

Rock-Slope Failures in the North West Highlands

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Abstract

Over 400 postglacial rock-slope failures $>0.1 \text{ km}^2$ in extent have been identified in the NW Highlands. Most are rock-slope deformations (40%) or arrested rockslides (38%), with smaller numbers of fragmented slides, rock avalanches and rockfalls or topples; 78% are located on schists. All can be considered paraglacial features, preconditioned by rock damage due to ice loading and unloading, glacial erosion, thermomechanical effects and hydromechanical fatigue during successive glacial episodes. Progressive failure (brittle shearing of internal rock bridges and reduction of friction angles to residual) has probably played a major role in reducing rock-mass strength to critical levels, and there is evidence that seismic activity caused by reactivation of faults during glacio-isostatic uplift may have triggered rock release in some (possibly many) cases. Numerous debris-free failure scars represent rupture surfaces of rock-slope failures where displaced rock or runout debris has been removed by glaciers during the Loch Lomond Stade or earlier. Rock-slope failures operating throughout much of the Quaternary have played a significant role in shaping the present form of mountain summits and ridges, glacial troughs and many cirques.

Keywords

Rock avalanches • Arrested rockslides • Fragmented rockslides • Rockfall • Toppling failures • Rock-slope deformations • Debris-free failure scars • Paraglacial • Progressive failure • Earthquakes

14.1 Introduction

The NW Highlands constitute mainland Scotland north of the Great Glen. West of the Moine Thrust Zone (Fig. 14.1), the NW Highlands comprise an undulating basement of Archaean Lewisian gneiss above which rise mountains of Neoproterozoic sandstones (here referred to as Torridonian sandstones) and Cambrian quartzite (Chap. 2). East of the Moine Thrust Zone, the terrain is dominated by the thrust and folded schists (metapsammites, metapelites and semipelites) of the Neoproterozoic Moine Supergroup, locally interleaved with inliers of 'Lewisianoid' gneisses or intruded by granitic rocks. In Caithness and around the Moray Firth, the Moine rocks are overlain by younger sedimentary rocks, mainly Devonian sandstones, and parts of Ardnamurchan and Morvern are composed of Palaeogene volcanic rocks. Most rock-slope failures in the NW Highlands occur in steep, mountainous terrain, though some (such as those bordering the Great Glen trough) occur on ground below 400 m.

The term *rock-slope failure* (RSF) describes the downslope movement of large rock masses, irrespective of the mode or amount of displacement or the rate at which it occurred. The term incorporates both rapid rock-slope failures (major rockfalls and toppling failures, rockslides and rock avalanches) and rock-slope deformations caused by the gradual downslope movement of mountain slopes, but excludes small-scale rockfalls and mass movements in unlithified sediments or soil. According to Jarman and Harrison (2019), over 660 and possibly as many as 920 postglacial RSFs are present in the Scottish Highlands. Moreover, the widespread occurrence of RSF cavities (hollows) or rupture surfaces that lack runout debris or displaced rock masses represent the sites of numerous RSFs where mobilised rock has been removed by glacier ice; these sites are referred to here as debris-free failure scars (DFFSs).

The classification of postglacial RSFs employed here follows a simplified version of the revised Varnes

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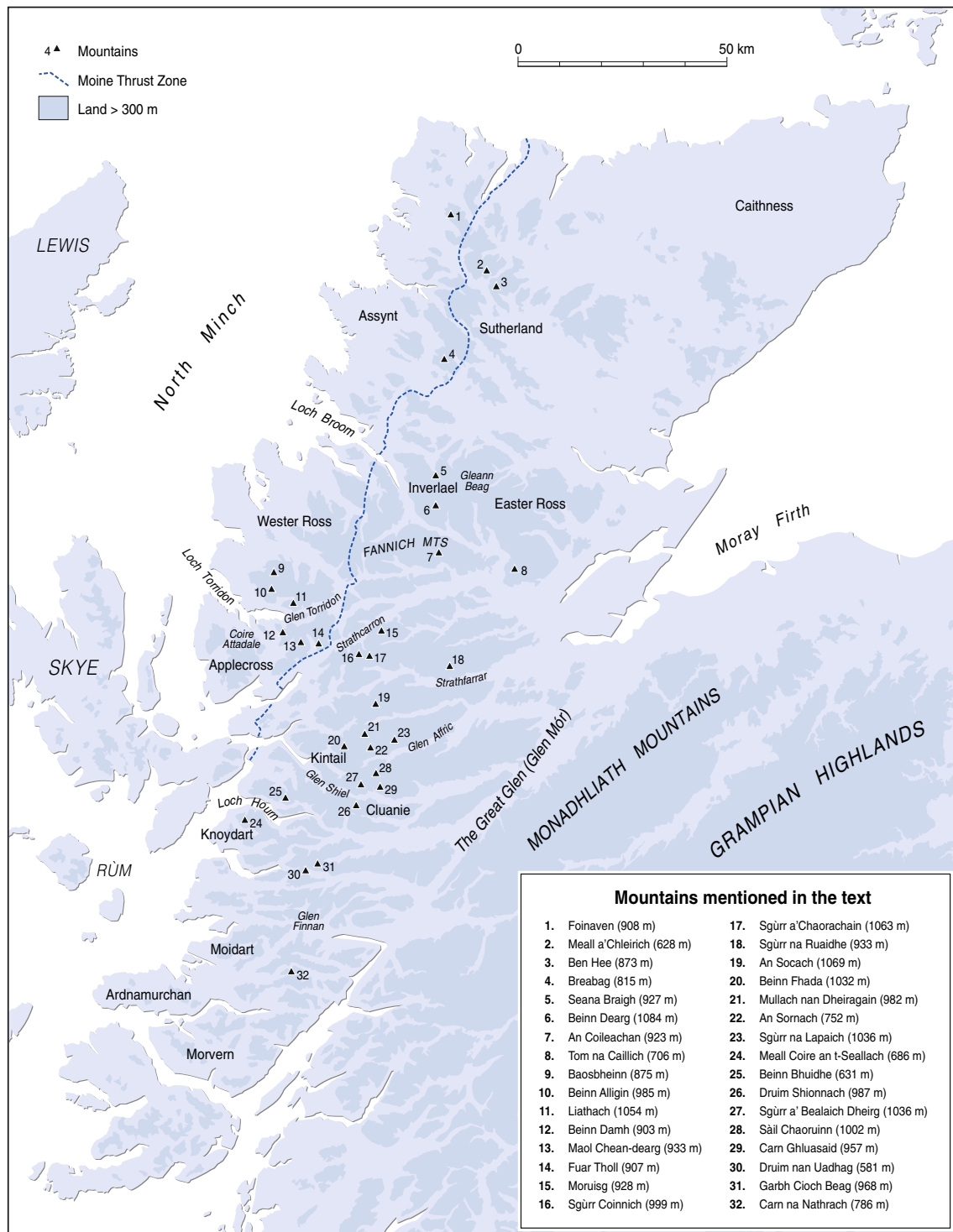


Fig. 14.1 The NW Highlands, showing the Moine Thrust Zone and sites mentioned in the text

classification (Hung et al. 2014; Fig. 14.2). Category RF (rockfall) includes discrete major rockfalls and topples from cliffs but excludes intermittent small-scale rockfalls that have accumulated as talus. Category AS (arrested slides) incorporates sliding failures where the detached rock mass

has largely retained integrity, irrespective of travel distance. Most arrested slides in the NW Highlands are planar, wedge or complex slides; rotational slides are rare. Category FS (fragmented slides and rock avalanches) comprises catastrophic landslides where the mobile rock has largely or

completely disintegrated, forming a tongue of runout boulders (Hermanns and Longva 2012); the term ‘rock avalanche’ is restricted to fragmented rockslides that exhibit extended debris runout. Category RSD (rock-slope deformation) identifies areas of slow gravitational deformation of mountain slopes, typically manifest in arrays of scarps and/or anticarps (upslope-facing scarps), rock benches, tension cracks, trenches and slope bulging; most RSDs lack a fully-defined rupture surface or clearly defined lateral margins.

The timeline for postglacial RSFs begins with local deglaciation. At ~ 17 ka, most of the region was still occupied by the shrinking remnants of the last ice sheet, but by ~ 16 ka nunataks had begun to emerge through the ice cover, and by ~ 15 ka glacier ice was largely confined to inland valleys and cirques (Ballantyne and Small 2019; Chap. 4). Under the cool temperate conditions of the Late-glacial Interstade (~ 14.7 to 12.9 ka), glaciers completely disappeared from low ground but may have persisted on some high plateaux. During the Loch Lomond Stade (~ 12.9 to 11.7 ka), a large icefield reoccupied mountainous terrain across much of the region, with smaller icefields in Assynt and Sutherland and on the Beinn Dearg massif, and numerous independent cirque and valley glaciers on outlying mountains (Bickerdike et al. 2018; Chap. 4). Postglacial RSFs within the limits of the Loch Lomond Readvance (LLR) glaciers must have occurred after these retreated (~ 12.5 to 11.5 ka), whereas RSFs outside or above these limits may have occurred at any time since ice-sheet retreat (~ 17.0 to 14.0 ka).

Early research on the RSFs of the NW Highlands was largely limited to pioneering theses by Watters (1972), Holmes (1984) and Fenton (1991), a few accounts of individual RSF sites (e.g. De Frietas and Watters 1973; Holmes and Jarvis 1985; Sellier and Lawson 1998), and a review by Ballantyne (1986). During the present century, the literature on the RSFs in Scotland has expanded markedly, focusing on the development and interpretation of RSF inventories (Jarman 2006, 2007a; Cave and Ballantyne 2016; Jarman and Harrison 2019), terrestrial cosmogenic nuclide (TCN) exposure dating of catastrophic RSFs (Ballantyne and Stone 2013; Ballantyne et al. 2014) and the significance of RSFs in the long-term evolution of Scotland’s mountain landscapes over multiple glacial-interglacial cycles (Jarman 2009; Ballantyne 2013, 2019).

