Beinn Alligin, Highland

[NG 867 603]

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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 down-valley 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 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 Mot- (Figure 2.60); (Figure 2.61); (Figure 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 x 10^6 m^3 of rock, equivalent to a mass of 8.3–9.5 x 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 cosmo-genic 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, 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 (Hsu, 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 Sorensen, 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). Hsu (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 Sorensen (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 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 down-wastage 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 (Figure 2.60) and (Figure 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 x 10^6 m^3 (0.5 x 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 rhy-olitic lavas and tuffs near Glencoe (see Coke 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, theserock 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.

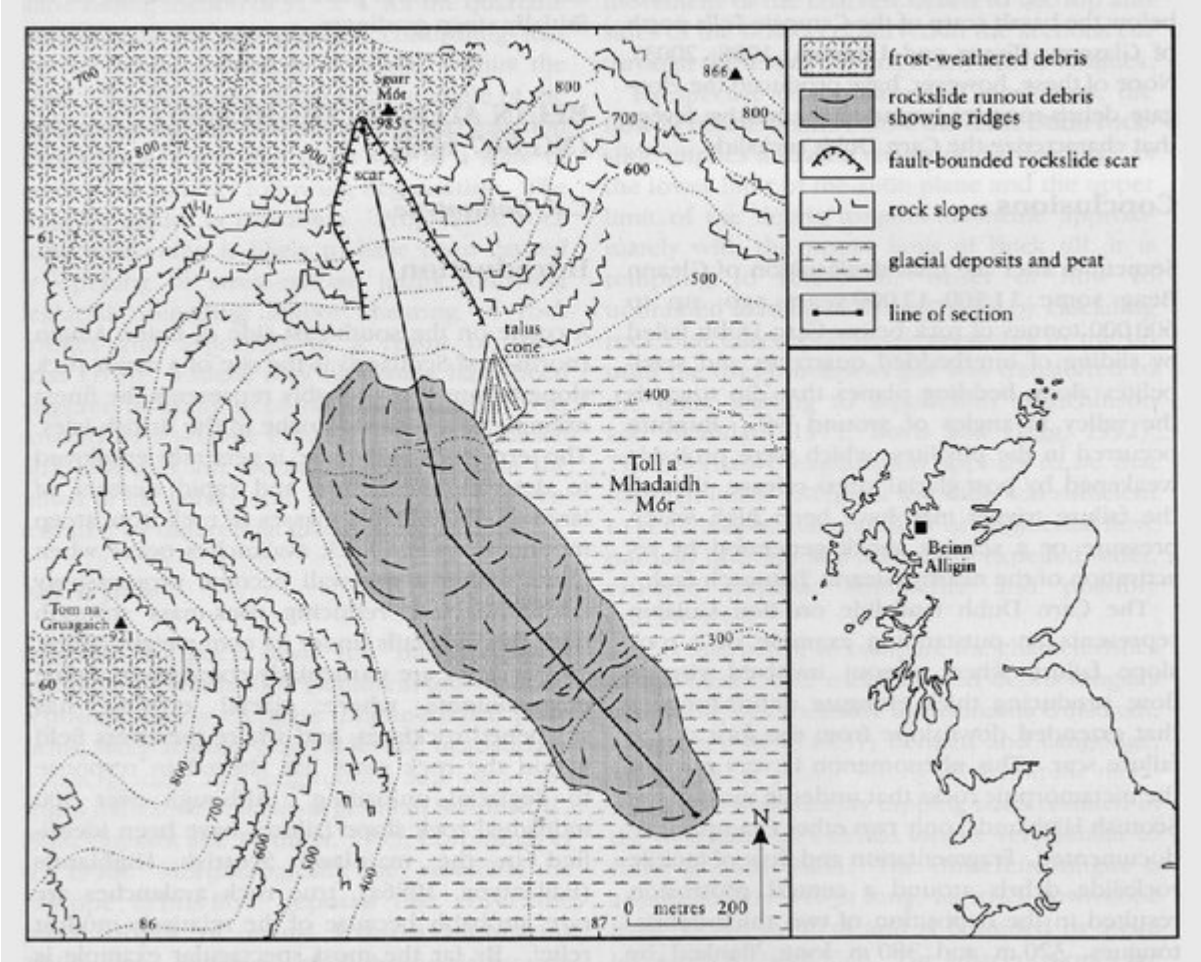
Conclusions

Approximately 4000 years ago, roughly 9 million tonnes of rock became detached from the northern rockwall of a corrie (Toll a'Mhadaidh Mór) 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.

