Beinn Fhada (Ben Attow), Highland

[NH 000 185]–[NH 021 185]

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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 x 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 Wafters (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 (Figure 2.19), (Figure 2.20), (Figure 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 01); and two sets that dip gently westwards 02 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 (Figure 2.19), (Figure 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 depressions 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 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 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 anti-scarps 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 deglacia-tion. 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 deglacia-tion 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 reoccupied 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 reactivation 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 anti-scarps, 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)).

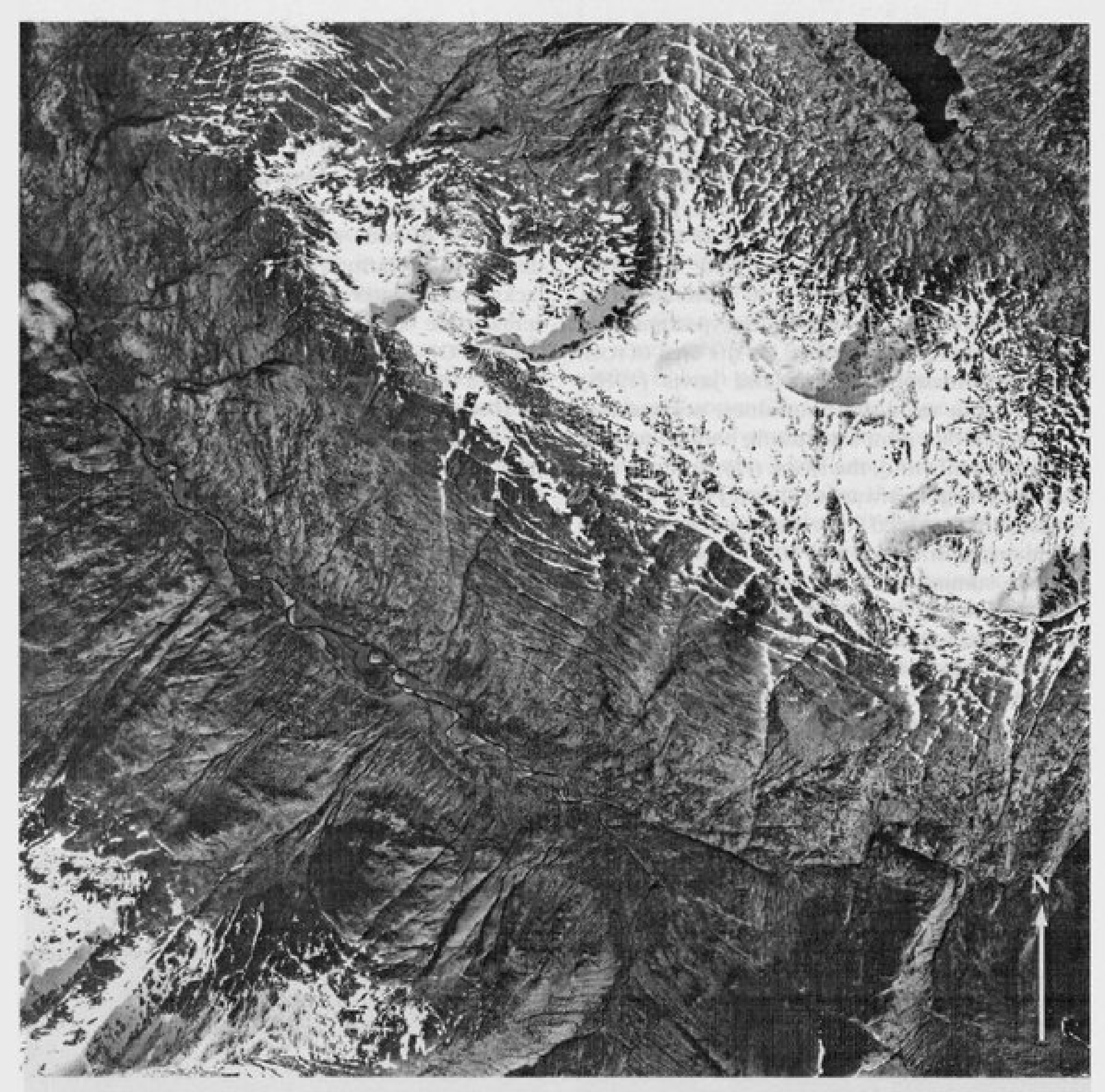
Conclusions

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 foot-slope 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.

