Trotternish Escarpment, Isle of Skye, Highland

[NG 450 717]–[NG 481 494]

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Introduction

The Trotternish peninsula is the northernmost part of the Isle of Skye, the largest island in the Inner Hebrides. The peninsula is dominated by the Trotternish escarpment, a bold cliff of Paleocene lavas up to 200 m high that extends almost continuously for 23 km along almost the full length of the peninsula. Foundering of the lava scarp over the underlying Jurassic sedimentary rocks has produced the largest continuous area of landslide terrain in the British Isles, covering nearly 40 km^2 (Ordnance Survey, 1964), and two of the most spectacular post-glacial landslides in Scotland, at The Storr and Quiraing. The Trotternish landslides were first described in detail by Godard (1965), who identified an inner zone of post-glacial failures and an outer zone of subdued, hummocky slipped rock that he inferred to have been over-ridden by glacier ice. Anderson and Dunham (1966) mapped the extent of landslide terrain, all of which they regarded as post-dating the last ice-sheet, and proposed that failure had been dominated by successive deep rotational slides seated on dolerite sills. Ballantyne (1990, 1991a,b) re-evaluated the age of the Trotternish landslides in the light of a revised glacial history of the escarpment, and described the characteristics of individual landslide blocks and other landforms produced by rock slope failure along the escarpment. The age and cause of post-glacial failure at The Storr has been investigated by Ballantyne *et al.* (1998b) using cosmogenic radionuclide dating of landslide pinnacles, and the history and processes of rockfall accumulation along part of the escarpment have been reconstructed by Hinchliffe *et al.* (1998) and Hinchliffe and Ballantyne (1999) on the basis of talus stratigraphy. These investigations have thrown light on the post-glacial evolution of the Trotternish escarpment, but the deep structure and mechanics of slope failure remain more speculative.

Description

Geology and topography

During the Palaeogene Period (65–23 Ma), the opening of the North Atlantic Ocean was accompanied by prodigious volcanic activity along the western seaboard of the Scottish Highlands. This volcanicity focused between 61 Ma and 56 Ma at the end of the Paleocene Epoch. Volcanoes on Skye, Mull and elsewhere discharged large quantities of fluid, primarily basaltic lavas that buried the underlying rocks and accumulated progressively to form extensive, near-horizontal lava plateaux (Bell and Williamson, 2002; Emeleus and Bell, 2005). In the area of Trotternish, a thick succession of lava flows buried a great thickness of relatively weak sedimentary rocks (mudstones, sandstones and limestones) of Jurassic age (Bell and Harris, 1986; Hallam, 1991; Hudson and Trewin, 2002). Paleocene volcanicity was also accompanied by the intrusion of dolerite sills deep within the Jurassic strata. Jurassic sedimentary rocks and dolerite sills now underlie the low ground east of the Trotternish Escarpment, whereas west of the escarpment crest these rocks are buried under *c.* 300 m of basalts that dip gently westwards (Figure 6.9).

Anderson and Dunham (1966) have suggested that the original scarp face in Trotternish formed as a result of tilting and faulting in Neogene times. Such scarp development probably exposed the full thickness of lavas and the uppermost underlying sedimentary rocks, and initiated a long-term process of scarp retreat through failure of the latter under the weight of the former. The present escarpment exhibits a scalloped planform attributed by Anderson and Dunham to intersection of arcuate failure planes. Scarp retreat has cut backward into a gentle dipslope of broad valleys and rounded spurs, so that the crest of the present scarp consists of alternating cols and summits, the latter including eight peaks over 500 m and culminating in The Storr (719 m).

Geomorphological mapping indicates that the last (Late Devensian) ice-sheet moved northwards across the Trotternish peninsula. Ballantyne (1990) identified a periglacial trim-line that descends northwards from 580–610 m to 440–470 m along the escarpment, and proposed that the higher peaks remained above the ice as nunataks, a proposition supported by X-ray diffraction analysis of clay minerals and cosmogenic nuclide dating of bedrock surfaces above and below the trimline; cosmogenic isotope dating also indicates emergence of the escarpment from under the last ice-sheet at *c.* 17.5 cal. ka BP (Ballantyne, 1994; Stone *et al.,* 1998). As a result of renewed cooling during the Loch Lomond Stade of *c.* 12.9–11.5 cal. ka BP, two small corrie glaciers developed east of the scarp, at Coire Cuithir [NG 470 592] and Coire Scamadal [NG 498 552], but the remainder of the escarpment appears to have been ice-free and exposed to severe periglacial conditions at this time (Ballantyne, 1990).

