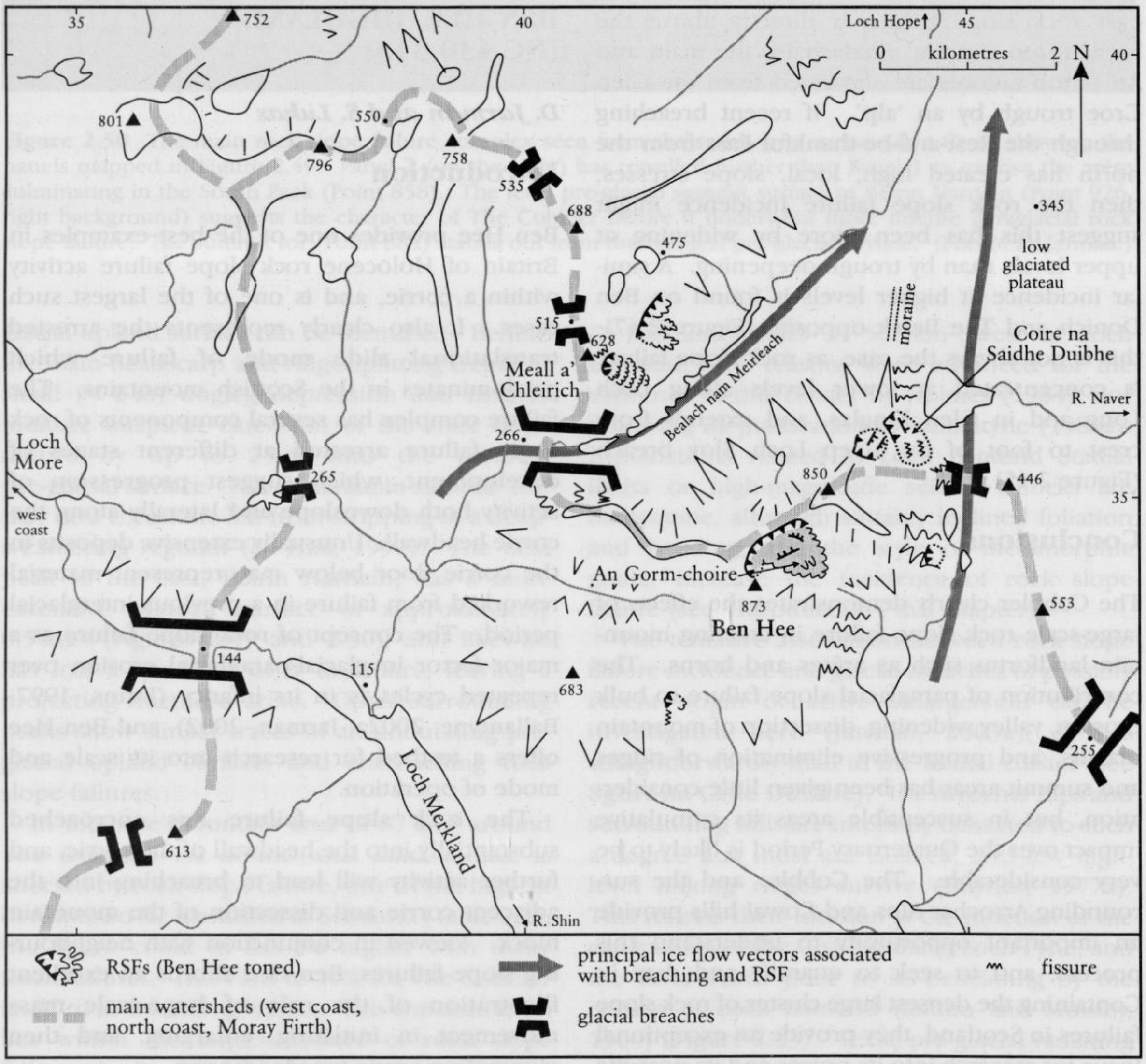


Figure 2.51 The Ben Hee rock slope failure (RSF) cluster, with glacial breaches and related ice movements.

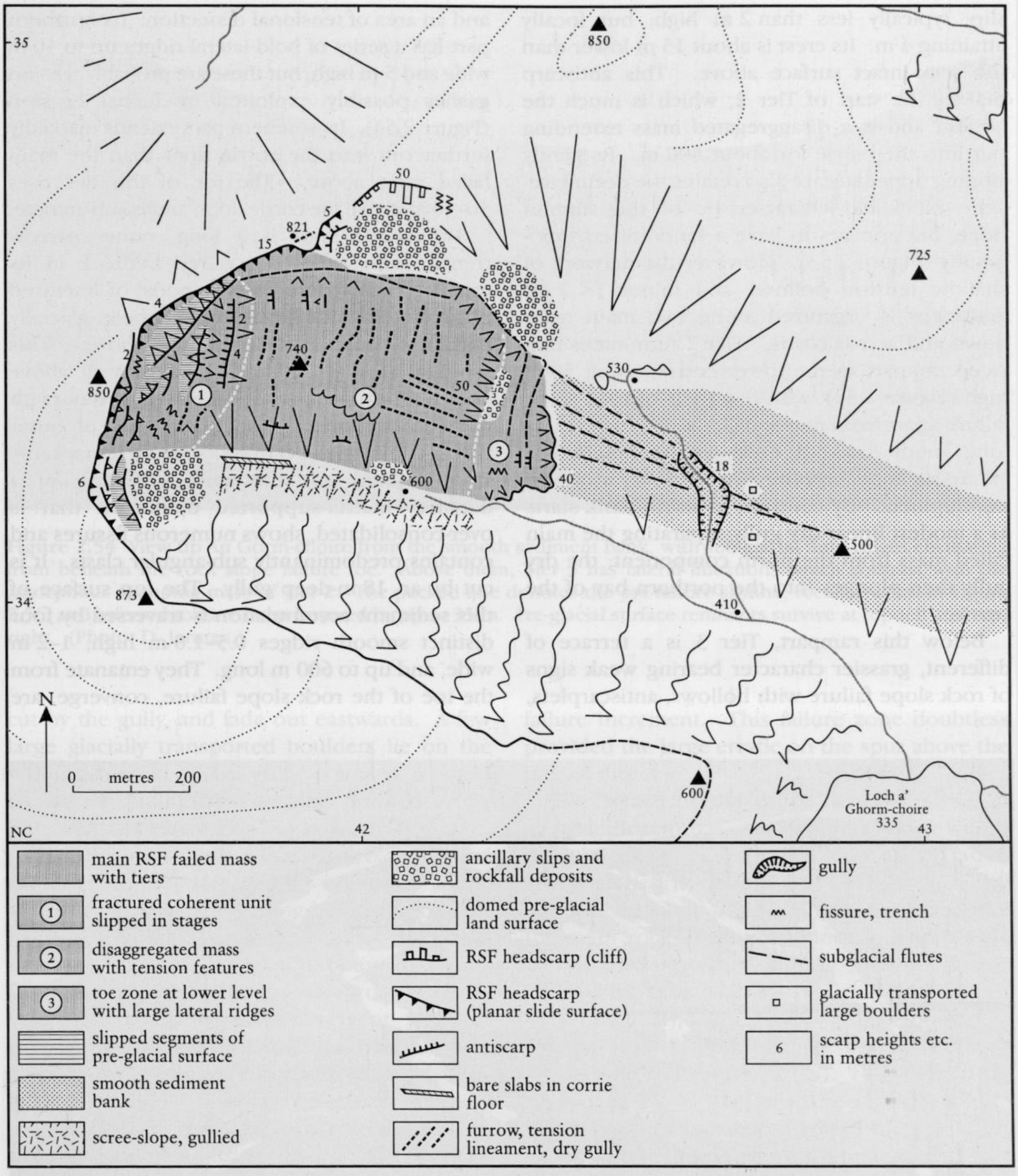


Figure 2.52 Geomorphology of the Ben Hee rock slope failure (RSF) in An Gorm-choire. The encroachment into the undulating pre-glacial surface is considerably greater than the extent of the 'slipped segments'.

begins at the upper (south) end as narrow 1–2 m-deep trenches, becoming a low angle (20°–25°) headscarp which attains 15 m in height at its north end in the col. In the obtuse angle, Tier 1 is a semi-intact slice of summit ridge 200 m long by 50 m wide, which has dropped by 2–4 m; its outer parts have broken away and slipped a little further, forming minor antiscarps. Periglacial blockfields cover its surface and are identical to those found on the summit ridge.