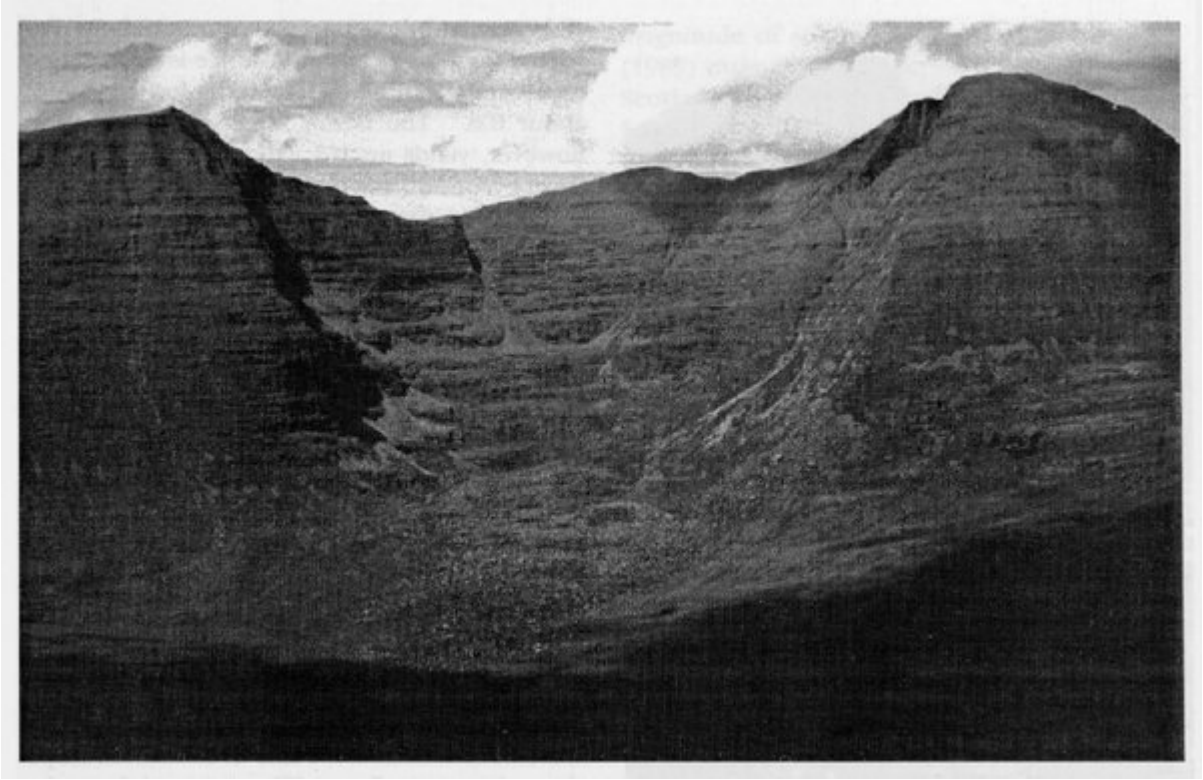
The Beinn Alligin landslide is classified as an excess-runout rock-avalanche and is probably the largest and finest example of its type in Scotland. It is thought to have occurred due to 'rebound' or stress-release in the rock after it emerged from under the weight of the last ice-sheet. Stress-release 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.