14.2 Characteristics and Distribution

An inventory of postglacial RSFs exceeding 0.01 km² in area in the NW Highlands has been compiled by the author using satellite imagery (Google Earth™) and extensive field verification (Fig. 14.3). Excluding coastal RSFs, a total of

403 RSFs were identified (Table 14.1), together with a further 105 possible RSF sites; the latter are not included in the analyses below.

As with all attempts to classify RSFs, the fourfold subdivision outlined above (RF, AS, FS, RSD) raises occasional problems of application, mainly in the form of hybrid landforms. Some RSDs exhibit zones of partial collapse, and over 25% of RSFs classified as arrested slides are partly fragmented. In some cases, differentiation of RSDs from arrested slides involving limited rock displacement is difficult, as both types may share common diagnostic features. At a few sites, delimitation of RSD extent proved problematic, as lateral margins are poorly defined, though the presence of a springline where groundwater percolating through fractured rock emerges at the surface aided identification of the margins of both RSDs and some arrested slides. A further problem arose in deciding whether some laterally-contiguous RSFs should be recorded as a single slope failure or two or more discrete RSFs.

Of the 403 recorded postglacial RSFs, 161 (40%) were identified as RSDs, 151 (37.5%) as arrested slides, 59 (14.6%) as fragmented slides or rock avalanches and 32 (7.9%) as rockfalls or toppling failures (Table 14.1). By comparison, an inventory of 358 RSFs compiled by Jarman and Harrison (2019) for the mountains of the NW Highlands (but apparently excluding RSFs on lower ground) identified 139 (38.8%) RSDs, 149 (41.6%) arrested slides and 70 (19.6%) ‘rock avalanches’, the latter being broadly equivalent to categories FS plus RF.

Figure 14.4 summarises size distributions of the different RSF categories. All distributions differ significantly ($p < 0.01$), except for categories AS and FS. Category RF failures are small (< 0.1 km²) and largely limited to cliffed scarps (Fig. 14.2f) and cirques. By contrast, 66% of RSDs exceed 0.1 km² in area, 32% exceed 0.25 km², and most occur on open valley-side slopes, typically on gradients of ~ 32 to 39° (Fig. 14.2e). Arrested and fragmented slides occupy a range of topographic settings and 33% of these failures exceed 0.1 km² in size.

Most RSFs ($\sim 78\%$) are seated on Moine metasedimentary rocks, mainly on dominantly psammitic schists ($\sim 54\%$) and on metapelites and semipelites ($\sim 24\%$). This predominance partly reflects the extensive outcrop of these lithologies east of the Moine Thrust Zone. However, a study by Cave and Ballantyne (2016) of the spatial density of RSFs and DFFSs on different lithologies normalised for slopes $> 25^\circ$ in areas bordering the Moine Thrust Zone showed that the density of sites on Moine schists exceeds that on all other lithologies by a factor of two or more. This conclusion supports the long-established view that Scottish mountain slopes underlain by schists have been especially prone to failure. In the NW Highlands, this is particularly true of RSDs, 87% of which are seated on schists. The susceptibility

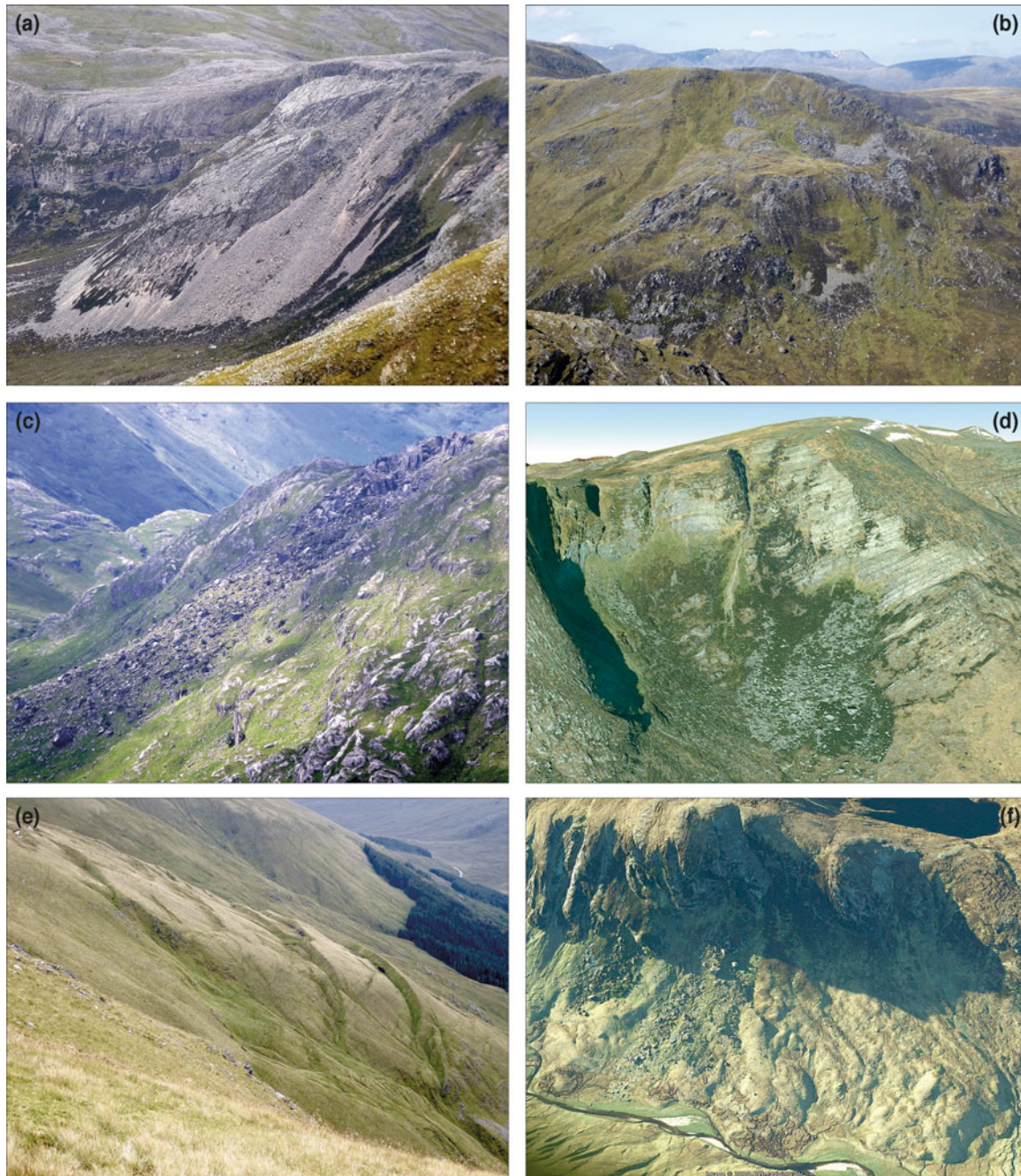


Fig. 14.2 Examples of different categories of rock-slope failures in the NW Highlands. **a** Arrested slide on Cambrian quartzite, Breabag, Assynt. **b** Large arrested slide, Sàil Chaoruinn, Cluanie. **c** Fragmented slide, Druim nan Uadhag, Dessarry; block toppling has occurred at the slope crest. **d** Rock avalanche in Garbh Choire Mór, An Coileachan, Fannich Mountains. **e** Part of the Sgùrr a'Bealaich Dheirg rock-slope

deformation in Glen Shiel, showing slope bulging and well-developed anticarps. **f** Gleann Beag, Easter Ross: on the left are two rockfalls; on the right, rockwall collapse has resulted in the formation of a hummocky runout lobe. (Images: **a**, **b**, **c**, **e** Colin Ballantyne; **d**, **f** Google Earth™)

of schistose rocks to failure and slope deformation was attributed by Watters (1972) and Holmes (1984) to their relatively low peak and residual friction angles and pronounced mechanical anisotropy, though failure on schistose rocks has occurred on anacinal and orthocinal as well as cataclinal slopes, and on slopes underlain by near-vertical

foliation. Jarman and Harrison (2019) claimed that thin pelites interleaved within psammitic rocks 'lubricate' mass movement but provided no evidence; moreover, 'lubrication' is not a component of rock-slope mobilisation.