Below this uppermost sector of recognizable provenance, the one major antiscarp of the rock slope failure crosses the full width of the main slip, typically less than 2 m high, but locally attaining 4 m. Its crest is about 15 m lower than the semi-intact surface above. This antiscarp defines the start of Tier 2, which is much the largest, and is a disaggregated mass extending out into the corrie for about 400 m. Its gently sloping upper surface also retains the decimetre-scale blockfield characteristic of the summit ridge, but appears to have a randomized topography (Figure 2.53). However the network of shallow tension hollows and minor (< 2 m) antiscarps is organized along two main axes, down and across corrie. Tier 2 terminates in a steep rampart to the lower corrie, about 50 m high (Figure 2.54), with few signs of rock slope failure apart from minor blockfalls. However its long south flank of even greater height has extensive side-slipping with some antiscarp development. By contrast, its north flank starts as a modest linear dry gully separating the main failed mass from the north component; the dry gully then plunges into the northern bay of the corrie.

Below this rampart, Tier 3 is a terrace of different, grassier character bearing weak signs of rock slope failure with hollows, antiscarplets, and an area of tensional dissection. Its northern part has a series of bold lateral ridges up to 10 m wide and 5 m high, but these are probably tension gashes possibly exploited by fluvial erosion (Figure 2.54). Its southern part extends markedly further out into the corrie floor than the main failed mass above. The toe of this tier rises 30–40 m above the corrie floor, and is sub-arcuate.

The corrie floor is a long, rather narrow trench, with exposed scoured bedrock in its middle reach. Here several 'pods' of fractured but coherent rock have probably been glacially entrained from a rockstep just above. This scoured area at 500 m OD hangs well above Loch a' Ghorm-choire at 330 m, which is outwith the corrie proper. The north side of outer Gorm-choire is occupied by a remarkably smooth bank of sediment consisting of a massive, matrix-supported diamicton that is over-consolidated, shows numerous fissures and contains predominantly sub-angular clasts. It is cut by an 18 m-deep gully. The top surface of this sediment accumulation is traversed by four distinct smooth ridges 0.5–1.0 m high, 1–2 m wide, and up to 600 m long. They emanate from the toe of the rock slope failure, converge, are

Figure 2.53 View across Tiers 1 and 2 of the main failed mass, and both flanking increments, from the north rim to the summit of Ben Hee. The reconstructed pre-deglaciation crest follows the axis of the picture, whereas the pre-Quaternary crest probably curved more to the left between gentle domes. (Photo: D. Jarman.)

Figure 2.54 View up An Gorm-choire from the smooth sediment bank, with sub-glacial flute ridges emanating from beneath the rock slope failure toe. Above them, Tier 3 has lateral lineations which contrast with the amorphous slumping mass of Tier 2. The pecked line denotes the pre-failure skyline, reconstructed in Figure 2.56, and inferred to have been lowered by up to 35 m. Pre-glacial surface remnants survive at top-left and top-right. (Photo: D. Jarman.)

cut by the gully, and fade out eastwards. A few large glacially transported boulders lie on the sediment bank. The gully contains a small stream emanating from lochans ponded up by this bank in a broad side bay of Gorm-choire.

To the north of Gorm-choire, a broad shoulder of Ben Hee throws out three spurs, which, with their intervening bays, are abruptly truncated on the east by steep cliffs. The northmost spur spawns a medial moraine indicating Devensian ice movement northwards along the east flank of Ben Hee, convergent with ice coming through the breach of Bealach nam Meirleach. Along the truncated east side, the cliffs are deeply fissured, with local toppling failures (Figure 2.51). Coire na Saidhe Duibhe has a remarkable midslope in-dipping open cleft approximately 250 m long and up to 10 m wide and 15 m deep. This heads a zone of fissuring and grabening with some toppling debris. The south flank of the bay is a 20 m crag heading an apparent rock slope failure cavity, with incipient fissuring. Above the great cleft, the slope is stable until a degraded short-travel debris-mass encroaches from a possible 40 m source scarp, which continues down the north-east ridge as a weak lineament defining a further large slope failure increment. This failure zone doubtless provided the large erratic on the spur above the medial moraine.

The breach north-west of Ben Hee (Bealach nam Meirleach) has a striking rock slope failure complex on its opposite flank. Torn vegetation and fresh debris indicate that creep and rockfall are still unusually active. Open fissures above the main rockslide suggest incipient encroachment into the residual summit plateau of Meall a' Chleirich (Figure 2.51).

Geologically, Ben Hee consists of Moine psammites with occasional pelitic schist bands (Johnstone and Mykura, 1989). The dip is rather regular, at 5°–15° to the east/ENE at An Gorm-choire, and a little steeper and to the south-east at the north end. Several prominent joint-sets are seen in the cliffs, and one inclined at about 25° may control the general slope to the ESE of the Ben Hee plateau.

The smoothness of the summit ridge, with shattered bedrock, 5–10 m deep, mantling most of it, suggests that it has not been vigorously glaciated (i.e. covered by active ice), and may even be a remnant of the pre-glacial land surface (cf. Hall, 1991). A periglacial trim-zone between 680 m and 750 m OD indicates the upper limit of the Late Devensian ice-sheet (Ballantyne *et al.*, 1998b). However, cold-based ice may have extended to higher levels, and also warm-based ice may have extended higher in earlier glaciations (Lukas, 2005).

Holmes (1984) records the main rock slope failure from aerial photographs as covering 0.36 km² (actually 0.40 km²), the east cliff slope failure as 0.04 km², and the north-east corrie bay as having three slope failures totalling 0.14 km² (actually 0.09 km² for the upper and 0.17 km² for the lower failure). He gives the Meall a' Chleirich rock slope failure as 0.15 km² whereas it is part of a complex extending for over a kilometre and affecting approximately 0.5 km².

Interpretation

The main Ben Hee rock slope failure was first described by officers of the British Geological Survey (unpublished field slips, 1913–1926) as 'possibly not truly *in situ* but a whole crag slipped'. They noted 'scree has slipped away from the corrie edge in parallel ridges (leaving) a gully behind it'. Godard (1965) mis-interpreted these features as moraines, his Photo 17 showing the neat narrow ridge where the headscarp intersects the north corrie as a '*bourrelet morainique laissé par un petit glacier perché, tardiglaciaire*' (cf. Figure 2.55). Haynes (1977b) corrected this, and mapped the compound landslip with its two flank elements.

No geotechnical analysis has been made of Ben Hee. The simplest interpretation of its failure geometry invokes the joint-set dipping at 20°–25° south-east, which can be seen in the summit cliffs, and which forms the main head-scarp plane. A failure plane of approximately 18° is indicated by terrain reconstruction (Figure 2.56), and would just permit arrested translational sliding within the range of residual friction angles in the psammites (Watters, 1972). The tripartite scarp of the main failed mass (including the dry gully on its northern side) suggests an obtuse armchair-source configuration, with travel down the corrie axis plus