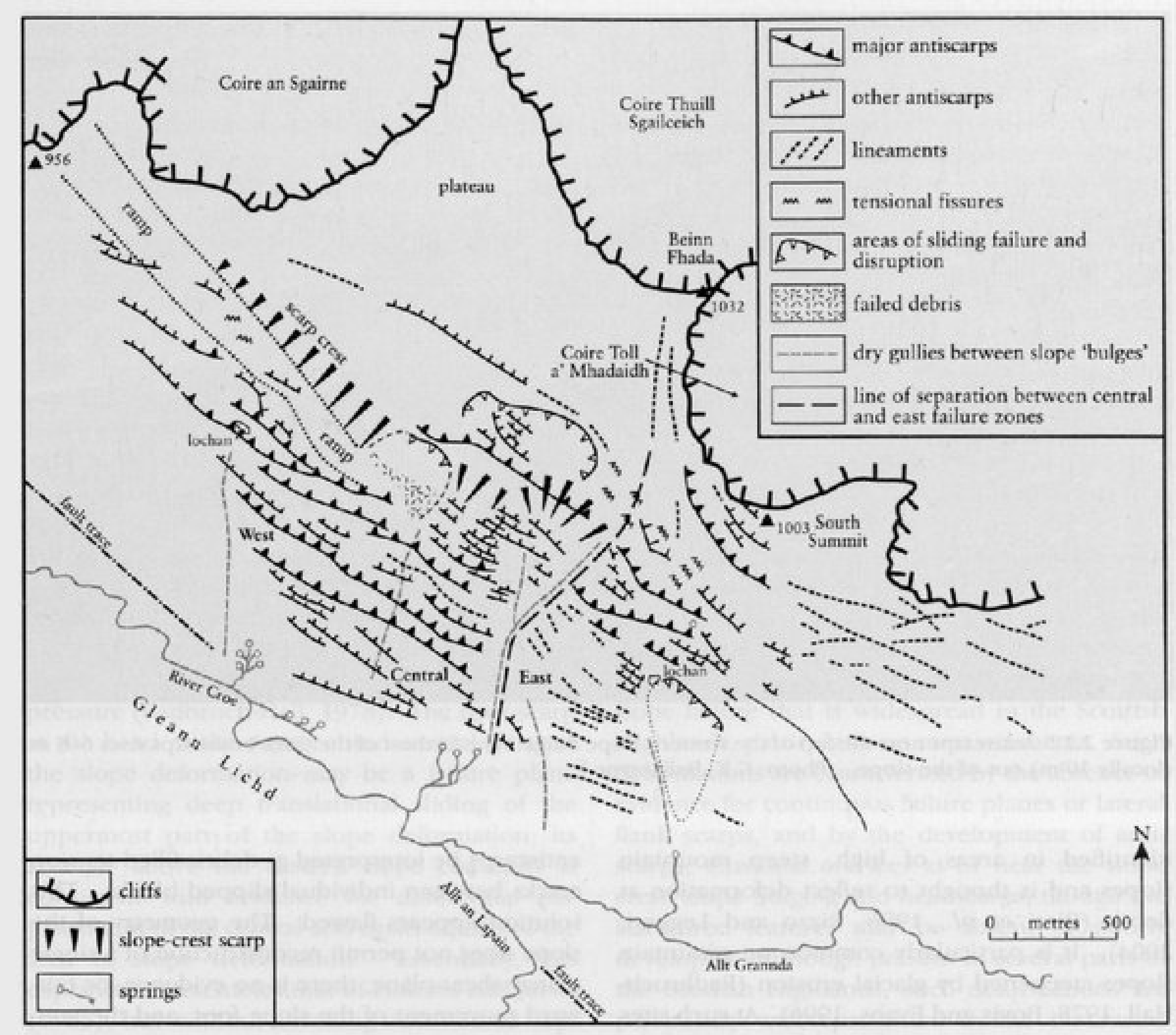
Like many major rock slope failures in the Scottish Highlands, the development of the Beinn Fhada rock slope deformation can be attributed to slope steepening by glacial erosion and rock-mass weakening associated with deglacial unloading and paraglacial stress-release. Displacement was probably gradual 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.