The overall distribution of RSFs in the NW Highlands is uneven (Fig. 14.3). About 75% lie within 20 km of the main

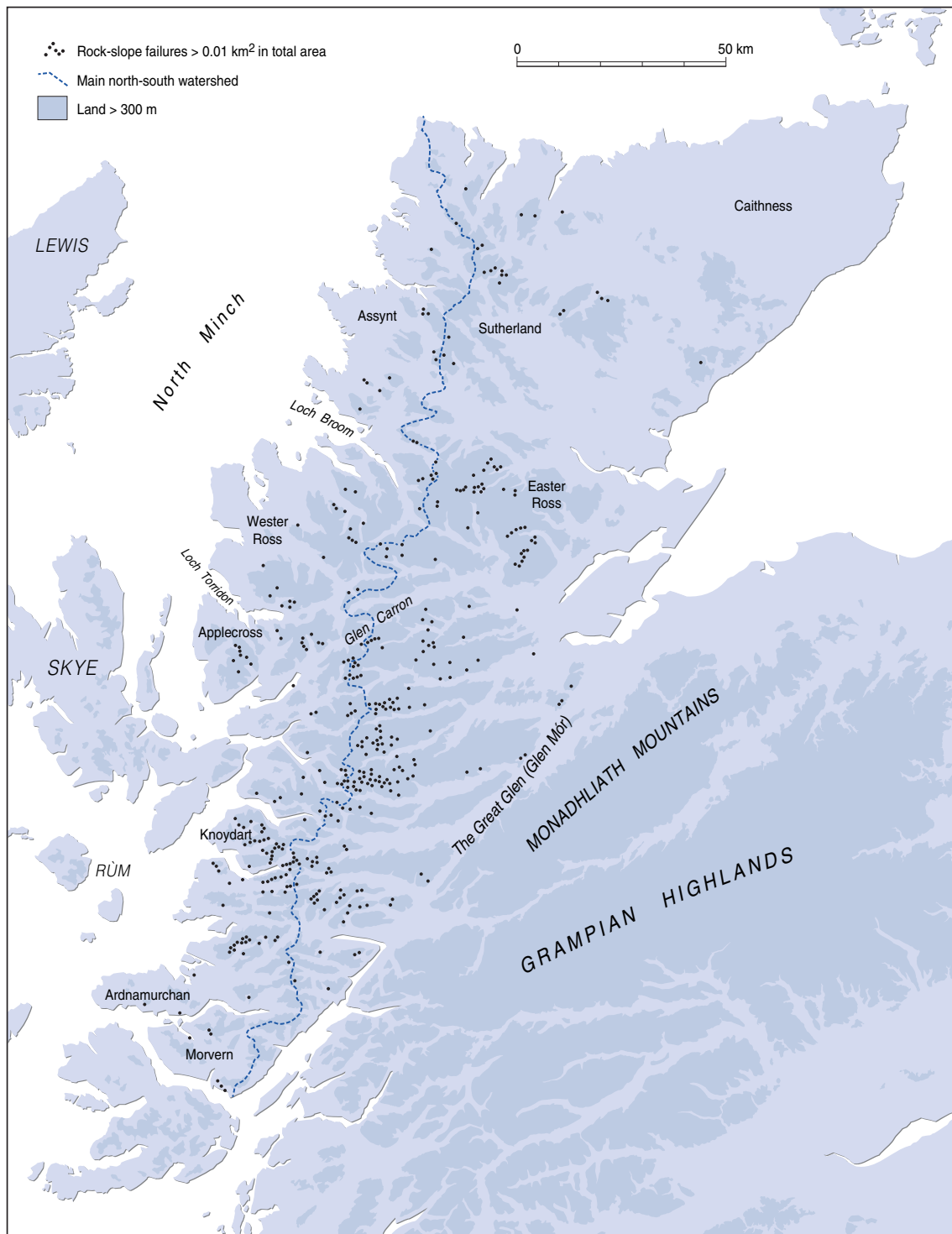


Fig. 14.3 Distribution of rock-slope failures $> 0.01 \text{ km}^2$ in the NW Highlands

north-south drainage divide, with clusters in the Kintail-Cluanie-Glen Affric area, particularly east of the main drainage divide, and the Knoydart-Glen Finnan area, with several smaller outlying clusters, such as those in Easter Ross and Moidart (Figs. 14.1 and 14.3). Jarman and

Harrison (2019) explained such clustering in terms of zones of ‘concentrated erosion of bedrock’ operating through ‘catastrophic’ rates of glacial erosion in ‘late-developing’ glacial breaches and trough heads during ‘recent glacial cycles’. Their argument is circular: ‘association’ of RSFs

Table 14.1 Characteristics of rock-slope failures (RSFs) in the NW Highlands

Category ^a	n	%	Lithology (%) ^b						Location (%) ^c			
			MPs	MPe	TS	LG	Q	Other	1	2	3	Crest
RSD	161	40.0	64.6	22.4	7.4	0.6	1.9	3.1	73.3	22.4	4.3	69.6
AS	151	37.5	47.7	26.5	5.3	9.9	6.0	4.6	61.6	20.5	17.9	78.1
FS	59	14.6	45.8	25.4	20.3	5.1	1.7	1.7	49.2	22.0	28.8	89.8
RF	32	7.9	43.7	18.7	18.7	6.3	6.3	6.3	53.1	9.4	37.5	78.1
All RSFs	403	100	53.8	24.1	9.4	5.2	3.7	3.7	63.8	20.6	15.6	76.4

^aRSD: rock-slope deformations. AS: arrested slides. FS: fragmented slides and rock avalanches. RF: rockfalls and toppling failures

^bMPs: Moine metasediments, dominantly psammitic. MPe: Moine metasediments, dominantly pelitic or semipelitic. TS: Torridonian sandstones. LG: Lewisian gneiss. Q: Cambrian quartzite and Moine quartzite. Other: granite, diorite, Devonian sedimentary rocks and Palaeogene volcanic rocks

^c1: open valley-side slopes. 2: spurs. 3: cirque headwalls, sidewalls and adjacent slopes. Crest: RSFs that originate at the slope crest

with selected breaches and trough heads is inferred to indicate ‘intense erosion in recent [glacial] cycles’ and hence ‘late-development’ of these locations, which in turn is assumed to explain the ‘association’ of RSFs with such ‘late-developing’ glacial breaches and trough heads. As they acknowledged, many breaches and trough heads contain few or no RSFs. They argued that slopes at such sites have become ‘stress-hardened’ by repeated episodes of glacial erosion, but this concept has no physical meaning; it has been demonstrated that cyclic loading, erosion and unloading of slopes during successive glaciations results in rock-slope weakening, not slope ‘hardening’ (e.g. Grämiger et al. 2017, 2018, 2020; Riva et al. 2018). An additional implication of their argument is that major watershed breaches with numerous ‘associated’ RSFs, such as Glen Shiel, developed only during ‘recent cycles’, and were unaffected by throughflow of glacier ice during earlier periods of ice-sheet glaciation, which is implausible. The author has plotted the distribution of RSFs relative to all possible glacial breaches in the NW Highlands (main watershed breaches, secondary breaches and col breaches). Only 71 RSFs (17.6%) occur within 3 km of the site of watershed breaching, and only 28 (6.9%) occur within 3 km of the main watershed breaches. Even a generous interpretation of what constitutes a glacial breach therefore fails to substantiate a causal connection between breaching and the distribution of RSFs.

A more meaningful control is slope height and gradient: RSFs in the NW Highlands tend to cluster in the highest, steepest and most dissected terrain, primarily on valley-side slopes (Table 14.1). Analysis of a sample of such slopes in areas underlain by Moine rocks where there are dense concentrations of RSDs and arrested slides indicates significantly steeper modal slope values in comparison with similar slopes lacking RSFs. This contrast suggests that gradient has played an important role in determining limit-equilibrium conditions for failure (cf. Cossart et al. 2014) and partly

explains the variable density of RSF occurrence on Moine schists, and in particular the clustering of postglacial RSFs on the exceptionally steep slopes of the Kintail-Cluanie-Glen Affric and Knoydart-Glen Finnan areas.

14.3 Causes of Postglacial RSFs

As in other deglaciated mountain areas, rock-slope failure in the Scottish Highlands has been conditioned by multiple episodes of glaciation and deglaciation, and postglacial RSFs are essentially paraglacial landforms (Ballantyne 2002). Paraglacial slope failure in deglaciated terrain reflects preconditioning, preparatory and trigger factors (McCull 2012). Preconditioning factors include lithology, structure, stress history and rock-mass strength. Because recurrent cycles of glaciation impose mechanical stress on rock slopes as glaciers advance, erode and retreat, all slopes must have been weakened by incremental rock damage before the onset of the most recent glacial cycle, some to potentially critical levels. Preparatory factors associated with the most recent cycle of glaciation and deglaciation include glacial erosion, differential glacial loading and unloading of high-relief terrain (which induces rock-mass dilation (‘rebound’), stress redistribution and fracture extension and criticality), seismic fatigue (rock damage caused by earthquakes), thaw of permafrost ice in joints, rock damage due to thermomechanical effects, particularly thermoelastic strain induced by exposure to seasonal temperature changes during deglaciation, and hydromechanical fatigue caused by long-term changes in groundwater pressures as glaciers advance and retreat (Leith et al. 2014; Gischig et al. 2015; Grämiger et al. 2017, 2018, 2020). Potential triggers include debuttressing (reduction of lateral support provided by glacier ice to a critically-stressed slope), excess joint-water pressures, thaw of permafrost, earthquakes, and progressive failure in the form of rock-mass degradation over long timescales caused by