The Trotternish landslides

Slipped rock-masses extend continuously along the foot of the escarpment over a horizontal distance of 23 km, and for a further 9 km below the basalt cliff that extends south-west from the northern end of the escarpment. A further small area of slipped rock fringes the basalt cliffs of Glen Uig on the west side of the peninsula (Figure 6.9). Two distinct zones of landsliding can be identified: an inner zone, adjacent to the scarp face, of bold angular detached blocks and pinnacles (Figure 6.10) and (Figure 6.11) and an outer zone of subdued, rounded landslip terrain, extensively covered by peat (Ordnance Survey, 1964). Anderson and Dunham (1966) suggested that erosion by the last ice-sheet removed all evidence of previous landslides, implying that all of the present area of slipped rock represents failure following ice-sheet retreat. Godard (1965), however, proposed that the outer zone represents slipped rock-masses that were subsequently over-ridden by glacier ice. Various lines of evidence favour Godard's interpretation, particularly northwards-oriented ice moulding of landslide blocks, the presence of till deposits in hollows, and over-riding of landslide blocks by lateral moraines deposited by the two corrie glaciers that developed east of the escarpment during the Loch Lomond Stade (Ballantyne, 1990). Conversely, angular blocks and delicate pinnacles of the inner zone show no evidence of glacial modification and appear to represent failure and sliding of rock masses after ice-sheet retreat.

Several different landslide forms occur within the inner zone adjacent to the basalt scarp. Adjacent to the escarpment crest are a number of incipient failures, where basalt blocks have become detached from the crest along master joints aligned northwards, but have experienced little or no displacement. Resting against or detached a short distance from the scarp are foundered blocks of intact rock, for example at Baca Ruadh [NG 478 576], Coire Cuithir [NG 470 586] and Dun Dubh [NG 441 666]. Farther out from the crest are isolated tabular blocks such as Cleat [NG 447 669] and shattered rock pinnacles such as the Old Man of Storr (Figure 6.11) and the Quiraing needle. Along many stretches of the escarpment, however, evidence for major post-glacial rockslides is absent, and the scarp face is fringed with relict talus slopes, now extensively gullied and eroded (Hinchliffe, 1998, 1999; Hinchliffe *et al.,* 1998).

The Storr and Quiraing

The most impressive areas of landsliding occur at The Storr ([NG 485 540]; see also Emeleus and Gyopari, 1992) and Quiraing [NG 455 692]. The entire south-east face of The Storr has collapsed to form a great hollow, Coire Faoin [NG 497 537], that is bounded to the south-west and north-west by sheer lava cliffs 200 m high. The undercliff zone of the landslide is a labyrinth of lava-capped blocks, narrow defiles and pinnacles of shattered rock, of which the 49 m-high Old Man of Storr is the largest (Figure 6.11). Below the eastern threshold of Coire Faoin, however, the landslipped blocks are subdued and rounded by glacial erosion, indicating that post-glacial landsliding was confined to an area of about 0.25 km^2 above the 350 m contour. Older, glacially modified slipped rock, however, extends down to 200 m, up to 1.5 km from the present cliff-face.

The Quiraing landslide at the northern end of the escarpment is one of the largest landslides in Great Britain. It occupies an area of *c.* 8.5 km^2 and extends 2.2 km eastwards from the scarp crest to the coastline. Like The Storr landslide, it consists of an inner (post-glacial) zone of tabular and toppled landslip blocks, pinnacles and deep clefts, and an outer zone of more subdued landslide terrain representing remnants of ancient landslides that occurred before the last and possibly earlier ice-sheets crossed the area. In the central part of the slide area, landslip blocks up to 70 m high have dammed a chain of small lakes, of which Loch Fada [NG 458 698] is the longest, with a length of over 300 m.

Interpretation

Structure and mode of landsliding

Interpretation of the deep structure of the Trotternish landslides has focused on The Storr and Quiraing slides. Anderson and Dunham (1966) estimated that prior to the failure of slipped rock at The Storr, the scarp crest lay about 600 m east of its present position. They observed repetitive outcrop of steeply dipping Jurassic sediments, palagonite tuffs and lavas in the lower parts of the slide mass, and inferred that the landslide represents successive rotational failures of a thickness of up to 300 m of sedimentary rocks and tuff under a similar thickness of basalt (Figure 6.12). They concluded that the most recent (i.e. proximal) failures were seated on an upper sill, the Creag Langall Sill, but that earler failures took place over a thicker lower sill, the Armishader Sill (Figure 6.12). The outer part of the Quiraing slide also appears to exhibit cyclic outcrop of Jurassic sediments, tuffs and lavas. Here Anderson and Dunham (1966) inferred that a thickness of *c.* 200 m of sedimentary rocks and tuff had failed under the weight of *c.* 300 m of lavas, again in the form of successive deep rotational slides, here seated on a transgressive, westward-dipping dolerite sill that crops out in nearshore islands.