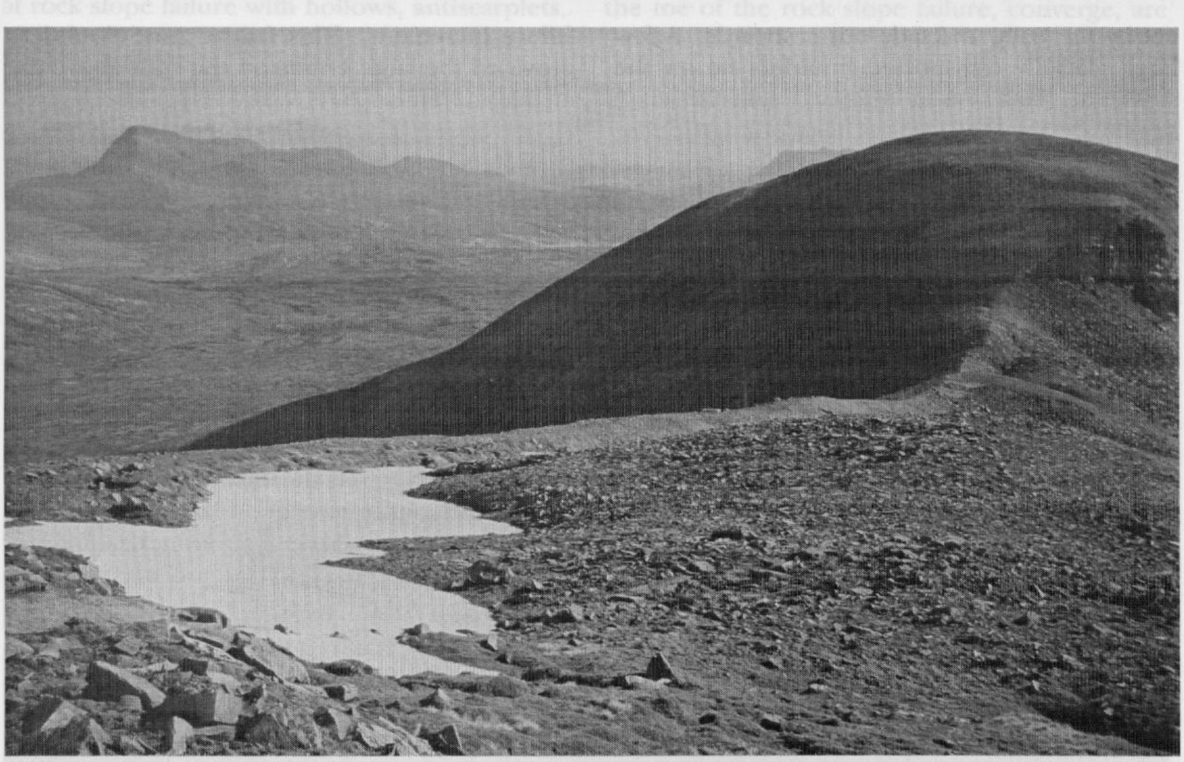


Figure 2.55 The source fracture for the main failed mass and north flank component, mis-interpreted by Godard (1965) as a glacial moraine. The slipped segment retains much of its pre-glacial character. (Photo: D. Jarman.)

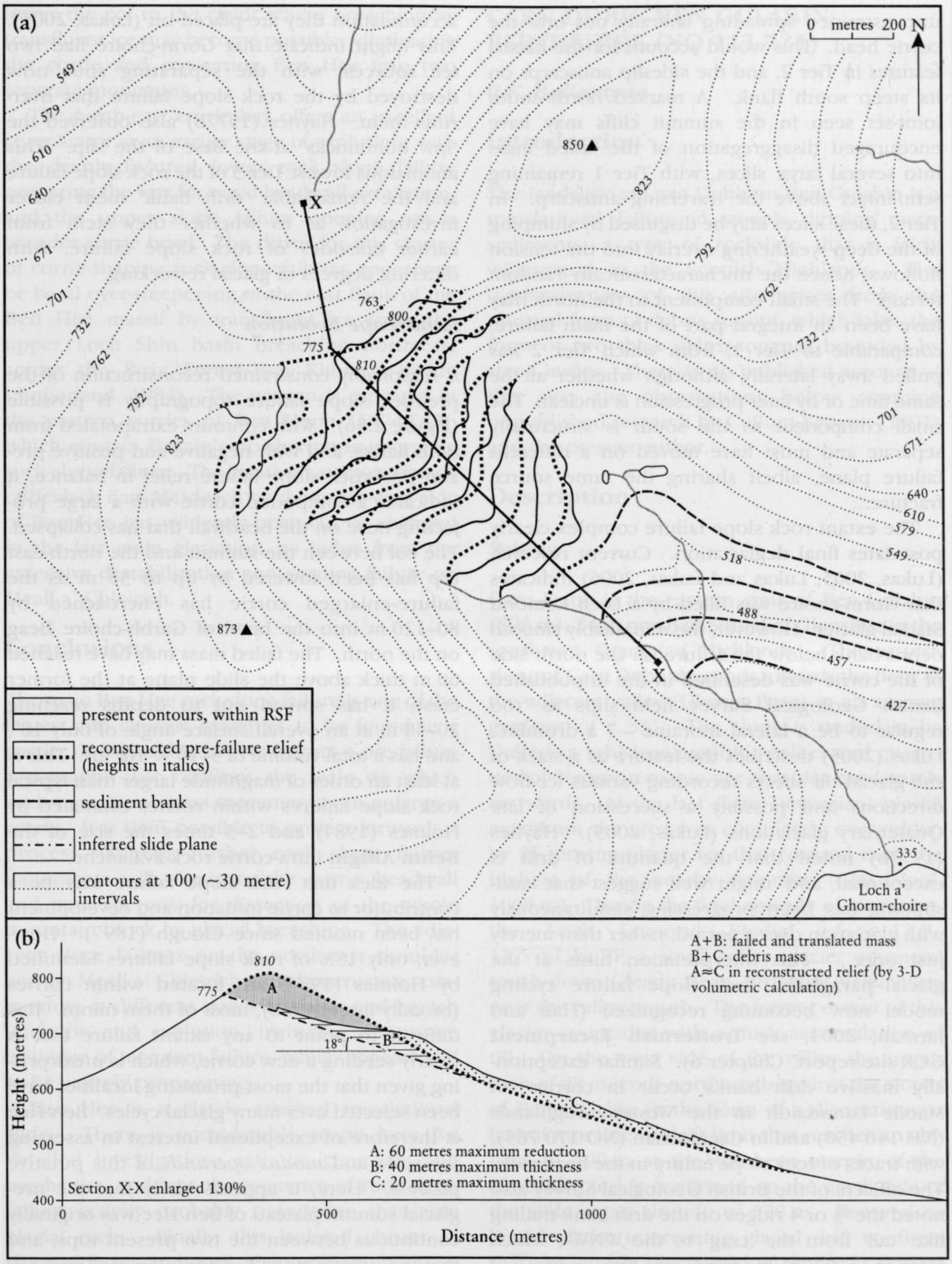


Figure 2.56 The reconstructed pre-failure topography of An Gorm-choire, with the long-section of the main rock slope failure showing reduction of the summit ridge by up to 35 m and the scale of mass displacement.

unconstrained spreading laterally out into the corrie head. This would account for the biaxial features in Tier 2, and the sideslip antiscarps on its steep south flank. A marked north–south joint-set seen in the summit cliffs may have encouraged disaggregation of the failed mass into several large slices, with Tier 1 remaining semi-intact above the traversing antiscarp. In Tier 2, these slices may be disguised by slumping of the deep weathering overlay into the tension hollows, hence the uncharacteristically random terrain. The small component to the north may have been an integral part of the main failure, comparable to Tier 1, from which Tier 2 has pulled away laterally, although whether at the same time or by later progression is unclear. The small component to the south is structurally separate and must have moved on a different failure plane, albeit sharing the same source fracture.

The extant rock slope failure complex clearly post-dates final deglaciation. Current research (Lukas, 2005; Lukas and Lukas, 2006) indicates that Gorm-choire was filled by a Loch Lomond Stadial glacier. However, the remarkably smooth debris-bank below the failure on the north side of the corrie was described in the unpublished British Geological Survey field slips as 'too regular to be a lateral moraine – ? a drumlin'. Lukas (2005) describes the feature as a stack of sub-glacial till sheets recording various ice-flow directions and possibly a succession of late Quaternary glaciations (Lukas, 2005). Haynes (1977b) noted that the quantity of drift is exceptional, and 'might well suggest that landslipping has been progressing simultaneously with glaciation over a period, rather than merely just once'. This interpretation hints at the glacial–paraglacial rock slope failure cycling model now becoming recognized (Hall and Jarman, 2004; see **Trotternish Escarpment** GCR site report, Chapter 6). Similar exceptionally massive drift banks occur in corries on Maoile Lunndaidh in the Western Highlands (NH 140 450) and in Caenlochan (NO 170 765), with traces of rock slope failure in the headwalls. The officers of the British Geological Survey also noted the '3 or 4 ridges on the drift bank trailing like 'tail' from the 'crag' to the WNW', which Haynes (1977b) mapped as five ridges of 'streamlined drift' (Figure 2.54). These are probably sub-glacial flutes, as they are parallel to the palaeo-ice-flow direction indicated by the fabric analyses taken from the sub-glacial till accumulation they are placed on (Lukas, 2005). This might indicate that Gorm-choire had two ice sources, with the separating spur now destroyed by the rock slope failure that overruns them. Haynes (1977b) also observed the 'low hummocks' at the base of the slip. This anomalous lowest Tier 3 of the rock slope failure and the remarkable 'drift bank' merit closer investigation as to whether they stem from earlier episodes of rock slope failure, with differing degrees of glacial reworking.