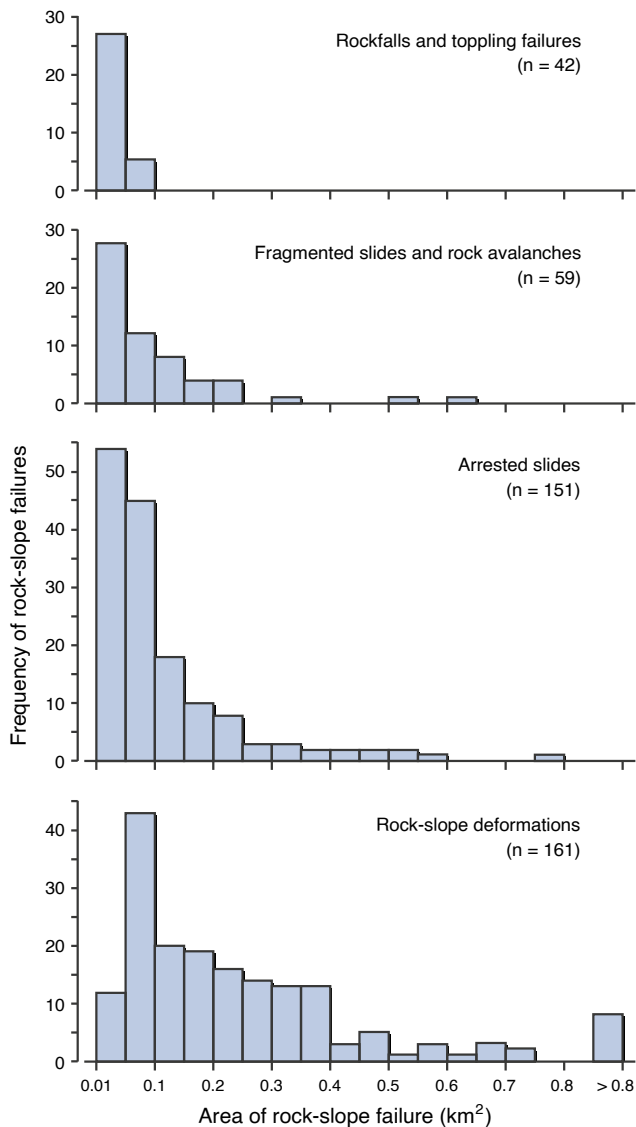


Fig. 14.4 Size distributions of rockfall/toppling failures (category RF), fragmented slides and rock avalanches (FS), arrested slides (AS) and rock-slope deformations (RSD). The measured areas extend from the failure crest to the toe of RSFs, including any debris runout zone

internal deformation and brittle failure of internal rock bridges (Eberhardt et al. 2004; Brideau et al. 2009).

Figure 14.5 illustrates possible trajectories of rock-mass weakening leading to slope failure during and after the last glacial cycle. During glacial advance, resisting forces increase through ice loading and joint closure, but during glacial retreat (ice thinning) accumulated rock damage due to glacial loading and unloading, erosion of rock and a combination of thermomechanical effects and hydromechanical fatigue lowers resisting forces to below previous levels. Depending on the initial disparity between resisting and driving forces, increased rock damage may lead to

failure during or soon after deglaciation. Most slopes, though weakened, remain intact, though time-dependent reduction in resisting forces (progressive failure) may lead to rock-slope deformation that eventually stabilises or accelerates to catastrophic collapse. Rapid failure may also be triggered by debuttressing, earthquakes (which cause a transient increase in driving forces) and excess joint-water pressures (which cause a transient decrease in resisting forces). Pathways to failure are therefore both spatially and temporally non-uniform.

The limit-equilibrium analyses of Highland RSFs carried out by Holmes (1984, p 113–116) showed that all of the sliding failures he examined could not have failed under self-weight stresses alone, implying that glacial steepening of rock slopes has been ‘relatively unimportant as a direct cause of slope failure’. At most of the sites he investigated, failure surfaces lie well below peak friction angles but close to residual friction angles, suggesting that progressive failure could have triggered rapid sliding failure. Others lie below the residual friction angle, implying that some other factor triggered failure.

Some insight into the causes of rock-slope failure has been provided by TCN exposure dating of 31 fragmented slides and rock avalanches on mountain slopes in the Scottish Highlands and NW Ireland (Ballantyne et al. 2014). Most of these lagged deglaciation by centuries or millennia, implying that only a small number of the sampled RSFs could have been triggered by debuttressing or elevated joint-water pressures during deglaciation. Similarly, the timing of dated RSFs exhibits no relationship to periods of rapid warming, implying that thaw of permafrost was not a widespread cause of failure. Ballantyne et al. (2014) concluded that the time lag between deglaciation and most catastrophic RSFs indicates that many were the outcome of progressive failure through time-dependent strength degradation within fractured rock, leading to either spontaneous failure or failure triggered by an extrinsic agent. They also noted a temporal correspondence between the timing of RSF activity and rates of glacio-isostatic crustal rebound (Fig. 14.6), suggesting a causal connection via fault (re)activation and triggering of failure of critically-stressed slopes by earthquakes.

The NW Highlands form part of a tectonically-stable intraplate region, and recent seismic events with $M_L > 4$ are rare. However, numerical modelling has demonstrated that faults become unstable during the crustal unloading that accompanies ice-sheet deglaciation (e.g. Hampel et al. 2010), resulting in a pulse of medium- to high-magnitude earthquakes, though shallow fault activation and associated earthquake activity may lag deglaciation by centuries or millennia because of long crustal response times. There is evidence that stable intraplate areas, including Scotland, experienced uplift-driven faulting and seismic activity

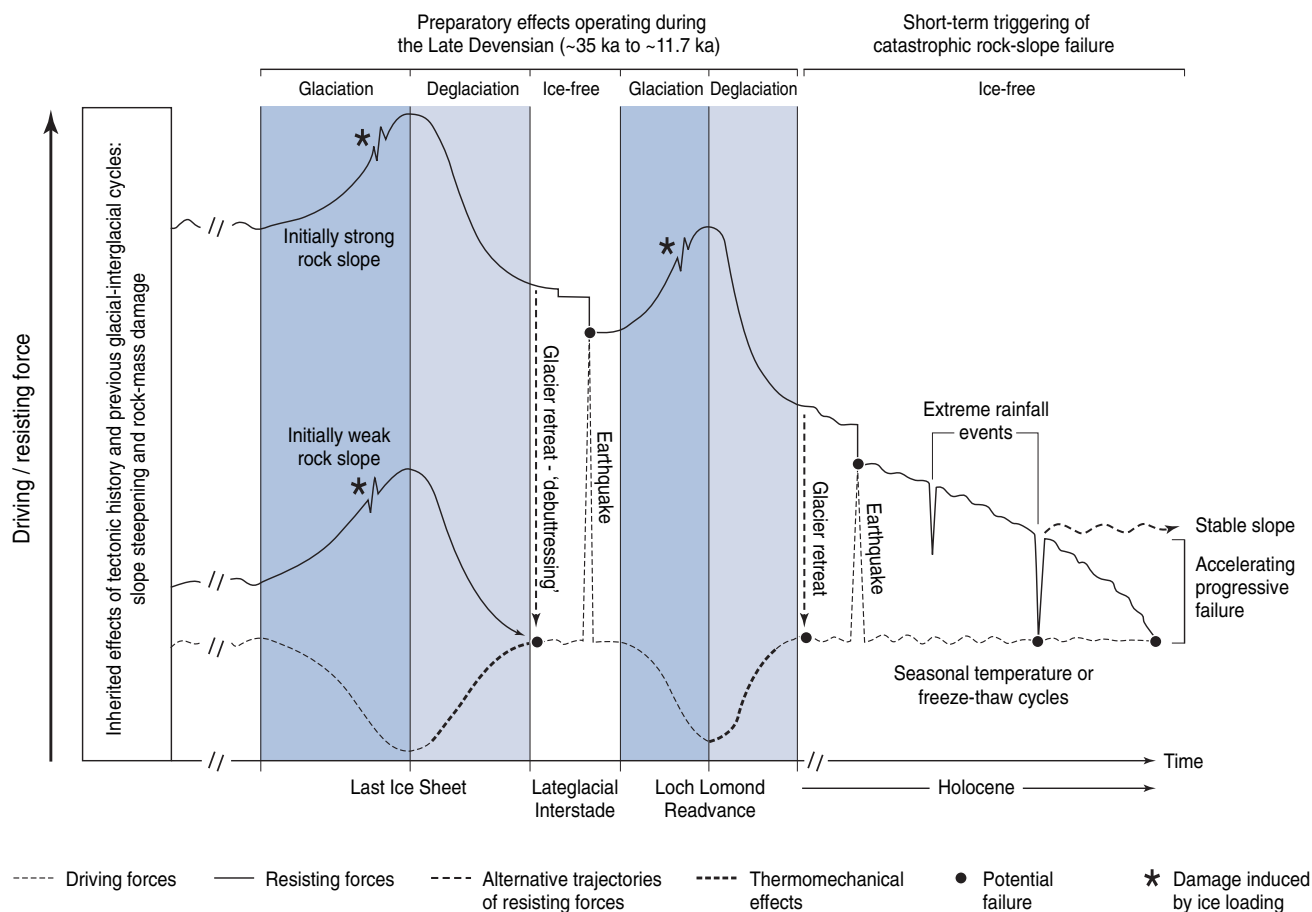


Fig. 14.5 Trajectory of paraglacial preparatory and trigger factors leading to failure (schematic), showing the changes in driving and resisting forces in hypothetical rock slopes after ~35 ka. Rock damage induced by ice loading/unloading and thermomechanical/hydromechanical effects during deglaciation reduces resisting forces during each glacial-deglacial cycle. Failure may be triggered by ‘debuttressing’ during glacier retreat, a transient increase in driving forces during earthquakes, extreme rainstorm events that cause excess

joint-water pressures, or progressive failure due to time-dependent brittle failure of internal rock bridges. Earthquakes also act as preparatory factors causing subcritical rock damage and reduction in resisting forces (seismic fatigue). Rock-slope deformations represent a subcritical response to reduction in resisting forces, ultimately evolving into catastrophic failures or stable slopes. (Adapted from Grämiger et al. 2018)

following ice-sheet deglaciation (e.g. Firth and Stewart 2000; Stewart et al. 2001). Because of topographic amplification of seismic waves (Meunier et al. 2008), coseismic RSFs tend to originate at or near slope crests (Densmore and Hovius 2000), as is the case with 76% of postglacial RSFs in the NW Highlands (Table 14.1). The effect of topographically-amplified ground shaking in Scotland may also be evident in collapses of low anacinal rock scarps along mountain ridges (Ballantyne 2019). It is also notable that ~75% of RSFs occur within 20 km of the main drainage divide (Fig. 14.3), close to the uplift axis, where rates of glacio-isostatic rebound were greatest. Collectively, both the timing of dated RSFs (Fig. 14.6) and the above evidence suggest that many catastrophic RSFs (and probably arrested slides) in the NW Highlands were triggered by uplift-induced earthquakes, or occurred on slopes weakened

by seismic fatigue, leading to later failure (Gischig et al. 2015). Dynamic loading during earthquakes has also been implicated in the initiation and acceleration of RSDs (Moro et al. 2007, 2012; Agliardi et al. 2012; Pedrazzini et al. 2016), so it is possible that some of those in the NW Highlands were activated or influenced by seismic activity.