Although the cyclic repetition of Jurassic sedimentary rocks, palagonite tuffs and lavas identified by Anderson and Dunham (1966) appears consistent with their model of rotational sliding and consequent back-tilting of slipped blocks (Figure 6.12), other evidence suggests that it represents over-simplification of the nature of rock displacement. It requires rotation of slipped masses against the regional westwards dip of the strata, until the outmost slipped masses are resting at improbably low angles, and infilling of the huge gaps between slipped blocks with 'rock debris' of unspecified origin. Moreover, some landslide blocks, for example at The Storr, are tilted forward (eastwards) and not backward as the rotational model suggests (Figure 6.11). The model, moreover, does not account for the detachment of large intact landslide blocks without back-tilting, notably Cleat [NG 447 669], Leac nan Fionn [NG 453 704] and Dun Dubh [NG 459 687]. These suggest a different interpretation, involving planar sliding or gliding of thick lava blocks over the weaker sedimentary rocks, probably the Upper Jurassic Staffin Shales, which in Trotternish achieve a thickness of over 117 m (Hallam, 1991). Lateral displacement and subsidence of thick lava blocks would have been accompanied by pronounced deformation of underlying sedimentary strata under the weight of the lavas; this, rather than block rotation, may account for the outcrops of steeply dipping sedimentary rocks and tuffs between the outermost lava blocks. By contrast,backward rotation is evident in a similar context nearby at Hallaig (Isle of Raasay — see GCR site report, this chapter) where active landslipping is entirely in Jurassic sedimentary rocks (Russell, 1985).

The present position and altitude of such intact blocks implies displacement and subsidence without fragmentation of the lava caprock, possibly indicating gradual movement analogous to that proposed for cambering of limestone caprocks over Jurassic mudstones in England (see Postlip Warren GCR site report, this chapter). Like these, block movement may relate to reduction of shear strength in underlying argillaceous strata during thaw of ice-rich permafrost (Parks, 1991; Hutchinson, 1991; Ballantyne and Harris, 1994). In contrast, the shattered lava pinnacles of the post-glacial slides at The Storr and Quiraing imply catastrophic failure after deglaciation. It thus appears likely that no single mode of failure and block movement accounts for all attributes of the slipped rock-masses.

Not all rock slope failures along the Trotternish Escarpment have involved block displacement. Ballantyne (1990) mapped four smaller post-deglaciation failures, probably rock topples or translational slides, that have produced runout of coarse debris below the scarp face. South of Baca Ruadh (at [NG 476 568]), a tongue of vegetated debris terminates down-slope in a *c.* 100 m-wide zone of bouldery mounds and hummocks, and a similar but smaller deposit occurs at [NG 441 651]. At [NG 449 646], a jumble of limestone boulders covers an area of nearly 0.2 km^2 and records collapse of the cliff upslope. At Carn Liath [NG 464 593] a tongue of rock debris 260 m wide and 500 m long descends from 400 m to 260 m. The visible debris consists of large angular boulders, many exceeding 2 m in length. The lower part of the debris tongue extends for 250 m over a slope of only 8°–9°, and appears to be about 10 m thick. The debris tongue reflects collapse of the lava scarp upslope, probably as a small rock-avalanche, and its extended runout over gentle gradients suggests flow (debris flow or grainflow) of the landslide debris (Ballantyne, 1991b).

Timing and activity

The lateral extent of landslipped rock along the Trotternish Escarpment implies a long history of slope instability and failure, with evidence of post-deglaciation sliding confined to a few sites adjacent to the present scarp. Although the age of failures that pre-date the advance of the last ice-sheet over the area is unknown, the evidence for multiple landslide events suggests a probable link with glaciation. Successive Pleistocene ice advances northwards along the escarpment are likely not only to have steepened the scarp face and removed earlier landslide debris from the footslope, but may also have induced scarp failure due to paraglacial stress-release (Ballantyne, 2002a). It is possible that deglaciation and consequent debuttressing of the scarp face created conditions favourable for failure on several different occasions throughout the Pleistocene Epoch. Hence the broad zone of ice-moulded landslide terrain along the length of the escarpment represents a sequence of landslides that occurred in response to several episodes of deglaciation, much as the post-glacial slides at The Storr and Quiraing represent response to Late Devensian deglaciation. The long-term evolution of the escarpment may thus be envisaged in terms of alternating glacial erosional and interglacial (paraglacial) land-sliding episodes.