Landscape Evolution

A reasonably constrained reconstruction of the pre-rock slope failure topography is possible (Figure 2.56). With contours extrapolated from both flanks, and with negative and positive pre- and post-rock slope failure relief in balance, it indicates a compound corrie with a large projecting nose on the headwall that has collapsed. The col between the summit and the north-east top has been lowered by up to 35 m as the failure-enlarged corrie has encroached by 80–120 m into the bowl of Garbh-choire Beag on the north. The failed mass may have reached 60 m thick above the slide plane at the former crest; it has spread out to depths reaching 20–40 m at an overall surface angle of only 18°, and has a total volume of 5–10 × 10^6 m^3. This is at least an order of magnitude larger than typical rock slope failures within corries estimated by Holmes (1984) and 2–3 times the size of the **Beinn Alligin** intra-corrie rock-avalanche.

The idea that rock slope failure may be a contributor to corrie initiation and development has been mooted since Clough (1897). However, only 18% of rock slope failures identified by Holmes (1984) are located within corries (broadly interpreted), most of them minor. It is difficult to point to any extant failure that is clearly seeding a new corrie, which is unsurprising given that the most promising localities have been selected over many glacial cycles. Ben Hee is therefore of exceptional interest in assessing the scale and *modus operandi* of this putative process. Here, it appears likely that the pre-glacial summit plateau of Ben Hee was originally continuous between the two present tops, and that the linking ridge has been lowered and displaced to the north-west by vigorous headward extension of An Gorm-choire, aided by repeated episodes of paraglacial rock slope failure on the favourable structural dip. Further episodes will lower the col to the point where breaching by transfluent ice may become possible, eliminating the corrie and converting Ben Hee into two separate mountains.

The north-east corrie bay offers an excellent comparator at an earlier stage of evolution, with the deeply fissured lower rock slope failure preparing the way for rapid headwall excavation, and the upper slope failure opening out a broader corrie bowl. The driver for this cluster of corrie-shaping rock slope failures appears to be basal over-steepening of the east flank of the Ben Hee massif by transfluent ice from the upper Loch Shin basin breaching north-east across the Reay Forest–Ben Klibreck divide (Sutherland, 1984). The pattern is repeated in the eastern corries of Ben Hope (NC 48 49), which contain Britain's northernmost montane rock slope failure. The relatively narrow breach of Bealach nam Meirleach on the north-west side of Ben Hee has evidently been cut or enlarged in the last main glaciation, to judge from the extensive destabilization and ensuing failure on Meall a' Chleirich.

Conclusions

The main Ben Hee rock slope failure is one of the largest and clearest examples to be found in a corrie. It is possible to reconstruct a pre-failure topography that confirms the scale on which such paraglacial mass movements can enlarge a corrie. It is then possible to project forwards a process whereby further rock slope failure increments will eliminate the corrie headwall and pave the way for dissection of the whole mountain block by glacial breaching. The adjacent slope failures on the north-east shoulder and on Meall a' Chleirich afford instructive comparators at different stages of corrie and breach initiation and evolution, including impressive evidence of incipient failure, which appears still to be actively propagating.

Ben Hee is a classic arrested translational slide. There is considerable scope here for detailed investigations into its geometry and mechanics, and into the sequence of rock slope failure activity probably over more than one glacial cycle. Finally, this isolated cluster of slope failures indicates that erosion both by corrie glaciers and by transfluent ice breaching has been sufficiently intense in Late Devensian times to destabilize mountain slopes even in the far north of Scotland.

CARN DUBH, BEN GULABIN, PERTHSHIRE (NO 113 721)

C.K. Ballantyne

Introduction

The landslide at Carn Dubh on Ben Gulabin is a translational failure in steeply dipping metasediments, a type of rockslide that is fairly widespread in the Scottish Highlands. The distinctiveness of this site arises from the unusual form of debris runout, which takes the form of two thick debris-tongues bounded by steep levées. There is no published account of this site; the observations below combine unpublished research by Cullum-Kenyon (1991) and the present author.

Description

Setting

Carn Dubh is the eastern spur of Ben Gulabin (806 m), 2 km north of Spittal of Glenshee in the south-east Grampian Highlands. The eastern slope of Carn Dubh descends towards the floor of the adjacent valley (Gleann Beag) at an average gradient of *c.* 33°. The slope is underlain by Dalradian schistose graphitic pelites and quartzites of Neoproterozoic age that dip moderately eastwards. At the last (Late Devensian) glacial maximum the area was completely over-ridden by SE-moving glacier ice that covered even the highest of the nearby summits (Glas Maol, 1068 m). During the final episode of glaciation, the Loch Lomond Stadial of *c.* 12.9–11.5 cal. ka BP, a small valley glacier advanced south down Gleann Beag, probably terminating near the valley mouth. The former extent of this glacier co-incides with a thick accumulation of till. On the west side of the valley the upper limit of till ascends northwards against the slopes of Ben Gulabin in the form of a discontinuous lateral moraine or drift limit that reaches an altitude of 490 m at the southern margin of the landslide, and is continued on the north side of the slide at an altitude of 520 m. Removal or burial of the intervening glacial drift confirms that the landslide occurred after glacier retreat. The failure scar occurs immediately upslope from the site of the former drift limit; and the debris tongues occur mainly downslope from this limit (Figure 2.57).

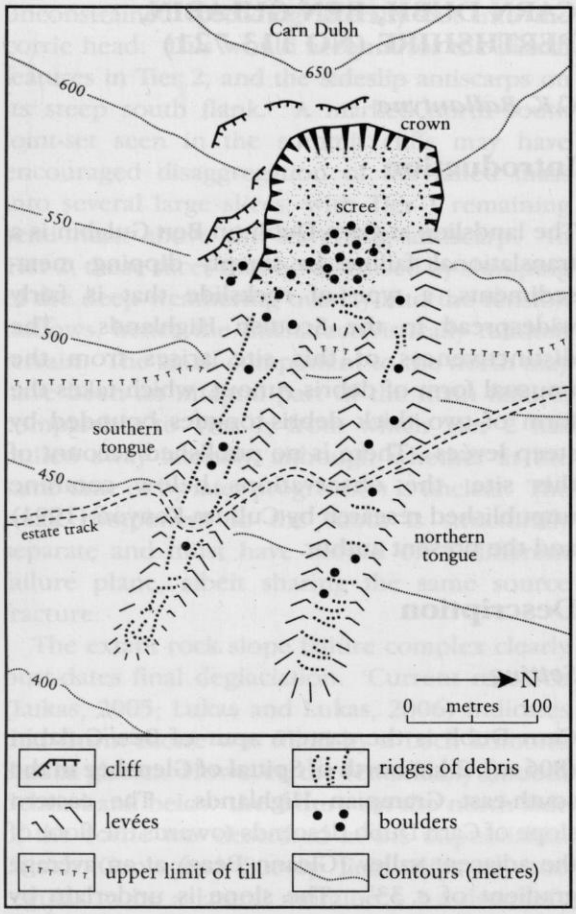


Figure 2.57 Map of the Carn Dubh rockslide scar and debris tongues, Ben Gulabin.

The failure scar

The failure scar has a roughly trapezoidal plan, but is extensively obscured by bouldery scree (Figure 2.57). Its southern margin is, however, defined by a partly vegetated cliff 10–15 m high, and a rockwall 20–30 m high crops out along the crown of the scar. The southern sidewall reveals a succession of well-jointed quartzites (Creag Leucach Quartzite Formation) in beds 1–4 m thick, interbedded with strongly foliated, weathered phyllitic semipelite and micaceous psammite beds generally less than 1 m thick. The bedding and foliation planes dip eastwards, sub-parallel with the slope at angles of 25° to 43°, forming part of a broad anticline. An exposure at the base of the southern sidewall suggests that rupture occurred (at least locally) along a 0.5 m-thick semipelite unit.