14.4 Catastrophic RSFs

Only seven or eight RSFs are classified here as rock avalanches, four of which have been dated using cosmogenic ^{10}Be . All exposure ages cited below are from Ballantyne et al. (2014).

The largest rock avalanche in Scotland resulted from failure of $3.3\text{--}3.8 \times 10^6 \text{ m}^3$ (~9 Mt) of rock from Beinn

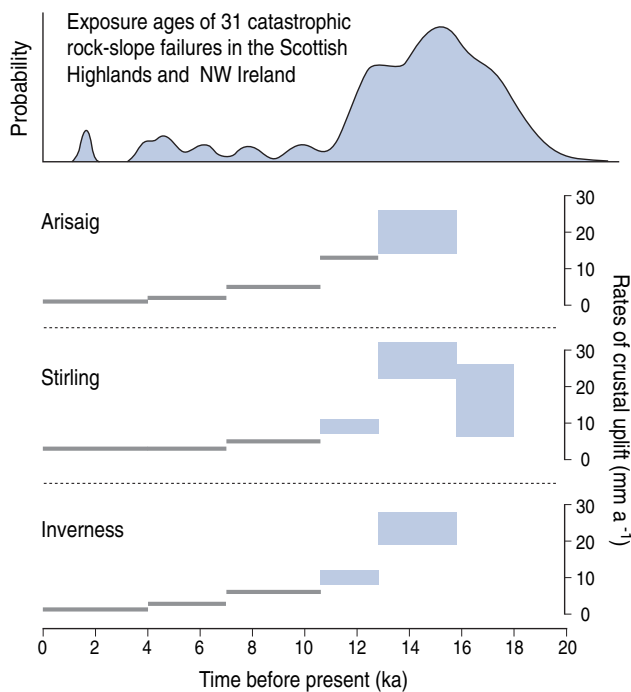


Fig. 14.6 Summed normal kernel density estimates generated by the ages and associated uncertainties of 31 fragmented slides and rock avalanches in the Scottish Highlands and NW Ireland, plotted against average rates of glacio-isostatic crustal uplift for three locations in Scotland. (From Ballantyne et al. (2014) *Quat Sci Rev* 86:144–157 © 2014 Elsevier Ltd; reproduced under Creative Commons CC-BY Licence)

Alligin (985 m), a Torridonian sandstone mountain in Wester Ross. The source of the rock avalanche is a steep (42°) rupture surface flanked by upslope-converging scarps that meet near the mountain summit; the eastern scarp is a fault scarp, and the almost vertical western scarp is the RSF headwall (Fenton 1991). The adjacent cirque floor is occupied by a tongue of runout debris comprising sandstone boulders up to and sometimes exceeding 5 m in length (Fig. 14.7a) that exhibits crude inverse sorting. This deposit is at least 15 m thick along the runout axis, occupies an area of 0.38 km^2 and extends continuously along the cirque floor for 1.25 km, descending at an average gradient of 8° from near the base of the cirque headwall. The margins of the runout tongue are sharp. The regularity of the rupture surface suggests that failure took the form of a planar slide that completely disintegrated during movement.

The Beinn Alligin rock avalanche occurred at $4.4 \pm 0.3 \text{ ka}$, over 7000 years after deglaciation of the site. This long delay suggests that failure was due to progressive failure (reduction of cohesive strength through shearing of rock bridges) initiated by deglacial unloading, though seismic activity caused by reactivation of the fault scarp that borders the rupture zone may have triggered release of the intervening rock mass (Fenton 1991). This rock avalanche

represents the most striking example in Scotland of the phenomenon of excess runout that greatly exceeds that which would be expected of a frictional flow of dry, angular debris. Calculations by Ballantyne and Stone (2004) suggest that in this case over 680 m of excess runout occurred. The causes of this phenomenon are still debated, but appear to be related to the high potential energy of the released rock mass (Dade and Huppert 1998), and may be due to the development of a mobile basal layer (Kilburn and Sørensen 1998) or crushing of grains under large dynamic stresses, causing fluid-like behaviour that reduces friction within a flowing mass of debris (McSaveney and Davies 2007).

Two further rock avalanches involved failures on Torridonian sandstones. Partial collapse of a cirque headwall on Liathach (1054 m) in Wester Ross released $>0.5 \text{ Mt}$ of rock debris onto the cirque floor, and failure of $\sim 0.6 \text{ Mt}$ of rock from the NW shoulder of Baosbheinn (875 m) in the same area resulted in the accumulation of a massive arcuate boulder ridge that is draped over a lateral moraine (Ballantyne and Stone 2009). The moraine was deposited by a readvance of the last ice sheet at $\sim 15.3 \text{ ka}$ (Chap. 13) and the rock avalanche occurred at $15.0 \pm 0.7 \text{ ka}$, suggesting that it may have been triggered by seismic activity during the period of most rapid glacio-isostatic uplift (Fig. 14.6). A further rock avalanche in Wester Ross involved collapse of a quartzite rockwall on the eastern flank of Maol Chean-dearg (933 m). At this site a broad runout tongue of quartzite boulders covers $\sim 0.20 \text{ km}^2$ of the underlying gently-sloping Torridonian sandstone bedrock (Fig. 14.7b) and locally terminates at a low boulder ridge, suggesting that it may represent failure onto the surface of a shrinking LLR glacier (Ballantyne and Stone 2013). The TCN exposure age of $12.4 \pm 0.6 \text{ ka}$ obtained for this RSF is consistent with this interpretation.

Rock avalanches *sensu stricto* are rare on Moine rocks, though collapse of a cirque headwall in the eastern Fannich Mountains has resulted in deposition of a 370 m long tongue of boulders that extends across the cirque floor (Fig. 14.2d). Holmes (1984) showed that rock-mass release at this site took the form of planar sliding along a major joint set inclined at 35° , 6° below the friction angle of the rock, implying that excess joint-water pressures or possibly seismic acceleration were responsible for triggering failure. A similar rockwall failure from the SW spur of Carn Ghluasaid (957 m) in the Cluanie mountains spread a 450 m long lobe of runout boulders across the subjacent slope (Fig. 14.7c) at $12.7 \pm 0.7 \text{ ka}$.

Over 50 fragmented slides have been recorded in the NW Highlands. Most ($\sim 70\%$) occur on Moine schists but few have been documented in detail. That at Druim nan Uadhag (upper Glen Dessarry) occurred at $9.9 \pm 0.5 \text{ ka}$ and involved disintegration of a detached mass of rock, accompanied by block toppling at the slope crest and release of a



Fig. 14.7 Catastrophic rock-slope failures. **a** The Beinn Alligin rock avalanche, Torridon (4.4 ± 0.3 ka). **b** The Maol Chean-dearg rock avalanche, Torridon (12.4 ± 0.6 ka). **c** The runout lobe of the Carn Ghluasaid rock avalanche, Cluanie (12.7 ± 0.7 ka). **d** The Druim nan

Uadhag fragmented rockslide, Dessary (9.9 ± 0.5 ka). **e** The Carn nan Gillean fragmented rockslide, Sutherland (7.9 ± 0.4 ka). **f** Fragmented rockslide and debris flow, Meall Coire an t-Seallach, Knoydart. (Images: **a–d** Colin Ballantyne; **e, f** Google EarthTM)

spread of large boulders that extends 550 m downslope to the valley floor (Figs. 14.2c and 14.7d). A fragmented slide at Carn nan Gillean (Meall a'Chleirich) in Sutherland (Chap. 12) forms part of a larger RSF, exhibiting tension cracks and displaced blocks at the slope crest and a thick runout tongue of large boulders that extends downslope for 370 m but fails to reach the valley floor (Fig. 14.7e); failure

occurred at 7.9 ± 0.4 ka. Both of these examples occur on the flanks of troughs formerly occupied by LLR glaciers.

At a few sites, catastrophic rock-slope failure has been succeeded by downslope flow of debris, either in the form of a broad lobe (Fig. 14.2f) or a narrow tongue bounded by bouldery levées. An example of the latter is a fragmented slide on Meall Coire an t-Seallach (686 m) in Knoydart,

where part of the runout debris forms a narrow tongue bounded by bouldery levées up to 10 m high (Fig. 14.7f). Extended downslope flow of debris at this site was attributed by Ballantyne (1992) to momentum transfer through inertial collisions within the mobile mass of boulders.