Godard (1965) proposed that most post-glacial (inner zone) failures from the Trotternish Escarpment occurred soon after deglaciation, suggesting that they represent collapse of glacially steepened cliffs following the withdrawal of a supporting buttress of glacier ice. Cosmogenic ^{36}C1 radionuclide dating of the exposure age of two separate basalt pinnacles at The Storr landslide, however, yielded virtually identical ages averaging 6.5 ± 0.5 cal. ka BP (Ballantyne *et al.,* 1998b), consistent with radiocarbon-dated evidence for exposure of the present cliff at this time (Ballantyne, 1998). These dates indicate that the landslide occurred 7–10 ka after ice-sheet deglaciation, and at least 4 ka after the end of the Loch Lomond Stade, the final period of permafrost 'conditions in Scotland. Ballantyne *et al.* (1998b) inferred that progressive rock-mass weakening due to stress-release had been critical in conditioning failure, but noted that a seismic trigger could not be discounted. They also observed the significance of the age of failure in terms of indicating persistence of major landslide events well into the Holocene Epoch, an observation subsequently re-inforced by the even more recent date (*c.* 4 cal. ka BP) obtained for the Beinn Alligin rock-avalanche, 30 km east of The Storr (Ballantyne and Stone, 2004). The rock avalanche at Carn Liath [NG 464 693] on the Trotternish escarpment appears to have occurred even more recently, as limited lichen cover on the source rockwall suggests failure within the past few centuries (Ballantyne, 1991b).

Although the slipped rock-masses at Trotternish appear to be stable at present, Anderson and Dunham (1966) suggested that where the toe of the Quiraing slide is being eroded by the sea there is 'continuous though not extensive movement' and that the main road near Flodigarry [NG 465 716] is 'frequently dislocated'. However, deformed sediments at the landside toe are overlain by undisturbed raised beach deposits and cut into by Holocene raised shorelines, suggesting that recent movement has been slight (Ballantyne, 1991a).

Talus accumulations

Since deglaciation, only limited areas of the Trotternish Escarpment have been affected by major rock slope failures. Much of the remainder, however, has experienced post-glacial cliff recession due to intermittent rock-fall, with concomitant accumulation of talus at the scarp foot. Such talus accumulations are now essentially relict (Figure 6.13). They support an almost continuous vegetation cover and are deeply dissected by gullies, many of which exhibit evidence of recent reworking of talus sediments by debris flows. The morphology, sedimentology and stratigraphy of a section of talus near the southern end of the escarpment ([NG 492 533]; (Figure 6.13)) have been investigated by Hinchliffe (1998, 1999), Hinchliffe *et al.* (1998) and Hinchliffe and Ballantyne (1999). Calculations based on the volume of talus accumulations at the foot of the basalt cliff indicate that 4.3–7.8 m of rockwall recession has occurred since deglaciation at *c.* 17.5 cal. ka BP The composition of the talus sediments indicates that approximately 70% of overall rockwall retreat has been due to rockfall, and that the remainder reflects granular weathering of the cliff-face. Radiocarbon-dated soil horizons within the talus imply that rockfall inputs have been very limited since the end of the Loch Lomond Stade at *c.* 11.5 cal. ka BP, and suggest that about 80% of total rockwall retreat occurred between 17.5 cal. ka BP and 11.5 cal. ka BP, during which period rockwall retreat rate averaged about 0.75 m ka^{-1}. Hinchliffe and Ballantyne (1999) attributed this high rate of late-glacial cliff recession to stress-release following ice-sheet deglaciation, and/or frost wedging under severe periglacial conditions. The stratigraphy of the upper parts of the talus accumulations reveals stacked debris-flow horizons intercalated with occasional slopewash horizons and buried organic soils, implying that rockfall debris has been extensively reworked by intermittent debris-flows throughout much of Holocene time.