The debris lobes

Two thick tongues of debris extend downslope from the foot of the failure scar, and form the most conspicuous feature of the site (Figures 2.58 and 2.59). The two are separated just below the failure scar by a bulbous protrusion, probably underlain by bedrock, that split the mobile landslide debris into two separate flows. The top of the protrusion is covered by a wedge of angular bouldery landslide debris up to 7 m thick, formed into three transverse ridges.

The southern debris-tongue extends 320 m downslope from an altitude of 520 m to 415 m. It averages about 70 m in width and stands 3–10 m above the adjacent terrain. The gradient of the tongue declines downslope from 27° to 18°. The lobe margins are sharply defined by steep-sided boulder levées that decline in height downslope to terminate in overlapping ramp-like ridges 1–3 m high. Smaller longitudinal ridges occur inside the outer levées, suggesting that a pulse of flowing sediment occurred after the main body of the flow had stabilized.

The northern debris-tongue extends 380 m downslope from about 525 m to 420 m altitude, declining in gradient downslope from 31° to 15°. It averages about 80 m in width and 5 m in thickness, but is bounded by boulder levées up to 12 m high. Unlike its southern neighbour, it terminates abruptly downslope in a bold arcuate ridge that impounds a thick wedge or plug of debris, but lacks interior longitudinal ridges (Figure 2.58).

Between the outer levées, both tongues are crossed by arcuate transverse boulder ridges 1–3 m high. The central parts of the tongues are extensively vegetated, but numerous large angular boulders, mainly of quartzite, are scattered over the surface, and spreads of quartzite boulders mantle the higher parts of the levées. Sections in the levées occur where an estate track cuts across both debris-tongues (Figure 2.57). These reveal a predominantly clast-supported diamicton in which poorly sorted angular clasts, mainly of quartzite, are embedded in a compact, sandy matrix. Crude inverse grading is evident, with clasts increasing in both concentration and size towards the surface, forming a mantle of large (typically 0.3–2.0 m long) angular boulders. A small number of sub-angular facetted clasts, apparently derived from reworked till, are also exposed in the diamicton.

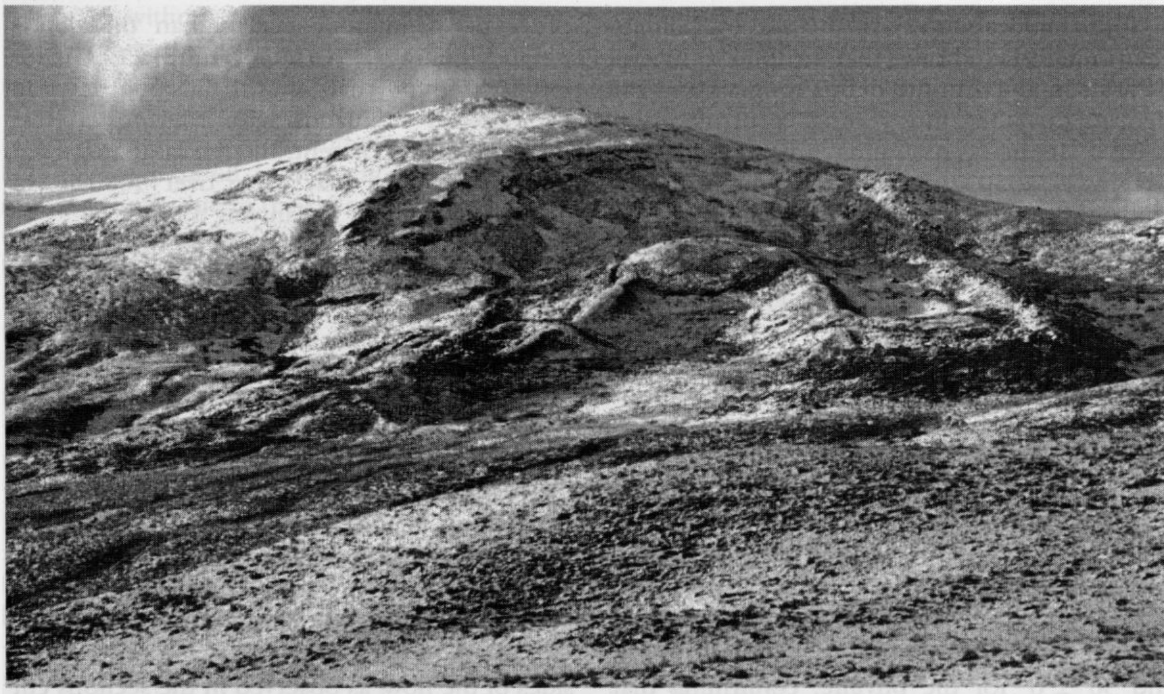


Figure 2.58 The Carn Dubh rockslide scar and debris tongues on Ben Gulabin. The southern debris tongue (left) peters out in low ridges and levées of vegetation-covered debris, whereas the northern tongue terminates in a bold bluff 5 m high. The inner levées of both lobes terminate upslope at the conspicuous bulbous protrusion that diverted flow of rockslide debris into two tongues. (Photo: C.K. Ballantyne.)

Figure 2.59 The Carn Dubh rockslide, Ben Gulabin, from above. (Photo: D. Jarman.)

Topographical survey of the site by Cullum-Kenyon (1991) indicates that the total volume of debris contained in the debris tongues and the debris on the intervening protrusion is *c.* $0.3 \times 10^6\,m^3$. Assuming an average rock density of $2550\,kg\,m^{-3}$ and allowing 20% for voids, this figure implies that the mass of failed rock was *c.* 600 000 tonnes. This figure is an upper estimate, as the debris lobes contain an unknown volume of reworked till.

Interpretation

Rock slope failure

Failure at this site took the form of a translational (planar) rockslide seated on quartzite strata that dip eastwards out of the slope at angles averaging around 34°. Tilt tests carried out by Cullum-Kenyon (1991) indicate an angle of plane sliding friction of 51° ± 4° for the quartzite and 36° ± 6° for the phyllite, confirming that rupture almost certainly occurred within the latter. The closeness of the friction angle of the phyllites to the dip of the bedding and foliation planes implies that the slope was in a state of conditional stability following deglaciation. The cause of failure is unknown. Progressive rock slope weakening is likely to have been caused by opening of stress-release joints following deglacial unloading and/or shearing of rock bridges and asperities as a result of rock-mass creep. Failure may ultimately have been triggered by build-up of joint-water pressures or possibly by a seismic event; the Glen Taitneach fault crosses Carn Dubh only 300 m from the crown of the failure scar, and may have been re-activated by differential glacio-isostatic uplift.

Debris flow

The two tongues have the morphological attributes of debris flow (sediment-gravity flow) deposits, namely elongate tongue-shaped plan-forms, steep bouldery lateral levées, near-surface inverse grading and longitudinal and transverse ridges indicative of flow surges (Van Steijn *et al.*, 1988; Coussot and Meunier, 1995; Corominas *et al.*, 1996). Morphologically, they resemble the hillslope debris-flow deposits that cover the lower slopes of many Scottish mountains (Ballantyne, 2002b,c), though the latter are produced by failure and flow within unconsolidated sediments and are generally at least an order of magnitude smaller than the debris tongues below Carn Dubh. Innes (1985), for example, found that 90% of hillslope flows in the Scottish Highlands have transported less than 60 m^3 of sediment, though large flows fed by gully systems may carry over 1000 m^3 of debris (Brazier and Ballantyne, 1989).

There are two competing models of flow movement. Some channelled flows move as Bingham flows, with a rigid plug of debris being transported by laminar shear of an underlying and surrounding mixture of sediment and water (Johnson and Rodine, 1984). Movement of most Scottish hillslope flows, however, appears to be dominated by cohesionless grainflow, in which momentum is maintained by inertial collisions, with boulders attaining partial buoyancy in a mobile mass of mud (Takahashi, 1981; Blikra and Nemec, 1998). The dispersive stresses implied by the latter mechanism account for movement of the coarsest debris to the top and sides of the flow, as observed in the sections cut through the levées of Carn Dubh debris-tongues.