14.5 Arrested Slides

Most (~66%) arrested slides in the NW Highlands are small failures (<0.1 km²; Figs. 14.4 and 14.8a), but several exceed 0.25 km² and represent major ruptures on steep (>25°) valley-side slopes, spurs and cirque sidewalls, though they are rare on steep rockwalls where catastrophic failures and rockfalls predominate. Rupture surfaces are typically planar, indicating translational sliding controlled by joint alignment or foliation. In most cases, the thickness of the displaced rock mass ranges from 10 m to ~50 m. At some sites, very limited downslope shift of failed rock has occurred (Figs. 14.2a and 14.8d), but many terminate on middle or lower slopes and some reach the valley floor (Fig. 14.8e). Most (~84%) are seated on schist or gneiss, though some outstanding examples occur on other rocks, such as the Breabag RSF on Cambrian quartzite (Fig. 14.2a) and those on Torridonian sandstones in Coire Attadale, Applecross (Fig. 14.8c).

Accounts of individual arrested slides in the NW Highlands tend to be descriptive and provide no information regarding the cause of failure, but study of a RSF on Sgùrr na Lapaich (Affric) by Holmes (1984) is instructive. The rupture surface is inclined at ~26°, and failure apparently took place along the principal joint set. Because the inclination of the failure surface is below the residual friction angle for psammite (~32°), rock-mass release cannot have resulted from progressive failure, even assuming zero cohesion. Holmes concluded that only an exceptionally unfavourable joint-water pressure distribution could have caused kinematic release, though it is feasible that failure was triggered by seismic shaking.

A particularly interesting large arrested slide is located on Moine psammities in a cirque below the summit of Ben Hee (873 m) in Sutherland (Fig. 14.8b). The main body of the slide consists of an upper zone of slipped rock, a middle zone of partly disaggregated rock that extends downslope for ~500 m, and (unusually) a terminal zone of broad transverse ridges. Jarman and Lukas (2007, p 102) described the ridged area as ‘tension gashes possibly exploited by fluvial erosion’, though the location of the ridges at the slide toe suggests that they may be of compressional origin. Jarman and Lukas concluded that the Ben Hee RSF involved translational sliding along a failure plane inclined at 18°, much lower than the residual friction angle of psammite (~32°), and indeed those of the failure surfaces of other

translational slides in the NW Highlands. The cirque was occupied by LLR glacier ice, and Haynes (1976, p 337) considered that the landslide occurred ‘while glaciation was in progress’, but if so there must have been only a tiny residual glacier in the cirque or RSF debris would have been carried farther. An alternative possible interpretation is that the failure surface is curved, and that the Ben Hee RSF is an atypical case of quasi-rotational sliding in schists, thus accounting for the development of compressional ridges at the slide toe.

14.6 Rock-Slope Deformations

Rock-slope deformations (RSDs), often termed deep-seated gravitational slope deformations (DSGSDs), are widespread in deglaciated mountain environments, but until the present century received remarkably little attention from geomorphologists. The burgeoning recent literature on these massive mountain landforms has been summarised by Agliardi et al. (2012) and Pánek and Klimes (2016), but there is still uncertainty regarding the causes and mechanisms of slow (10⁻¹–10² mm a⁻¹) deep-seated rock deformation. The onset of deformation has been widely attributed to deglacial unloading or debuttressing of slopes leading to immediate or delayed ‘creep’ of steep mountain slopes, particularly on anisotropic fractured schistose rocks. The nature of movement has been variously attributed to ‘rock-mass creep’, elasto-plastic deformation, shear along deep-seated discontinuities or shear zones, and/or progressive failure due to sequential shearing of rock bridges and reduction of frictional strength along joints. Seismic activity and high-joint water pressures are known to activate or episodically accelerate RSDs (Moro et al. 2007, 2012), particularly in areas with high uplift gradients (Pedrazzini et al. 2016). Over long timescales, RSDs eventually stabilise or may fail completely as rockslides or rock avalanches.

The most characteristic features of RSDs in the NW Highlands are arrays of anticarps up to ~10 m high produced by shallow faulting or block toppling within the mobile slope (Fig. 14.9a–d) and slope bulging (Figs. 14.2e and 14.9a, c), though the latter is not always evident. Lateral margins are often indistinct (Fig. 14.9b, c), headscarps are typically subdued, and some RSDs are represented only by a single scarp along the slope crest indicating subsidence of the adjacent slope. Most (87%) are located on schists (Table 14.1) though they also occur on other rocks; on Torridonian sandstones, RSDs are sometimes represented by anticarps (Fig. 14.9d) and elsewhere by downslope ‘sagging’ of sandstone strata.

The most extensive area of rock-slope deformation in Scotland occurs on the southern flank of Beinn Fhada (1032 m) in Kintail and covers an area of ~3.1 km²

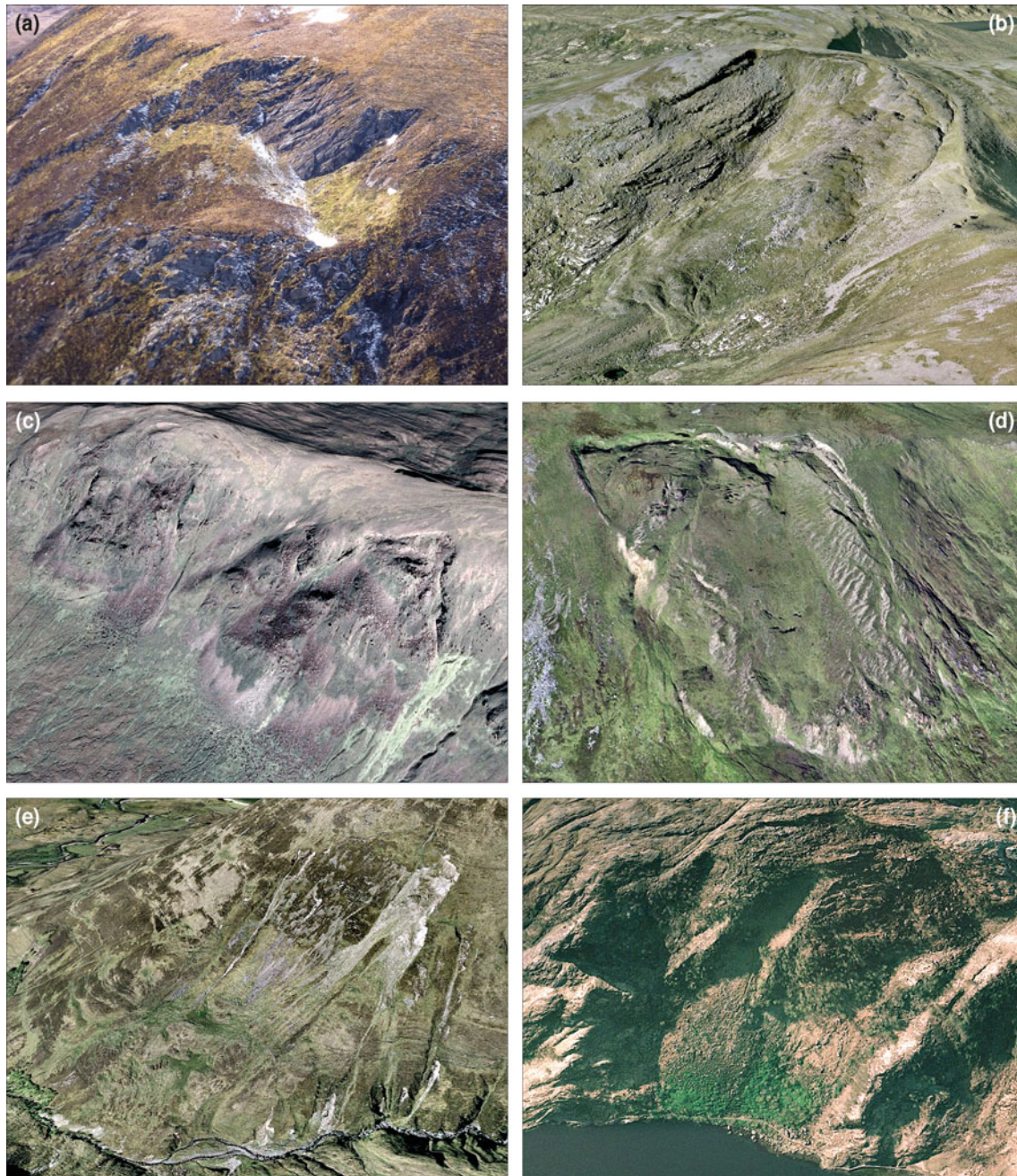


Fig. 14.8 Arrested slides; all except (c) are on Moine schists. **a** Small ($<0.02 \text{ km}^2$) failure at the slope crest, Tom na Caillich, Easter Ross. **b** The Ben Hee RSF, Sutherland; the main body of the slide covers $\sim 0.40 \text{ km}^2$. **c** Two partly fragmented arrested slides (0.14 and 0.19 km^2) on Torridonian sandstone, Coire Attadale, Applecross. **d** Arrested slide (0.14 km^2) with limited downslope displacement,

Sgùrr na Ruaidhe, Strathfarrar. **e** Full-slope rockslide on Beinn Bhuidhe, Arnisdale (0.11 km^2); the slide mass has translated to the slope foot. **f** Arrested slide (0.13 km^2) at the head of Loch Hourm. The headscarp is at 400 m , and the central part of the displaced rock mass has collapsed to form a debris tongue that extends to the shore of the fjord. (Images: **a** Colin Ballantyne; **b–f** Google Earth™)

