17 Western Grampian Highlands

John E. Gordon and D. Noel Williams

Abstract

The Western Grampian Highlands, including Ben Nevis and Glen Coe, form a rugged mountain landscape displaying classic features of glacial erosion developed across a range of metamorphic and igneous rocks. Glacial troughs radiate out from Rannoch Moor, which formed a major ice dispersal centre during successive Pleistocene glacial episodes. The area is also notable for glacier depositional landforms associated with the Loch Lomond Readvance, particularly a large valley sandur and associated landforms at the western end of Loch Etive and hummocky recessional moraines on Rannoch Moor—a key locality for establishing the timing of deglaciation of the West Highland ice cap. Excellent examples of Holocene rock-slope failures, debris flows, debris cones and alluvial fans add to the geomorphological diversity, while Glen Coe provides a geologically outstanding illustration of a caldera collapse. A large part of the area lies within Lochaber Geopark.

Keywords

Caldera collapse • Glacial erosion • Loch Lomond Readvance • Valley sandar • Hummocky recessional moraines • Debris flows and cones • Alluvial fans • Rock-slope failures • Geopark

17.1 Introduction

The Western Grampian Highlands (hereafter Western Grampians) contain some of the most impressive glacially eroded mountain landscapes in Scotland. They are underlain by Neoproterozoic and Palaeozoic metamorphic and igneous rocks whose characteristics have influenced processes of weathering and erosion. This chapter highlights the mountain heartland of Lochaber, centred on Ben Nevis and Glen Coe, the montane basin of Rannoch Moor and the landforms of the western coastal fringe along Loch Linnhe (Fig. 17.1). Numerous summits exceed 1000 m in altitude, including Ben Nevis (1345 m), the highest mountain in Britain. To the north of Glen Coe the mountain ridges of Aonach Eagach, the Mamores and the Ben Nevis–Aonach Mòr–Grey Corries range run west–east, while to the south of Glencoe the mountain blocks are more fragmented. The mountains are heavily dissected but there is a general accordance of higher summit altitudes at ~900–1100 m, with occasional plateau remnants (Fig. 17.2a). Geologically, both Ben Nevis and Glen Coe provide sections through eroded Palaeozoic volcanoes, and the latter was the location where evidence for 'cauldron subsidence' (caldera collapse) was first identified. During Pleistocene glacial episodes, the Rannoch Moor basin formed a major ice accumulation and dispersal centre for successive Scottish ice caps and ice sheets.

Classic features of glacial erosion include troughs, breached watersheds, cirques, deep rock basins, hanging valleys and extensive ice-scoured bedrock. Along the coast, the sea has flooded the lower reaches of the glacial troughs, forming sea lochs and fjords (Fig. 17.2b). Depositional landforms associated with the Loch Lomond Readvance (LLR) during the Loch Lomond (≈Younger Dryas) Stade (~12.9–11.7 ka) include hummocky recessional moraines on Rannoch Moor and glacifluvial valley sandar formed as the glaciers retreated from the coast. Rannoch Moor is also a critical locality for dating the timing of the demise of the LLR ice cap. In the Glen Coe area, the high precipitation

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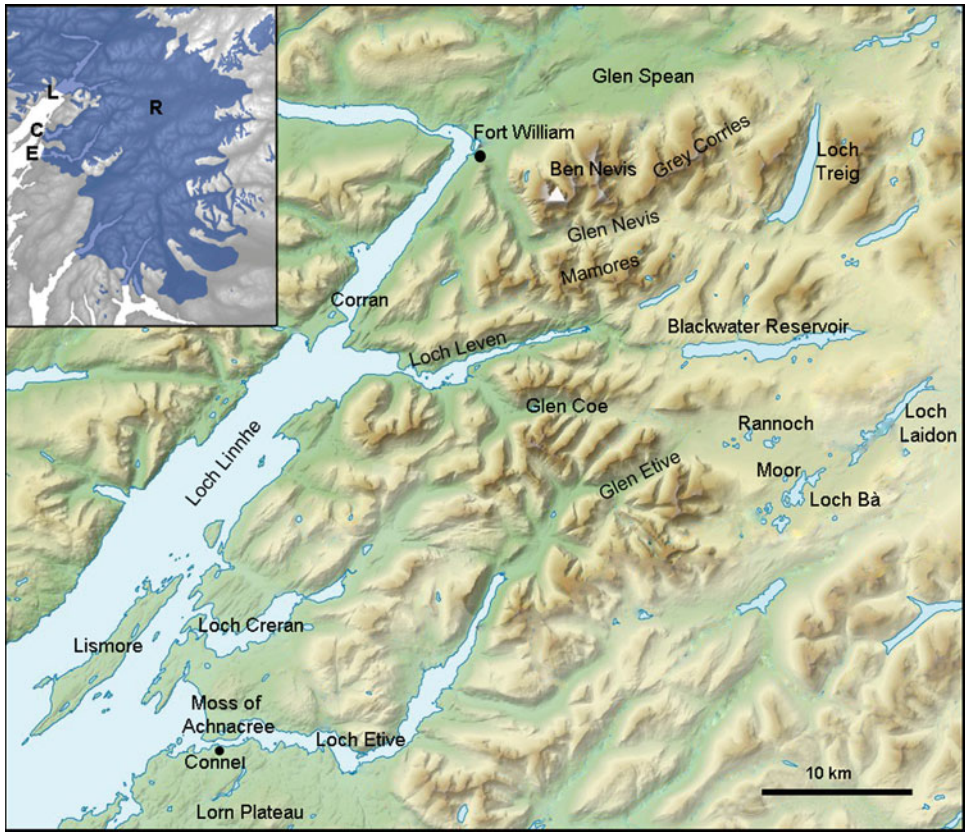