Irrespective of the nature of movement, the flow of coarse debris below the Carn Dubh rock-slide implies a drastic reduction in viscosity. As the lower limit of the slide plane and the upper limit of the debris tongues co-incide approximately with the upper limit of thick till, it is tempting to relate the onset of flow to undrained loading of saturated till by cascading rock that raised porewater pressures in the till until the over-burden weight was transferred to the fluid, leading to liquifaction (Hutchinson and Bhandari, 1971; Bovis and Dagg, 1992). The alternative explanation appears to be that the high initial energy of the slide was sufficient to generate inertial grainflow or fragmental flow, partially buoyant in a mixture of expelled water, crushed phyllitic semipelite and possibly entrained till.

It is instructive to compare the characteristics of the Carn Dubh rockslide and debris-tongues with those of a rockslide in Gleann na Guiserein, Knoydart (NG 774 057; Bennett and Langridge, 1990), where planar sliding of psammitic meta-sediments over steeply dipping slabs resulted in the formation of a debris tongue very similar to those at Carn Dubh. The Guiserein tongue is approximately 440 m long, narrows downslope from 105 m to 40 m and is bounded by steep levées up to 10 m high. The adjacent slopes are underlain by bedrock with localized thin soil cover, implying that here the debris tongue developed without deformation of underlying sediment, and thus solely as a result of fragmentation and flow of rock debris. Ballantyne (1992) inferred that the Guiserein debris-tongue formed through inertial grainflow or fragmental flow, probably aided by reduction in effective normal stresses due to the presence of mud and water. Similarly, formation of the Carn Dubh debris-lobes may also have occurred independently of till cover downslope of the failure zone.

Flow of debris following rock slope failure is poorly documented in Scotland. An extreme example occurs at **Beinn Alligin**, where sliding of nearly 9×10^6 tonnes of rock along a steep (42°) failure plane resulted in movement of very coarse debris over a distance of 1.2 km along a corrie floor. Other sites occur along the **Trotternish Escarpment** on Skye, (Ballantyne, 1991a) and on the scarp face of the Lomond Hills in Fife (Ballantyne and Eckford, 1984) and below the basalt scarp of the Campsie Fells north of Glasgow (Evans and Hansom, 1998, 2003). None of these, however, have produced the elongate debris-tongues bounded by massive levées that characterize the Carn Dubh rockslide.

Conclusions

Sometime after the final deglaciation of Gleann Beag some 11 500–12 000 years ago, up to 600 000 tonnes of rock below Carn Dubh failed by sliding of interbedded quartzites and semi-pelites along bedding planes that dip towards the valley at angles of around 34°. Rupture occurred in the phyllites, which were probably weakened by post-glacial stress-release, though the failure trigger may have been high water-pressure or a seismic shock generated by re-activation of the nearby Gleann Taitneach fault.

The Carn Dubh landslide on Ben Gulabin represents an outstanding example of a rock slope failure where runout involved viscous flow, producing thick elongate debris-tongues that extended downslope from the foot of the failure scar. This phenomenon is very rare on the metamorphic rocks that underlie most of the Scottish Highlands; only two other examples are documented. Fragmentation and flow of mobile rockslide debris around a central protrusion resulted in the deposition of two thick debris-tongues, 320 m and 380 m long, flanked by massive bouldery levées up to 12 m high. These thick debris-tongues resemble those produced by hillslope debris-flows, but are an order of magnitude larger. Movement of the boulders in the debris tongues probably took the form of inertial grainflow sustained by the momentum of colliding boulders, with coarse debris partially buoyant in mobile mud. The degree to which movement was aided by loading and liquifaction of underlying glacial deposits is uncertain, though comparison with a similar site in Knoydart suggests that formation of massive debris-lobes such as those below the Carn Dubh rockslide was not dependent on deformation of underlying sediments. The internal composition of the massive flow-tongues suggests that flow generated by the momentum of the initial rockslide involved a mixture of expelled water, crushed phyllites, quartzite boulders and a subsidiary component of entrained till. Debris flow at this site was probably aided by focusing of runout debris around the central protrusion and runout on to initially steep gradients.

BEINN ALLIGIN, HIGHLAND (NG 867 603)

C.K. Ballantyne

Introduction

A corrie on the south-east side of Beinn Alligin (north-west Scotland) is the site of a major rock slope failure that probably represents the finest example of a rock avalanche in the British Isles. The term 'rock avalanche' is generally employed to describe the failure and rapid descent of large (> 500 000 m^3) masses of rock from steep mountain walls. Rock avalanches occur when joints within a rockwall become progressively interconnected, reducing rock-mass strength until the rock fails under its own weight (Selby, 1993). They are particularly common in alpine environments where glacial erosion has steepened rockfaces, and where the stress field within the rock mass has altered in response to deglacial unloading. Although over 500 individual rock slope failures have been identified in the mainland Scottish Highlands (Ballantyne, 1986a), true rock avalanches are rare, probably because of the relatively modest relief. By far the most spectacular example is that at Beinn Alligin, which is particularly notable for the clarity of the failure scar and the exceptionally long runout of very coarse debris. The latter implies that the Beinn Alligin rock-avalanche may be classified as an excess-runout rock-avalanche or 'sturzstrom' (Ballantyne, 2003; Ballantyne and Stone, 2004).

Description

Beinn Alligin comprises two summits (Sgurr Mór, 985 m and Tom na Gruagaich, 922 m) joined by a narrow arête. On the south-east flank of the mountain, steep rockwalls of stepped Torridon sandstone strata rise 350–550 m above a deep corrie, Toll a'Mhadaidh Mór (Figure 2.60). The corrie floor is traversed by a tongue-shaped deposit of landslide runout debris composed of large Torridon sandstone boulders up to and occasionally exceeding 5 m in length, with no visible fine-grained interstitial sediment (Figure 2.61; see also fig. 6.12 in the *Quaternary of Scotland* GCR volume, Gordon and Sutherland, 1993). This deposit rises up to 15 m above the bedrock floor of the corrie, occupies an area of 0.38 km^2 and extends continuously downvalley for 1.25 km at an average gradient of 8°, from an altitude of 450 m at the base of the corrie headwall to 275 m. It tapers downvalley from a maximum width of 380 m to a width of 170 m at its terminus (Figure 2.60). The lateral margins of the runout deposit are sharply defined. Its surface relief consists of discontinuous and often poorly defined ridges and intervening depressions. The distal part of the debris tongue is dominated by arcuate-downvalley transverse ridges, but ridges in the upvalley part are transverse, sub-parallel and oblique to the downvalley trend of the deposit. The distal 360 m of the deposit is thinner than the remainder.

The source of this remarkable runout deposit is a deep failure scar on the northern wall of the

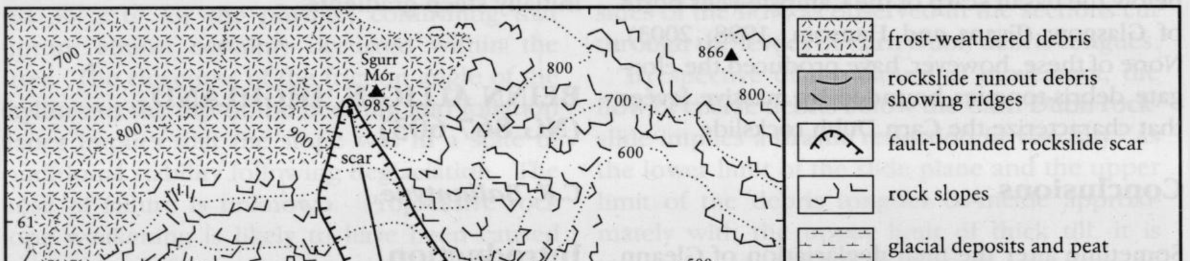


Figure 2.60 The Beinn Alligin rock-avalanche failure scar and runout deposit; map based on 1:25 000 aerial photographs and field mapping from adjacent summits.