(Ballantyne and Jarman 2007; Fig. 14.9a). The deformed slope rises $790\text{--}900 \text{ m}$ above the adjacent trough floor at average gradients of $30\text{--}35^\circ$. Although the valley was occupied by glacier ice $\sim 400 \text{ m}$ thick during the Loch Lomond Stade, the toe of the RSD exhibits no evidence of

glacial modification, suggesting that movement continued into the Holocene, though deformation of the upper slope may have been initiated much earlier. This huge RSD lacks distinct lateral margins but is defined by a remarkable array of anticarps that extend from near the valley floor to the

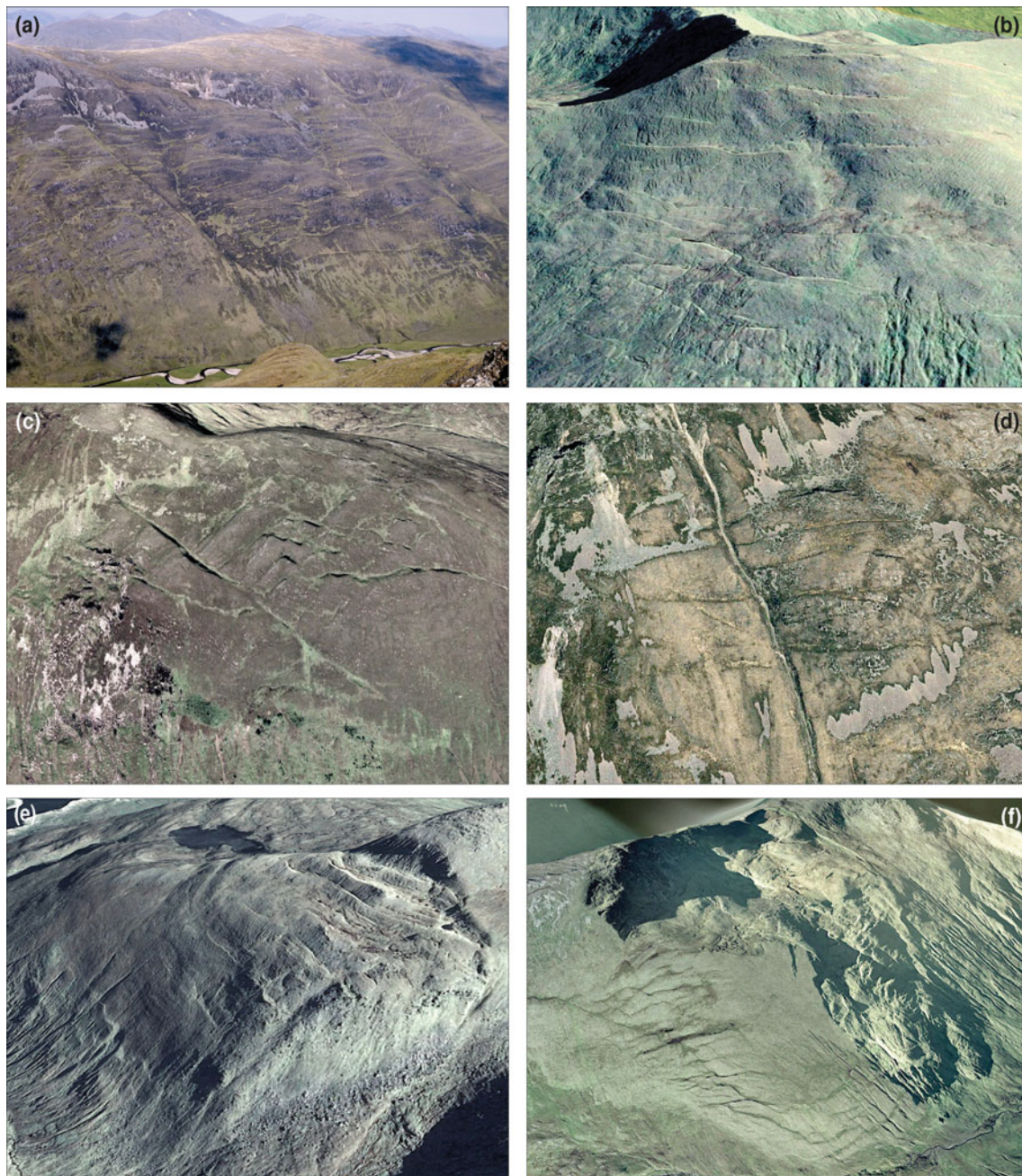


Fig. 14.9 Rock-slope deformations and related landforms. All are on schists except (d). **a** The Beinn Fhada RSD in Kintail, the largest in Scotland. **b** Antiscarp arrays of the An Socach RSD, Mullardoch. **c** The An Sornach RSD, Affric, showing partial collapse of the margin. **d** Antiscarps of a small (0.15 km^2) mid-slope RSD on Torridonian

sandstone, Liathach, Torridon. **e** The Druim Shionnach RSD, Glen Shiel, a hybrid RSD/arrested slide. **f** RSD on Mullach nan Dheiragain, Affric, where two-thirds of a large ($\sim 1.3 \text{ km}^2$) RSD have apparently collapsed to form an arrested slide. (Images: **a** Colin Ballantyne; **b**–**f** Google EarthTM)

slope crest: those on the upper slope are up to 10 m high and 800 m long. Most are aligned across the slope, though some dip gently and a few converge. The main area of deformation forms three prominent bulges below a degraded, discontinuous ($\sim 35^\circ$) scarp, but antiscarps link the west and central bulges and extend onto the plateau upslope, indicating that

deformation was not confined to the bulges. As with other RSDs in Scotland, the timing, cause and mechanics of movement remain conjectural: Watters (1972) inferred that the Beinn Fhada RSD represents a deep-seated translational slide; Fenton (1991) proposed seismically-triggered sliding failure; and Holmes and Jarvis (1985) postulated deep

internal rock deformation, with formation of antiscarps by joint-guided block-flexural toppling.

A large ($\sim 0.50 \text{ km}^2$) RSD on the southern slopes of An Sornach (Glen Affric; Fig. 14.9c) is defined by low antiscarps, with a headscarp up to 40 m high inclined at $\sim 40^\circ$ and a sidescarp at its western end, below which part of the RSD exhibits toppling collapse. Deformation has been attributed to translational sliding, possibly along slope-parallel stress-release joints, but if the headscarp represents an exposed failure surface this interpretation implies that downslope movement was accommodated entirely by slope bulging. The conspicuous antiscarp or trench that descends eastwards across the feature may represent a neotectonic fault scarp.

Another large ($\sim 0.56 \text{ km}^2$) RSD on Druim Shionnach (Glen Shiel) illustrates the hybrid nature of some slope deformations. The upper part of this landform consists of a headscarp up to 25 m high and a broad trench (tensional rift) that is bounded on its downslope side by a steep antiscarp (Jarman 2007b). Farther downslope the surface of the displaced block forms a broad bulge, interrupted by minor antiscarps and benches, that descends at an average gradient of 22° before terminating at a 150 m high slope inclined at up to 45° (Fig. 14.9e). Jarman (2007b) depicted movement of the displaced mass over a fracture zone inclined at 16° , ~ 100 to 150 m below the surface. This reconstruction implies (for a 100 m thickness of rock) a normal stress of $\sim 2.5 \text{ MPa}$ and a shear stress of $\sim 0.7 \text{ MPa}$ along the fracture zone. Shear under such conditions is improbable, and a more complex structural configuration is likely, but difficult to reconcile with the evidence for extensional movement downslope from the headscarp. It is possible that 'hybrid' RSDs such as that on Druim Shionnach belong to a category of large, slow-moving landslides as opposed to rock-slope deformations *sensu stricto* (Agliardi et al. 2012; Pánek and Klimes 2016), though differentiation of the two from morphology alone is difficult.

Some RSDs in the NW Highlands exhibit zones of catastrophic failure (topples or fragmented slides) at their margins (Fig. 14.9c). These have occurred where slow downslope movement has reduced rock-mass strength to criticality through brittle shear of rock bridges and reduction of frictional strength to residual values. The most striking example of a partly-failed RSD is that on Mullach nan Dheiragain (Affric), where a bulging RSD adjoins a large arrested slide (Fig. 14.9f), suggesting that both initially formed part of a large ($\sim 1.3 \text{ km}^2$) RSD, two-thirds of which subsequently collapsed. Some (possibly many) catastrophic failures and arrested slides in the NW Highlands almost certainly represent RSDs that accelerated towards kinematic release even as others gradually stabilised.

14.7 Debris-Free Failure Scars and the Role of RSFs in Long-Term Landscape Evolution

TCN dating of catastrophic RSFs has demonstrated that almost all of those located outside the limits of the LLR failed within the Lateglacial interval between ice-sheet deglaciation and the end of the Loch Lomond Stade (Ballantyne et al. 2014). An important implication is that numerous RSFs must have occurred inside the limits of the LLR within the same period, but that the resultant failed rock or runout debris was removed by glacier ice so that failure sites are now represented by debris-free failure scars (DFFSs). Such landslide scars were first recorded in Geological Survey memoirs, and Holmes (1984) recorded 68 large DFFS sites in the Scottish Highlands. Common attributes include a planar, stepped or irregular failure plane or rupture surface, a straight, arcuate, irregular or wedge-shaped headscarp (which may be absent where failure removed a ridge crest), sidescarps and tension cracks (Ballantyne 2013; Fig. 14.10). The author has identified over 250 possible DFFSs $> 0.01 \text{ km}^2$ in the NW Highlands. Most occur on schists though they are present on all lithologies (Cave and Ballantyne 2016). Large cavities or hollows representing DFFSs occur, for example, in Torridonian sandstone below the summits of Beinn Damh and Fuar Tholl in the Torridon-Strathcarron area, and spectacular debris-free failure surfaces are present on the Cambrian quartzite slopes of Foinaven in Sutherland. Most DFFSs are small ($< 0.1 \text{ km}^2$), but some represent the sites of major RSFs: that on Garbh Cioch Beag (Fig. 14.10b), for example, represents translational sliding of rock over an area of $\sim 0.5 \text{ km}^2$.