References

(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.)

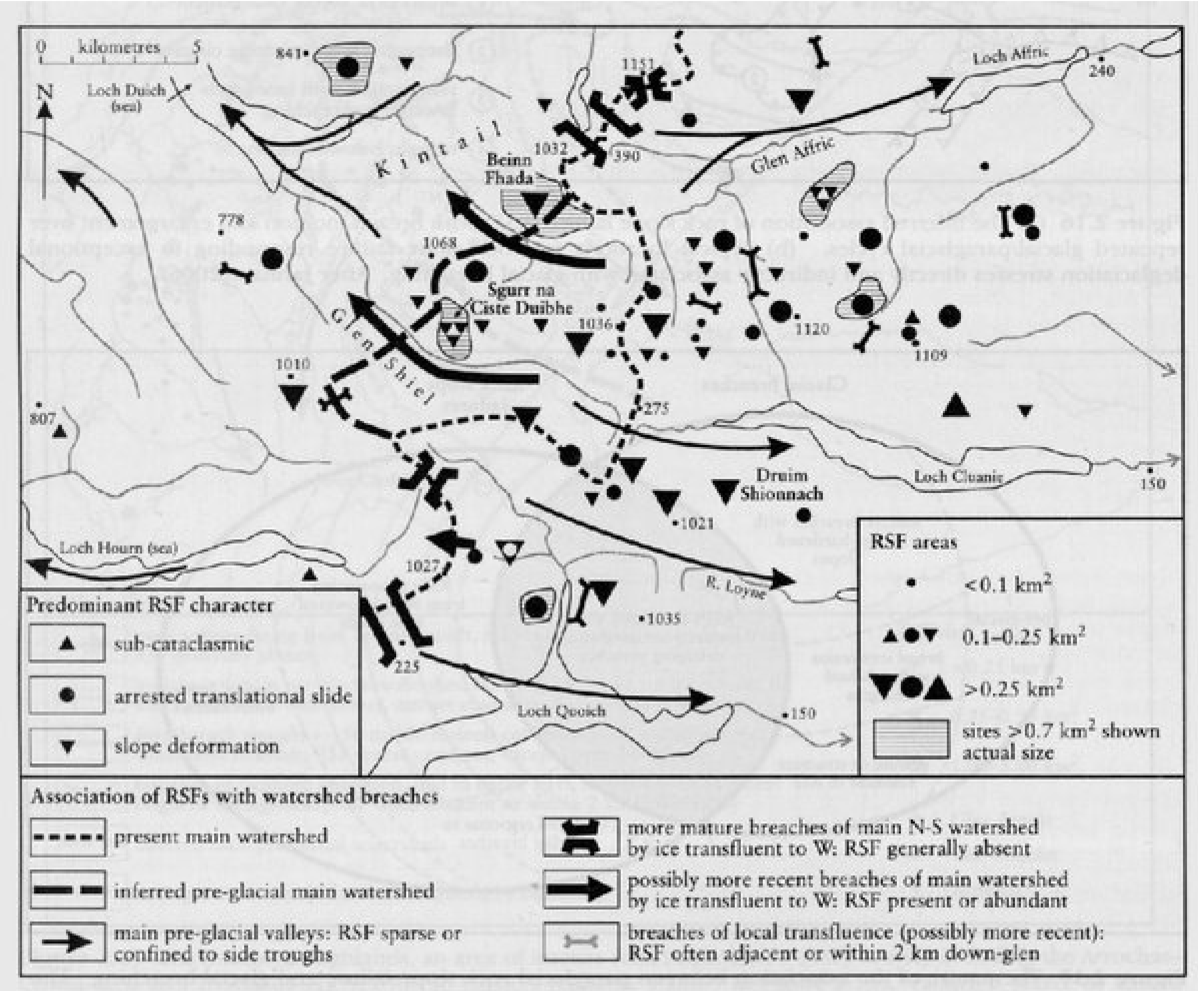


(Figure 2.20) Vertical aerial photograph of the Beinn Fhada rock slope deformation. The three major slope convexities are highlighted by antiscarp arrays, as is the extent of the pre-glacial land surface with its structural lineaments. (Photo: Crown Copyright: RCAHMS (All Scotland Survey Collection).)



(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).

(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.)



(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).