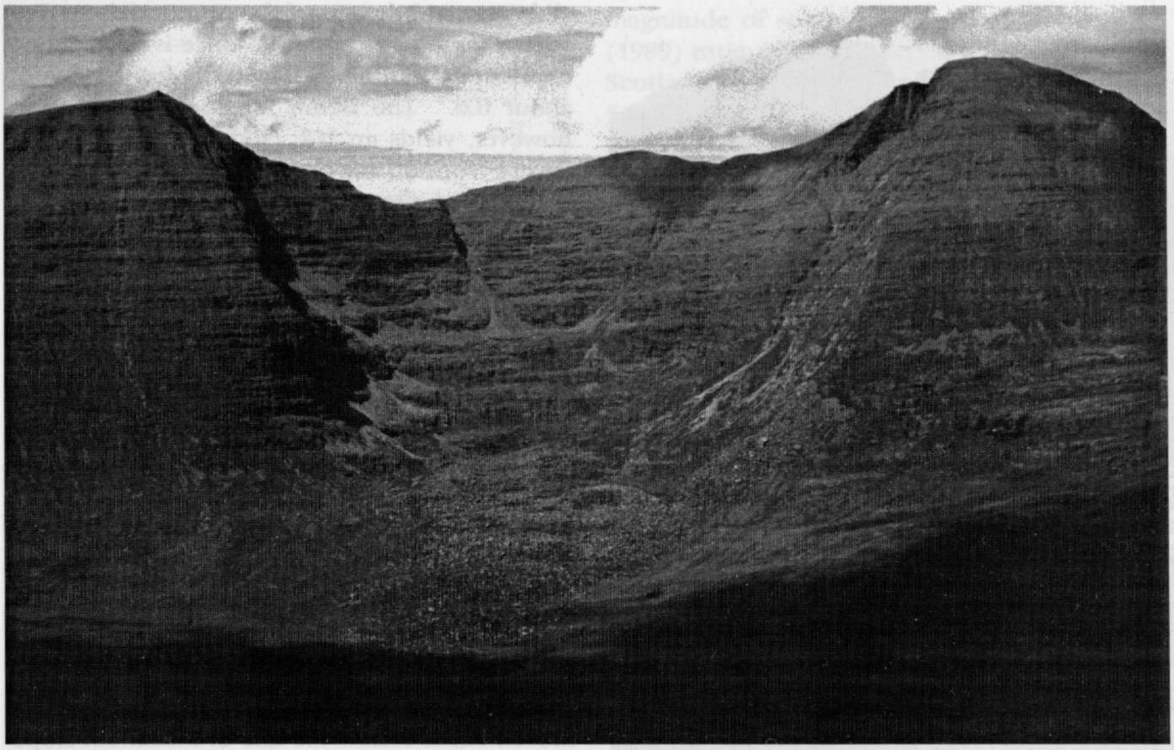


Figure 2.61 The Beinn Alligin rock-avalanche failure scar and runout deposit photographed from the western end of the neighbouring mountain, Liathach. (Photo: C.K. Ballantyne.)

corrie. The scar is defined on both margins by near-vertical fault scarps up to 60 m high that converge near the summit of Sgurr Mór (Figures 2.60–2.62). The failure plane has an average gradient of 42°, and in comparison with the adjacent stepped rockwalls is relatively smooth, suggesting that failure was dominated by sliding. The planimetric area of the scar is *c.* 107 000 m^2, and its true area (taking gradient into account) is *c.* 144 000 m^2. Ballantyne and Stone (2004) estimated the volume of failed rock represented by the scar by interpolating the contours of the pre-failure rockface across the scar. Their calculations indicate that the failure involved 3.3–3.8 × 10^6 m^3 of rock, equivalent to a mass of 8.3–9.5 × 10^6 tonnes. At the east end of the foot of the scar, a small steep talus cone of very coarse rockslide debris abuts the main rockslide deposit on the corrie floor.

At the last (Late Devensian) glacial maximum, the site of the Beinn Alligin rock-avalanche was occupied by glacier ice to an altitude of *c.* 820 m, with the twin summits remaining above the ice as nunataks (Ballantyne *et al.*, 1998a). The site was re-occupied by glacier ice during the Loch Lomond Stadial of *c.* 12.9–11.5 cal. ka BP, when a small corrie glacier, nourished in the corrie, fed a larger valley glacier to the south-east (Sissons, 1977).

Interpretation

The Beinn Alligin rock-avalanche has attracted considerable attention, particularly on account of the exceptionally long runout of debris along the corrie floor. This was initially explained in terms of downvalley transport of debris by remnant glacier ice at the end of the Loch Lomond Stadial, possibly in the form of a rock glacier (Sissons, 1975, 1976) or a supraglacial debris cover (Ballantyne, 1987a; Gordon, 1993). Whalley (1976), however, argued that the deposit could equally represent an excess-runout rock-avalanche, an interpretation also favoured by Fenton (1991). Ballantyne and Stone (2004) resolved the issue through cosmogenic radionuclide dating of the exposure age of the landslide debris. Three cosmogenic ^{10}Be ages obtained for the exposed upper surfaces of large boulders in the runout deposit yielded almost identical ages averaging 3950 ± 320 yr BP,

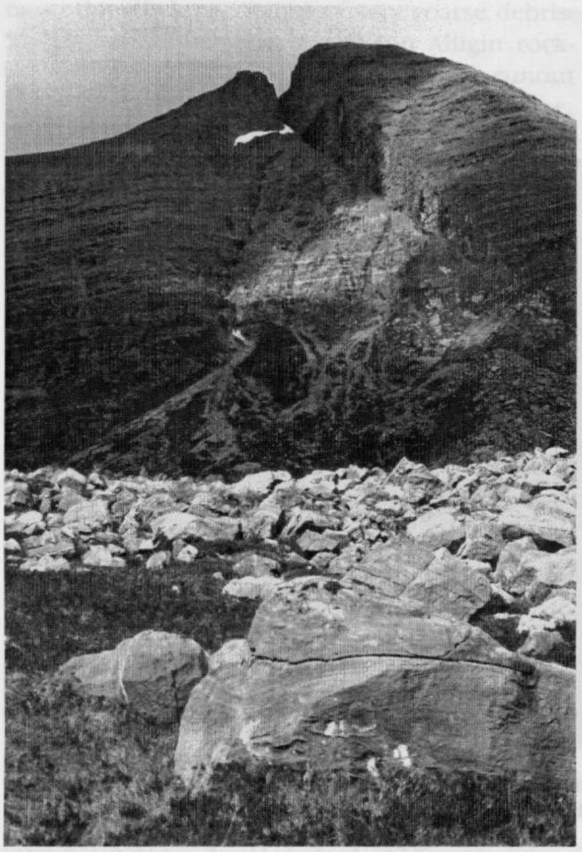


Figure 2.62 Rock-avalanche runout deposit with the failure scar in the background, showing the coarseness of the runout debris and the converging fault scarps that bound the scar. The vertical height of the fault scarp to the right of the failure scar increases upslope to nearly 60 m immediately below the summit of the mountain. (Photo: C.K. Ballantyne.)

implying that the rock avalanche occurred roughly 4000 years ago, and over 7000 years after the final disappearance of glacier ice. These findings demonstrate that the exceptional runout of the rock-avalanche debris cannot be attributed to transport by glacier ice, and must be related solely to landslide dynamics.

Causes of excess runout

Excess runout of rockslide debris has been defined as runout which exceeds that which might be expected from frictional sliding alone (Hsü, 1975). The expected travel distance of a rockslide can be estimated from the ratio H/L, where H and L are respectively the total vertical and horizontal distances between the top of the slide scar and the toe of the runout debris. For rockslides where runout distance is determined by frictional sliding, H/L typically has a value of about 0.6. The Beinn Alligin debris runout, however, yields an H/L ratio of 0.38, implying excess runout of *c.* 680 m (Ballantyne and Stone, 2004; Figure 2.63).