Fig. 17.1 Western Grampian Highlands: relief and main locations mentioned in the text. (Contains Ordnance Survey data © Crown copyright and database right / CC BY-SA; https://creativecommons.org/licenses/by-sa/3.0). Inset: Loch Lomond Readvance glacier limits; note that numerous nunataks protruded through the icefield complex but are not shown. (From Bickerdike et al. 2018) Glacial landsystems, retreat dynamics and controls on Loch Lomond Stadial (Younger Dryas) glaciation in Britain. Boreas 47:202–224. Attribution 4.0 International (CC BY 4.0). C: Creran glacier; E: Etive glacier; L: Linnhe glacier; R: Rannoch Moor

(~4000 mm a^{-1} on the mountains) and available paraglacial sediment sources have enabled the formation of many Holocene debris flows, debris cones and fluvially modified debris cones.

17.2 Geology and Landscape

The Western Grampians are part of the Grampian Highlands terrane and represent the deeply eroded roots of the Caledonian orogenic belt (Chap. 2). They comprise a varied assemblage of metasedimentary rocks belonging to the Dalradian Supergroup, together with significant outcrops of both intrusive and extrusive igneous rocks (Stephenson and Gould 1995; Fig. 17.3). This geological diversity and the NE–SW structural grain and weaknesses imparted during the Caledonian Orogeny have strongly influenced the processes of weathering and erosion and hence the form of the present landscape.

During the Grampian phase of the Caledonian Orogeny at ~470 Ma, folding occurred on both a large and small scale, with several recumbent folds extending many kilometres across the strike, including the Kinlochleven Anticline and Ballachulish Syncline. These large folds were dislocated by major thrusts or slides which resulted in an extremely complex overall structure. Striking examples of overturned rocks occur in the Mamores on the south side of Glen Nevis. Although much of the quartzite is inverted, on the summits of Sgùrr a' Mhaim and Stob Bàn the strata are folded the right way up in a large recumbent anticline (Fig. 17.2a).

Although igneous activity occurred before, during and after the Caledonian Orogeny, it is the igneous rocks formed after the main mountain-building events that dominate the Western Grampians. Fissure eruptions of large quantities of magma produced basalt and basaltic andesite lavas which at one time probably covered much of the Western Grampians. These Early Devonian rocks now form the >300 km^2 Lorn Plateau in the south of the area. Two smaller occurrences of volcanic rocks occur farther north around Glen Coe and Ben Nevis. Those at Glen Coe were probably preserved because they subsided >1 km during the piecemeal collapse of a large elliptical caldera. This phenomenon was originally discovered in the early twentieth century by Geological Survey geologists and termed 'cauldron subsidence' (Clough et al. 1909)—the first recognition in the world of caldera collapse in ancient volcanic rocks. Later work in the 1990s suggested that the collapse was not a single event, but took place in stages, involving different faulted blocks (Kokelaar and Moore 2006). The initial igneous activity at Glen Coe produced sills of andesite and basalt, which were intruded into wet sediments resting on an eroded land surface of