The fate of RSF debris removed by LLR glaciers is poorly understood. At a few sites, landslides appear to have deposited debris directly on to glaciers, which then transported it farther downvalley (Ballantyne and Stone 2013). Benn (1989) has shown that large lateral moraines occur downvalley from cliffed cirque sidewalls, suggesting that the moraines contain a substantial component of reworked RSF and rockfall debris. It is likely that Lateglacial RSFs that occurred before or during the LLR also contributed to the huge volume of sediment in the multiple recessional moraines that formed during oscillatory retreat of LLR glaciers. At a few sites, rock avalanche debris has survived over-riding by LLR glaciers, forming a lobe or tongue of streamlined hummocks (Ballantyne 2018).

DFFSs also occur outside the limits of the LLR, implying that such sites represent RSFs that occurred prior to the expansion of the last ice sheet. Moreover, some DFFSs inside the limits of the LLR exhibit ice moulding of

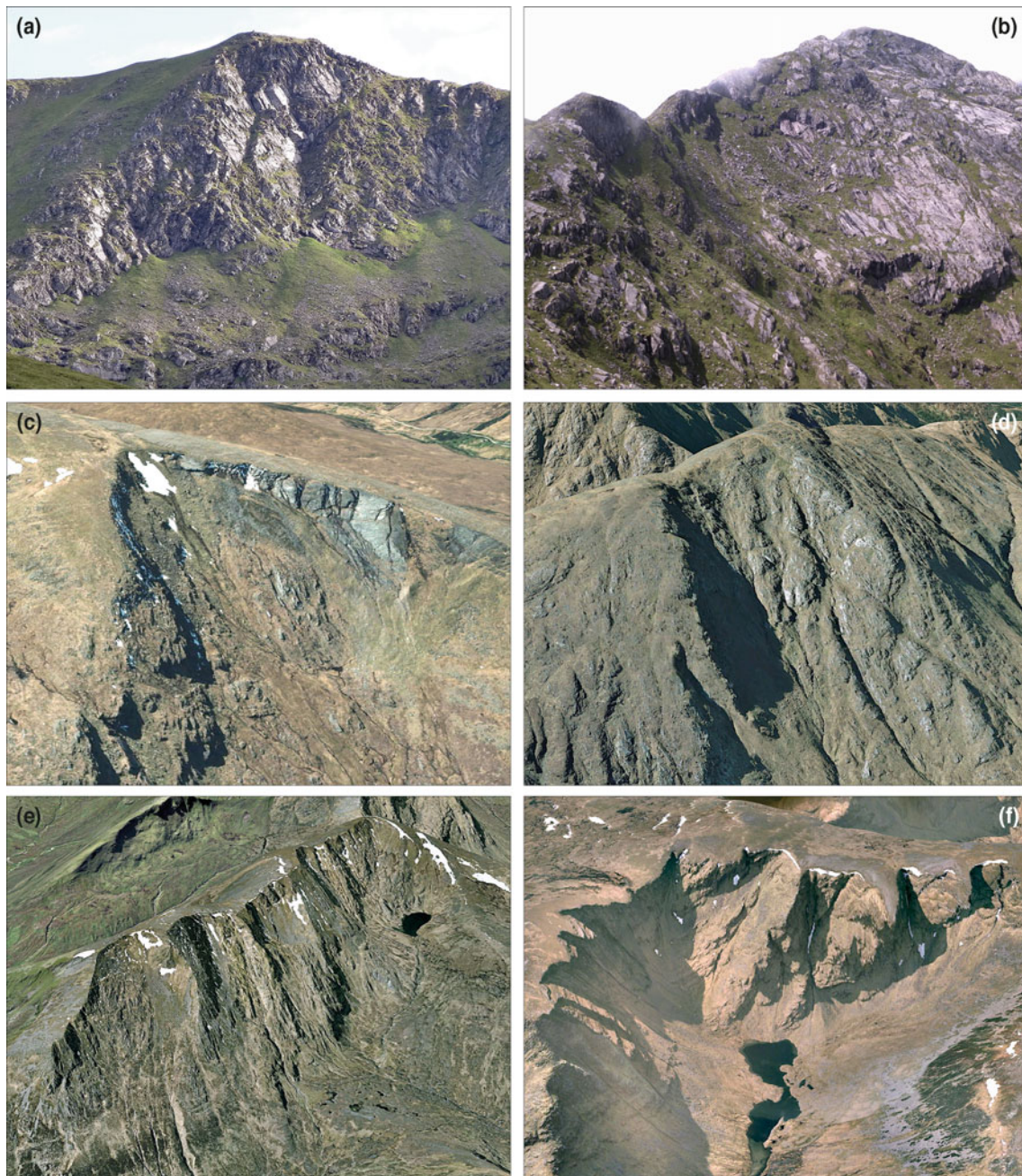


Fig. 14.10 Debris-free failure scars (DFFSs) on schists. **a** Small DFFS on Sgùrr Coinnich, Monar. **b** Stepped failure plane of a large ($\sim 0.5 \text{ km}^2$) DFFS, Garbh Cioch Beag, Dessarry. **c** Headscarp and failure surface of an arcuate DFFS (0.15 km^2), Moruisg, Strathcarron. **d** Cavity marking a large (0.23 km^2) DFFS on Cam na Nathrach, Ardgour. **e** Multiple DFFSs along the east ridge of Sgùrr a'Chao-rachain, Monar. **f** Multiple DFFSs along a cirque headwall, Seana

Braigh, Inverlael. All of these sites were partly occupied by glacier ice during the Loch Lomond Stade, implying that runout debris may have been removed by glaciers during the Loch Lomond Readvance, but ice moulding of the buttresses flanking (**d**) suggests that failure here may have pre-dated the last ice sheet. (Images: **a**, **b** Colin Ballantyne; **c**–**f** Google Earth™)

sidescarps and intervening buttresses (Fig. 14.10d), suggesting that these also represent the sites of ancient RSFs that occurred prior to ice-sheet expansion. Survival of pre-Last Glacial Maximum DFFSs demonstrates that the cavities formed by ancient rock-slope failures are persistent

landscape features and indicates limited erosion of upper slopes by the last ice sheet.

The abundance of DFFSs and postglacial RSFs in the NW Highlands suggests that rock-slope failure at a range of scales has played an important role during successive

interglacial periods in widening glacial troughs and tributary valleys, and probably a dominant role in the formation of arêtes (Ballantyne 2013, 2019; Chap. 13; Fig. 14.10e). Additionally, many cirques in the region are skirted by talus slopes that demonstrate postglacial retreat of headwalls and sidewalls by small-scale rockfalls, but others are scalloped by failure scars that demonstrate rockwall retreat and cirque widening by larger RSFs (Fig. 14.10f). As Figs. 14.2 and 14.10 illustrate, the large-scale morphology of many mountain summits and ridges in the NW Highlands has been strongly influenced by interglacial, interstadial and postglacial rock-slope failure, and is not simply an outcome of successive episodes of glacial erosion.

Jarman (2009) proposed a model of trough widening by rock-slope failure in Scotland. This postulates that valley modification by paraglacial RSFs was pronounced during early stages of trough development, then slowed as slopes became 'stress hardened', before being rejuvenated by 'glacial reincision' during the 'late Quaternary'. As noted in Sect. 14.3, however, *all* episodes of glaciation and deglaciation result in rock-slope weakening through ice loading and unloading, glacial erosion and both thermomechanical and hydromechanical rock damage. It follows that all glacial-deglacial cycles (and particularly those involving ice-sheet growth and decay) have induced widespread paraglacial rock-slope failure, with removal of displaced rock masses and runout debris during subsequent glaciations. The present form of the mountains, ridges, troughs, cirques and arêtes of the NW Highlands has been dictated by a synergic relationship between successive glaciations and ensuing episodes of paraglacial rock-slope failure that has operated since the earliest Pleistocene.

14.8 Conclusions

The North West Highlands contain an exceptional range of paraglacial rock-slope failures. Over 400 have been identified, mainly on schistose rocks, though they are represented on all lithologies. Most take the form of rock-slope deformations or arrested slides; fragmented slides are rarer, and rock avalanches *sensu stricto* are restricted to a few localities where rockwall collapse has fed runout tongues of coarse debris. Postglacial rockfalls and rock topples are small-scale failures mainly restricted to steep scarps and cirque headwalls. Understanding of the causes and nature of failure is limited by a paucity of rigorous geotechnical surveys and dating evidence. The available data suggest that many postglacial RSFs could not have occurred by self-weight sliding or toppling and that most catastrophic failures lagged deglaciation by centuries or millennia. This delay and the abundance of RSDs suggests that many rapid RSFs resulted

from progressive failure of slopes following deglaciation. The role of uplift-induced seismic activity in weakening rock slopes and triggering failure remains conjectural but may offer a solution to the problem of why many technically stable slopes have failed. Perhaps the most significant conclusion of recent research is that paraglacial rock-slope failure has operated at the end of multiple glacial cycles, playing an important role in trough and cirque widening and the formation of arêtes. The large-scale form of the mountain landscape of the NW Highlands has been dictated not only by successive episodes of glacial erosion acting on a dissected pre-glacial land surface, but also by recurrent failure of steep rock slopes during and after each period of deglaciation.

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