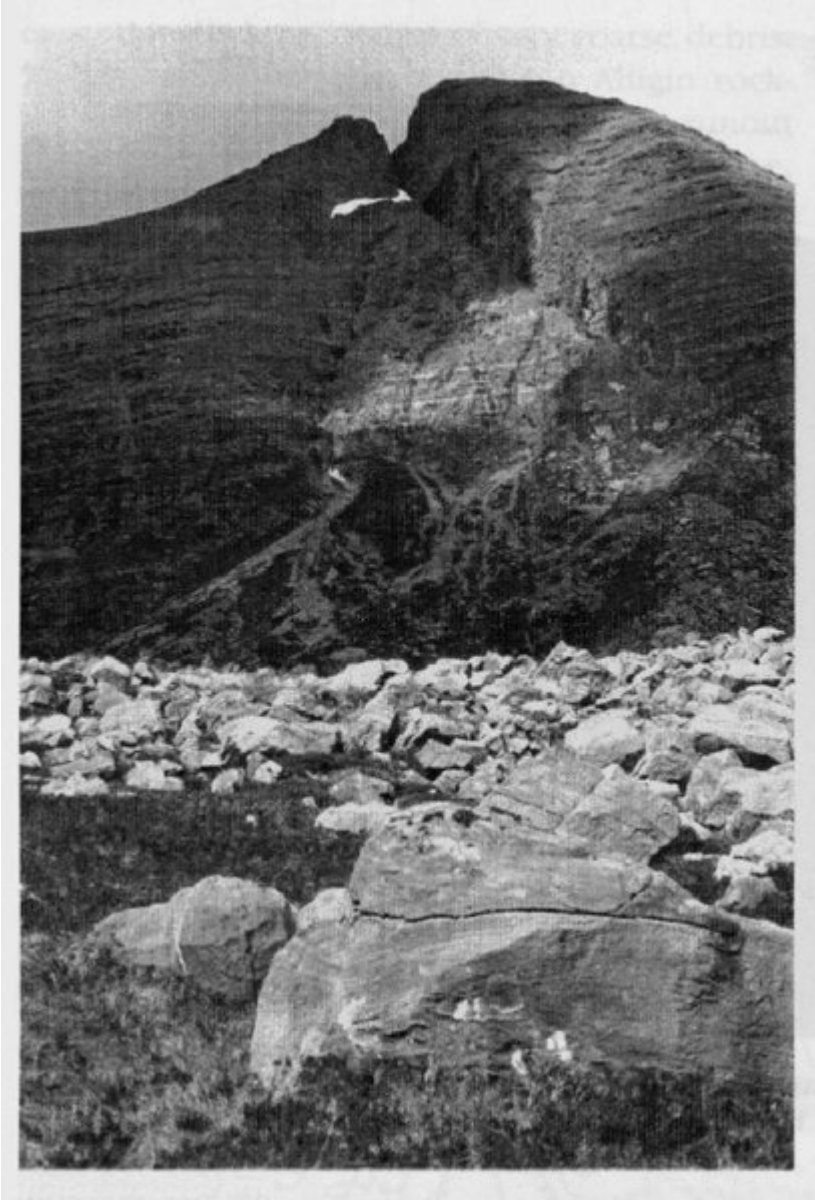
References



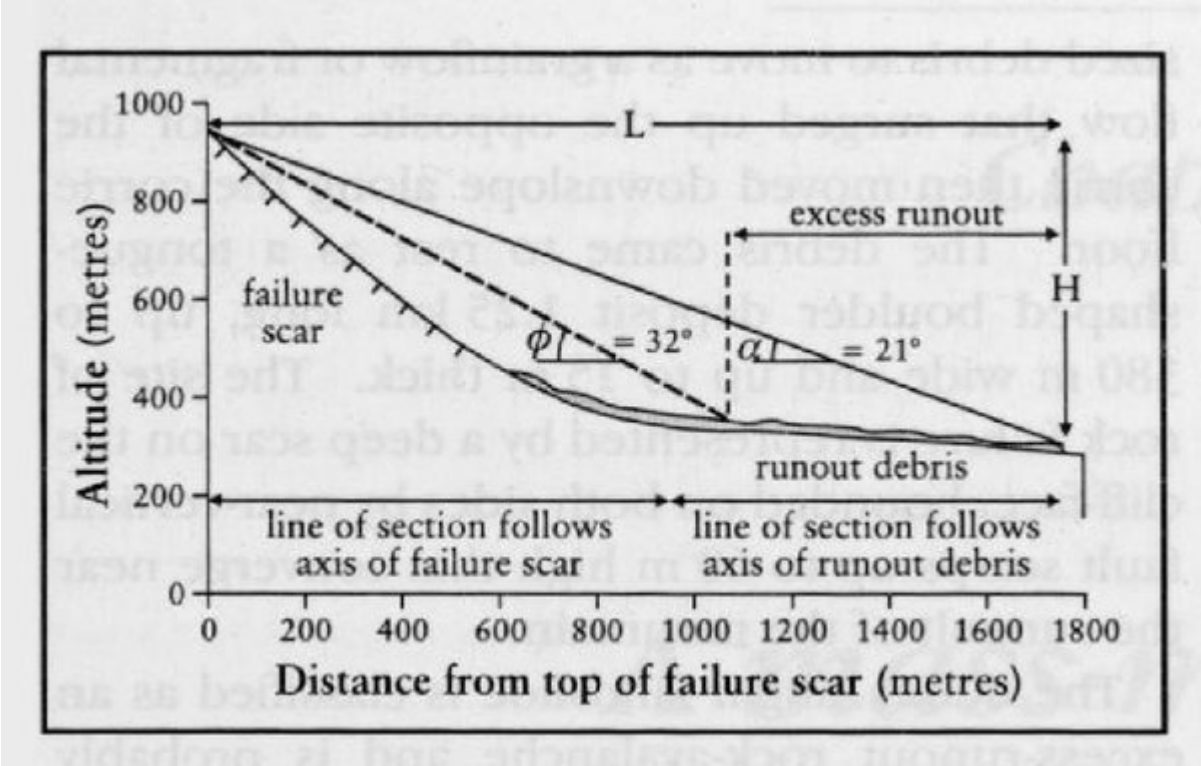
(Figure 2.60) The Beinn Alligin rock-avalanche failure scar and runout deposit; map based on 1:25 000 aerial photographs and field mapping from adjacent summits.



(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.)



(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. Ballanryne.)



(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.

(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 conic 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.)