Wider significance

The assemblage of landslide features represented along the Trotternish Escarpment is characteristic of those of basaltic successions not only along the western seaboard of Scotland, but also of areas of similar geological configuration in the wider North Atlantic Igneous Superprovince (Emeleus and Bell, 2005) and elsewhere (Evans, 1984). In Scotland, less extensive but equally spectacular areas of slipped basalts overlying Mesozoic sedimentary sequences occur at several locations in the Inner Hebrides, such as Score Horan [NG 285 594] and Ben Tianavaig [NG 517 410] on Skye, and at Gribun on Mull (Bailey and Anderson, 1925; Godard, 1965; Anderson and Dunham, 1966; Richards, 1971; Ballantyne, 1986a, 1991b). In all these cases the long-term history of scarp retreat probably reflects alternating periods of glacial steepening and loading, and intervening episodes of paraglacial stress-release, rock-mass weakening, rockfall and slope failure. Many of these occur at coastal locations, raising the possibility that coastal erosion may have triggered and accelerated post-glacial failure. Some exhibit signs of recent movement (Anderson and Dunham, 1966). These landslides constitute a family of structurally and lithologically conditioned slope failures quite distinct from those found on the Precambrian or Palaeozoic rocks of the Scottish mainland (cf. 'Introduction', Chapter 2). As at Trotternish, however, the deep structure of these landslides remains uncertain.

Although much of the literature on the Trotternish Escarpment focuses on post-glacial rock slope failures and slope modification, the outer zone of older, ice-moulded landslide terrain not only provides evidence for previous episodes of slope failure during past interglacials, but also forms the most extensive area of glaciated landslide topography in Great Britain. Most pre-glacial landslides in Scotland can be identified only as modified failure scars, as the failed rock-masses and runout debris have been removed by glacier ice (Clough, 1897; Ballantyne, 2002a). Only on Trotternish have extensive areas of slipped blocks survived the passage of one or more ice-sheets, leaving a landscape of ice-moulded lava blocks and intervening lochans or peat-filled hollows. Such terrain is particularly well exemplified by the outer (eastern) parts of the Quiraing landslide.

Conclusions

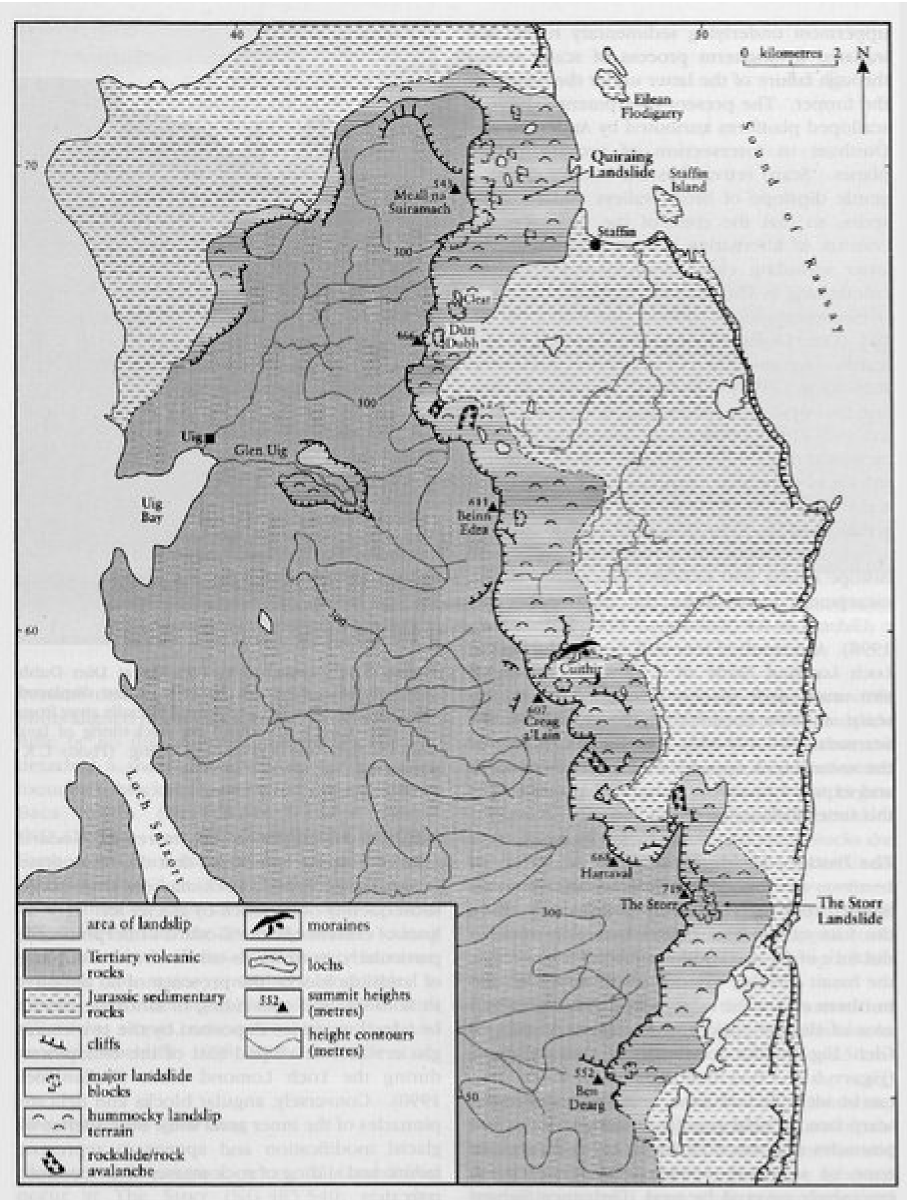
The Trotternish peninsula in northern Skye includes probably the largest continuous area of landslide terrain in Great Britain (totalling nearly 40 km^2), together with the largest individual rockslide (the Quiraing slide, 8.5 km^2) and some of the finest examples of landslides associated with Paleocene volcanic rocks. These distinctions reflect the geological configuration of Trotternish, where a succession of basalt lava flows roughly 300 m thick overlies a similar thickness of Jurassic mudstones, sandstones and limestones into which have been intruded thick dolerite sills. Westward tilting and faulting of this sequence, probably in Neogene time, created a steep escarpment of lavas overlying relatively weak sedimentary rocks. Throughout the Quaternary Period, this scarp face has retreated westwards through a combination of alternating episodes of glacial erosion and interglacial landsliding and rockfall. Trotternish provides probably the clearest example in Britain of this glacial—paraglacial cycling process.