The phenomenon of excess runout appears to be related to the energy of the mobilized rock mass (Dade and Huppert, 1998; Kilburn and Sørensen, 1998), and the unusual long runout of the Beinn Alligin rock-avalanche in comparison with other rock slope failures in the Scottish Highlands probably reflects the exceptionally large mass and long vertical drop of failed rock at this site. Excess runout implies a reduction in the basal or internal friction of the mobile debris, and numerous theories have been proposed to account for this (Selby, 1993, pp. 316–19). At Beinn Alligin, the long-axis of the runout debris is oblique to that of the failure scar (Figure 2.63), implying that the mobile debris was re-oriented (by about 30°) during movement to follow the line of maximum slope along the corrie floor. When viewed from the mountain summit, it is clear that the debris surged a short distance up the slope opposite the failure scar then moved downslope along the corrie axis. Such re-orientation suggests that the debris moved as a grainflow or fragmental flow rather than a frictional slide. The abrupt margins of the deposit and the formation of arcuate transverse ridges are also consistent with this interpretation (Dawson *et al.*, 1986). Hsü (1975) argued that excess-runout landslides move as cohesionless grainflows driven by transfer of kinetic energy between colliding particles, and energy-balance calculations by Dade and Huppert (1998) are consistent with runout of densely concentrated debris in a state of granular flow. Alternatively, Kilburn and Sørensen (1998) have suggested that the upper parts of excess-runout landslides may be carried downslope as a result of fragmentation of clasts in a mobile basal boundary layer.

Cause of failure

Ballantyne (2003) and Ballantyne and Stone (2004) have suggested that the principal cause of the Beinn Alligin rock-avalanche was paraglacial (glacially conditioned) stress-release. Loading by glacier ice increases internal stresses

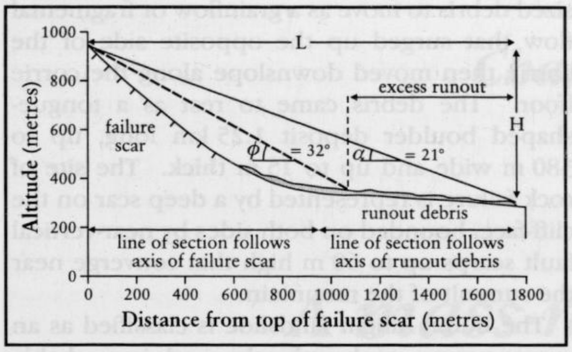


Figure 2.63 Long profile of the failure scar and runout tongue, projected along intersecting lines drawn down the axis of the scar and up the axis of the tongue (Figure 2.60). Excess runout is the difference between actual runout and the runout that is expected under frictional sliding alone. Under the latter condition $H/L = 0.6$ and $\tan^{-1}(H/L) = 32°$. At Beinn Alligin, $H/L = 0.38$ and $\tan^{-1}(H/L) = 21°$. Excess runout (Le) = (L – Htan 32°) = (1763 – 1080) m = 683 m, implying that the runout debris extended 683 m farther than would be expected under conditions of frictional sliding alone.

within underlying or adjacent rock masses, and part of the resulting ice-load deformation is stored as residual strain energy. During and after ice downwastage this strain energy is released, re-orienting the stress field within rock masses and resulting in the development of a region of tensile stress beneath rock slopes. Time-dependent relaxation of tensile stresses results in propagation of the internal joint network, ultimately reducing the strength of the rock mass to that of frictional contacts between joint-bound blocks. Depending on such factors as the steepness and height of the rockface and the orientation of joint-sets, this relaxation of internal stresses may lead to failure during or immediately after deglaciation, or, as in the case of the Beinn Alligin rock-avalanche, delayed failure conditioned by dissipation of residual stresses and consequent progressive joint propagation (Ballantyne, 2002a).

The actual trigger of failure, however, could have been an earthquake. Differential glacio-isostatic recovery during and after the downwastage and retreat of the last ice-sheet is believed to have re-activated ancient faults (Sissons and Cornish, 1982; Ringrose, 1989; Fenton, 1991). Although the diminishing rate of glacio-isostatic recovery following ice-sheet deglaciation implies a gradual decline in the magnitude of seismic activity, Davenport *et al.* (1989) estimated that the Western Highlands of Scotland may have experienced magnitude 5.0–6.0 events as late as *c.* 3.4 cal. ka BP. It is thus possible that even a fairly low-magnitude seismic event acting on a progressively weakening rock mass may have triggered failure on Beinn Alligin around 4000 years ago. The fact that the failure scar on Beinn Alligin is bounded by converging fault scarps (Figures 2.60 and 2.62) suggests that movement along one or both of these faults may have triggered the rock avalanche.

Wider significance

The Beinn Alligin rock-avalanche represents the largest documented rock slope failure on the Torridon sandstone terrain of north-west Scotland. Rock slope failures are rare in Torridonian rocks, despite the steepness of many corrie and valley rockwalls, suggesting that rock-mass strength in the gently dipping Torridonian arkosic sandstones is generally high. The closest analogue is a major rockslide at Creag an Fhithich, Baosbheinn (NN 856 676), 7 km north of the Beinn Alligin site. The Baosbheinn landslide, however, involved failure of an estimated 0.2×10^6 m^3 (0.5×10^6 tonnes) of rock (Ballantyne, 1986b), an order of magnitude less than that involved in the Beinn Alligin rock-avalanche. As a result, the mobilized rock mass at Baosbheinn had insufficient energy to generate excess runout, and was deposited as an arcuate boulder ridge at the foot of the failure scar. The exceptionally large scale of the Beinn Alligin failure reflects its unusual structural configuration, with two failure planes converging near the crest of a glacially steepened rock slope.

The Beinn Alligin landslide is also the largest known rock-avalanche in the Scottish Highlands and probably Great Britain. Other rock avalanches in the Highlands occur on a variety of lithologies, for example Tertiary basalts on Skye (see **Trotternish Escarpment** GCR site report, Chapter 6; Ballantyne 1991b), Devonian rhyolitic lavas and tuffs near Glencoe (see **Coire Gabhail** GCR site report, Chapter 4) and on Moine and Dalradian schistose rocks, for example at Carn Ghluasaid (NH 140 120) in Glen Cluanie, Beinn an Lochain (NN 217 083, Figure 2.11) in the south-west Grampians and Coire Ban (NN 618 447) in Glen Lyon. However, these rock avalanches are all roughly an order of magnitude smaller in terms of mass of failed rock, and runout distances are consequently much less (< 500 m), even where runout has been aided by moderate gradients. In a Scottish context, the phenomenon of pronounced 'excess runout' of debris is certainly best developed in the Beinn Alligin rock-avalanche.

The timing of the Beinn Alligin failure is also significant. Like The Storr landslide on Skye, which has been dated to *c*. 6.5 ± 0.5 cal. ka BP (Ballantyne *et al*., 1998b), the Beinn Alligin rock-avalanche occurred several millennia after deglaciation, demonstrating that major (paraglacial) rock slope failures were still occurring during Mid- and Late Holocene times in the Scottish Highlands and Hebrides. The long delay between deglaciation and failure at these sites suggests that the potential for major cataclasmic rock slope failures generated by deglacial unloading may not yet be exhausted in the Scottish Highlands.

Conclusions

Approximately 4000 years ago, roughly 9 million tonnes of rock became detached from the northern rockwall of a corrie (Toll a'Mhadaidh Mor) on the south-east side of Beinn Alligin and cascaded on to the corrie floor. The exceptionally large mass and height of fall of this landslide provided sufficient energy to cause boulder-sized debris to move as a grainflow or fragmental flow that surged up the opposite side of the corrie then moved downslope along the corrie floor. The debris came to rest as a tongue-shaped boulder deposit 1.25 km long, up to 380 m wide and up to 15 m thick. The site of rock failure is represented by a deep scar on the cliff-face, bounded on both sides by near-vertical fault scarps up to 60 m high that converge near the summit of the mountain.

The Beinn Alligin landslide is classified as an excess-runout rock-avalanche and is probably the largest and finest example of its type in Scotland. It is thought to have occurred due to 'rebound' or stress-release in the rock after it emerged from under the weight of the last ice-sheet. Stress-release resulted in the opening of joints (discontinuities) in the rock, so that the cliff became progressively weaker through time. The landslide may, however, have been triggered by movement along one or both of the faults that border the failure scar, causing the collapse of rock already weakened by stress-release. The Beinn Alligin rock-avalanche is the largest slope failure in Torridon sandstone bedrock. Its occurrence several millennia after final deglaciation suggests that the effects of unloading of rock from under the weight of the last ice-sheet may have continued to influence mountain-wall stability throughout most of the post-glacial period, and may persist to the present day.