The landslide terrain east of the Trotternish Escarpment can be subdivided into two zones: an outer zone of subdued, ice-moulded landslide blocks and an inner zone of fresh tabular landslide blocks, shattered basalt pinnacles and talus accumulations. The outer zone represents landslide terrain that was over-ridden and modified by the last (and possibly earlier) ice-sheets, and represents the most extensive area of glaciated landslip terrain in Great Britain. The inner zone represents the products of scarp failure, landsliding and rockfall since ice-sheet deglaciation, which probably occurred about 17 000 years ago. Scarp failure was probably caused by steepening of the basalt cliff by glacial erosion and stress-release within the rock mass caused by unloading as the last ice-sheet down-wasted. Stress-release results in slow opening of joints within the rock, resulting in progressive loss of strength. Although this effect often causes slope failure soon after deglaciation, failure may be delayed for millennia as the joint network propagates. The major landslide at The Storr occurred between 7000 and 6000 years ago, some 10 000 years after deglaciation.

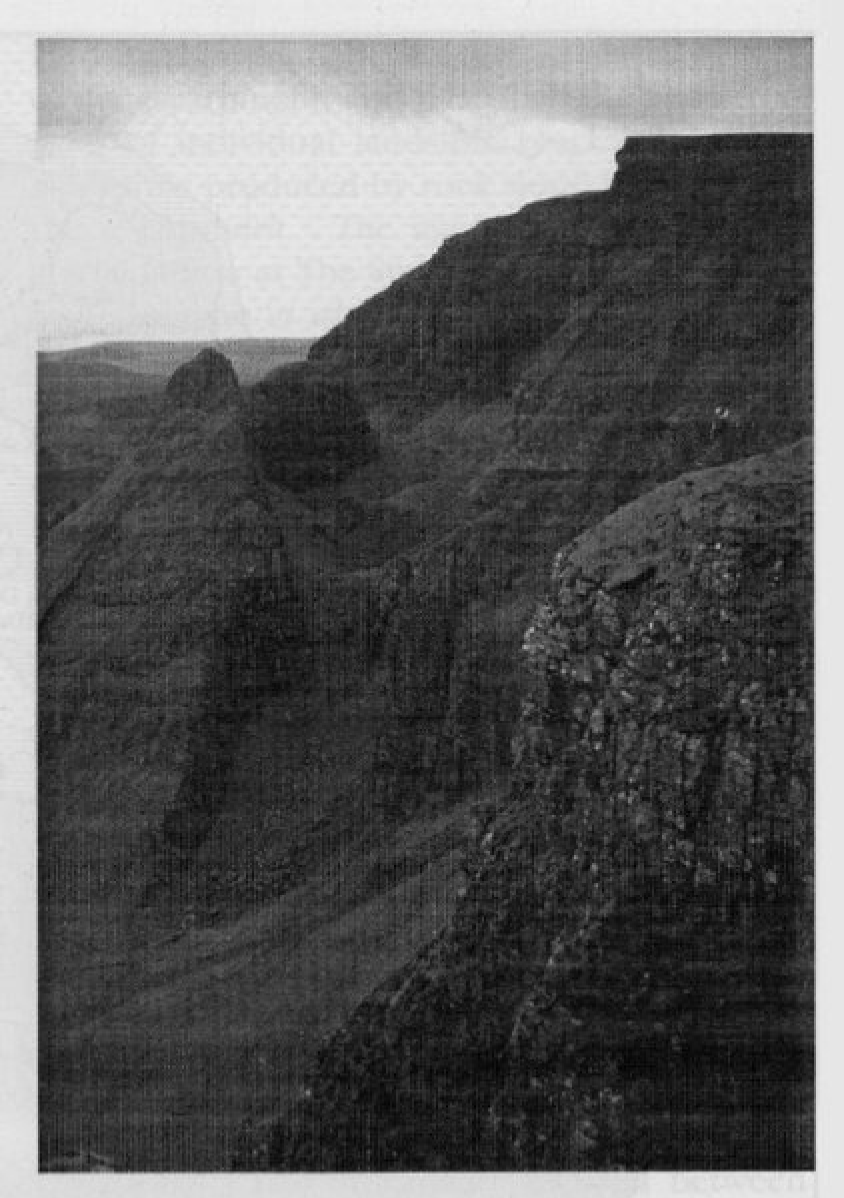
Various modes of slope failure and landsliding are evident along the escarpment, but the structure of the Trotternish landslides remains speculative. Anderson and Dunham (1966) proposed that scarp retreat has been dominated by deep rotational slides in the sedimentary rocks underlying the lavas, but the configuration of some intact landslide blocks suggests planar sliding or gliding of the lava caprocks over a layer of deforming shale, possibly when the strength of the latter was reduced by thaw of ice-rich permafrost. A small number of shallow rockslides or topples have also occurred since deglaciation, and extensive areas of talus have accumulated as a result of rockfall from lava cliffs. In the southern part of the escarpment, rockfall and weathering have resulted in 4.3–7.8 m of cliff retreat since deglaciation, most of which occurred in the interval between ice-sheet deglaciation and the end of severe periglacial conditions around 11 500 years ago. The resulting talus slopes were subsequently modified by intermittent debris-flows, and are now essentially relict and extensively eroded.

Much greater amounts of post-deglaciation cliff retreat have occurred at major landslide sites, notably at The Storr and Quiraing. Both of these famous landslides consist of a chaotic inner zone of tilted lava blocks, deep defiles and shattered lava pinnacles, and an outer zone of ancient landslide blocks modified by the passage of the last and probably earlier ice-sheets. The Storr landslide extends 1.5 km from scarp crest to toe, and Quiraing landslide reaches the sea 2.2 km from the escarpment crest. The toe of the latter is reported to have experienced recent movement, possibly due to coastal erosion.

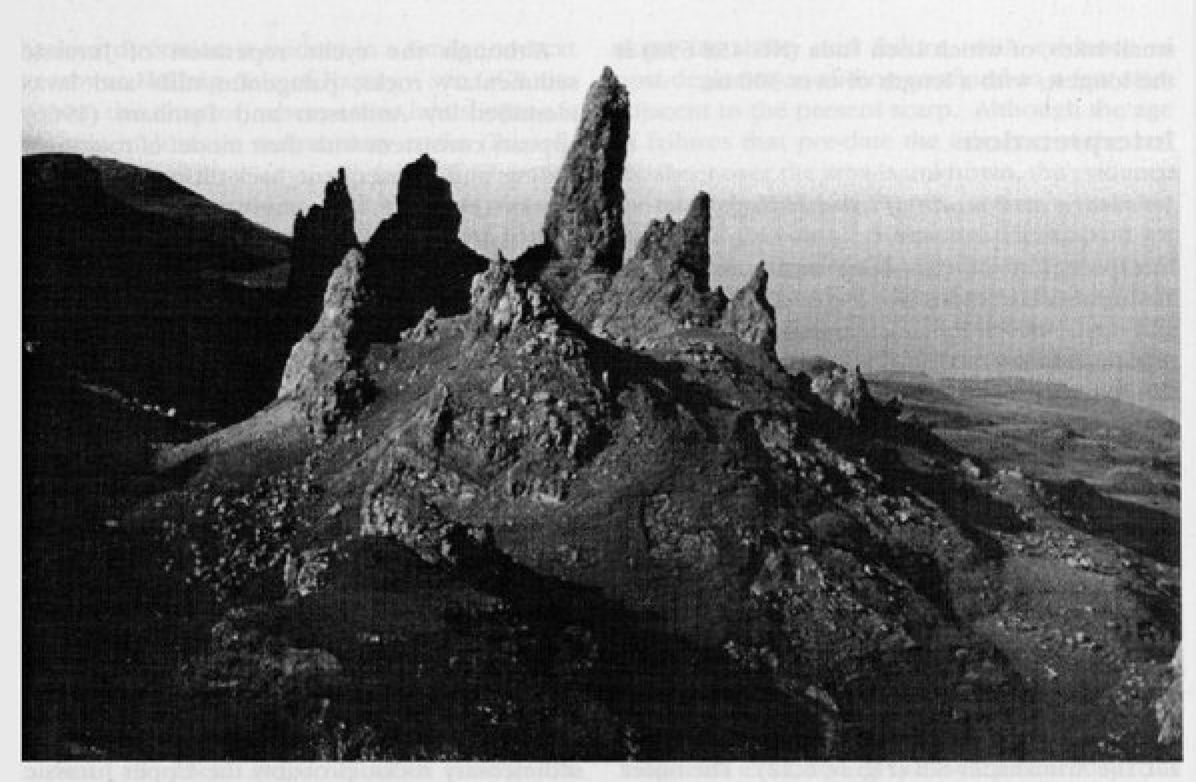
References



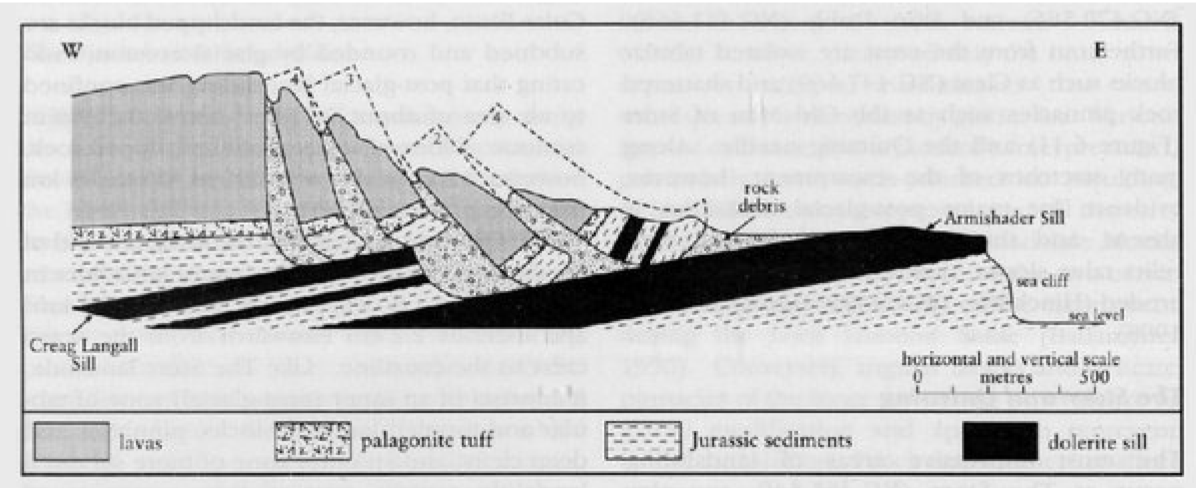
(Figure 6.9) Geological and geomorphological map of the Trotternish Escarpment GCR site. The extent of landslide terrain is based partly on British Geological Survey mapping. Modified after Ordnance Survey (1964).



(Figure 6.10) Detached lava blocks at Dun Dubh [NG 441 666]. Since deglaciation, these displaced blocks have foundered and moved laterally away from the scarp face, but without the back-tilting of lava flows characteristic of rotational sliding. (Photo: C.K. Ballantyne.)



(Figure 6.11) Pinnancles of shattered basalt at The Storr landslide. The highest pinnacle is the Old Man of Storr. Note the eastwards (forwards) tilt of the slipped mass, away from the escarpment. (Photo: C.K. Ballantyne.)



(Figure 6.12) A previous interpretation of The Storr landslide, redrawn from Anderson and Dunham (1966; The geology of northern Skye, Memoir of the Geological Survey of Great Britain, p. 191, fig. 23), by permission of the Director, British Geological Survey. Their model depicts slide evolution as a sequence of successive deep rotational slides in the sedimentary rocks and palagonite tuffs underlying the basalt scarp, and involves back-titling of lava blocks. Compare with (Figure 6.10) and (Figure 6.11).

(Figure 6.13) Relict talus accumulations at the southern end of the Trotternish Escarpment. The talus slopes are now vegetated and deeply dissected by active gullies. The main period of talus accumulation occurred prior to 11.5 cal. ka BP (Photo: C.K. Ballantyne.)