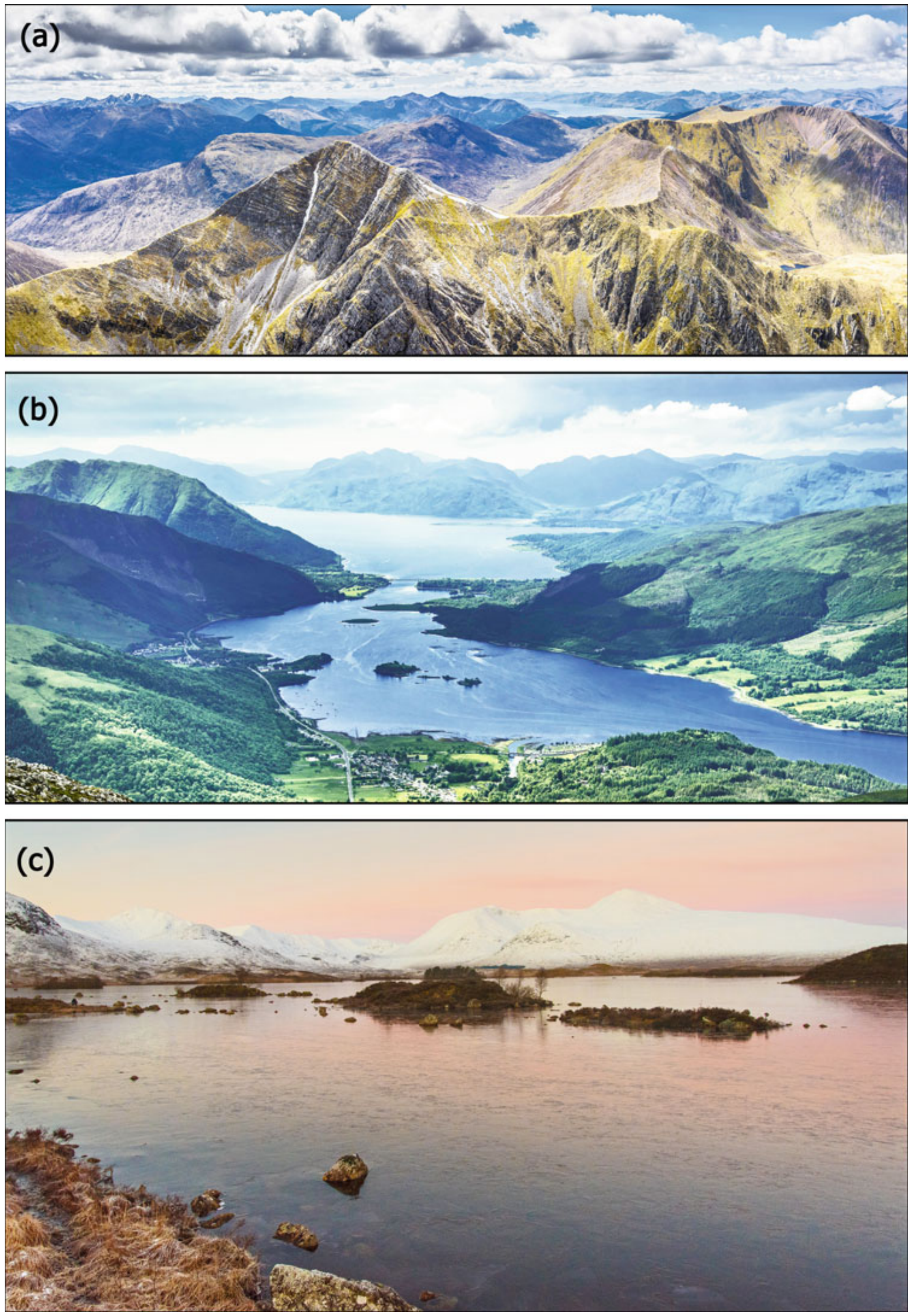

Fig. 17.2 **a** Aerial view of the Mamore range and the mountains to the south. Summits up to ~800 m in the middle distance are ice scoured, while higher summits often support a cover of frost-weathered regolith. The top half of a large recumbent fold can be seen in the quartzite strata of Stob Bàn (centre left), exposed in the headwall of a rock-slope failure. **b** View west along the drowned glacial trough of Loch Leven. A marine-reworked outwash fan forms the narrows at its junction with Loch Linnhe. **c** The high-level basin of Rannoch Moor. (Images: **a** © Kyle Macintyre**;** **b**, **c** John Gordon)

metamorphic phyllites. A conspicuous change from dark andesite to orange rhyolite on the flank of Aonach Dubh marks a transition to more explosive eruptions (Fig. 17.4a). Seven separate eruptions in the later volcanic sequence have been interpreted as intra-caldera ignimbrites formed during different stages of collapse.

Volcanic and sedimentary rocks form the upper half of the north face of Ben Nevis (Fig. 17.4b). These brecciated volcanic rocks are thought to represent block and ash flows, rather than lava flows, on the flank of a former volcano situated to the northwest. The volcanic pile is surrounded by several concentric intrusions. The unusually close proximity of extrusive and intrusive rocks led early geologists to interpret this structure as a deeply eroded caldera, rather smaller than that in Glen Coe. Recent work suggests that the volcanic pile may instead be a large roof pendant and that no collapse took place (Muir and Vaughan 2018).

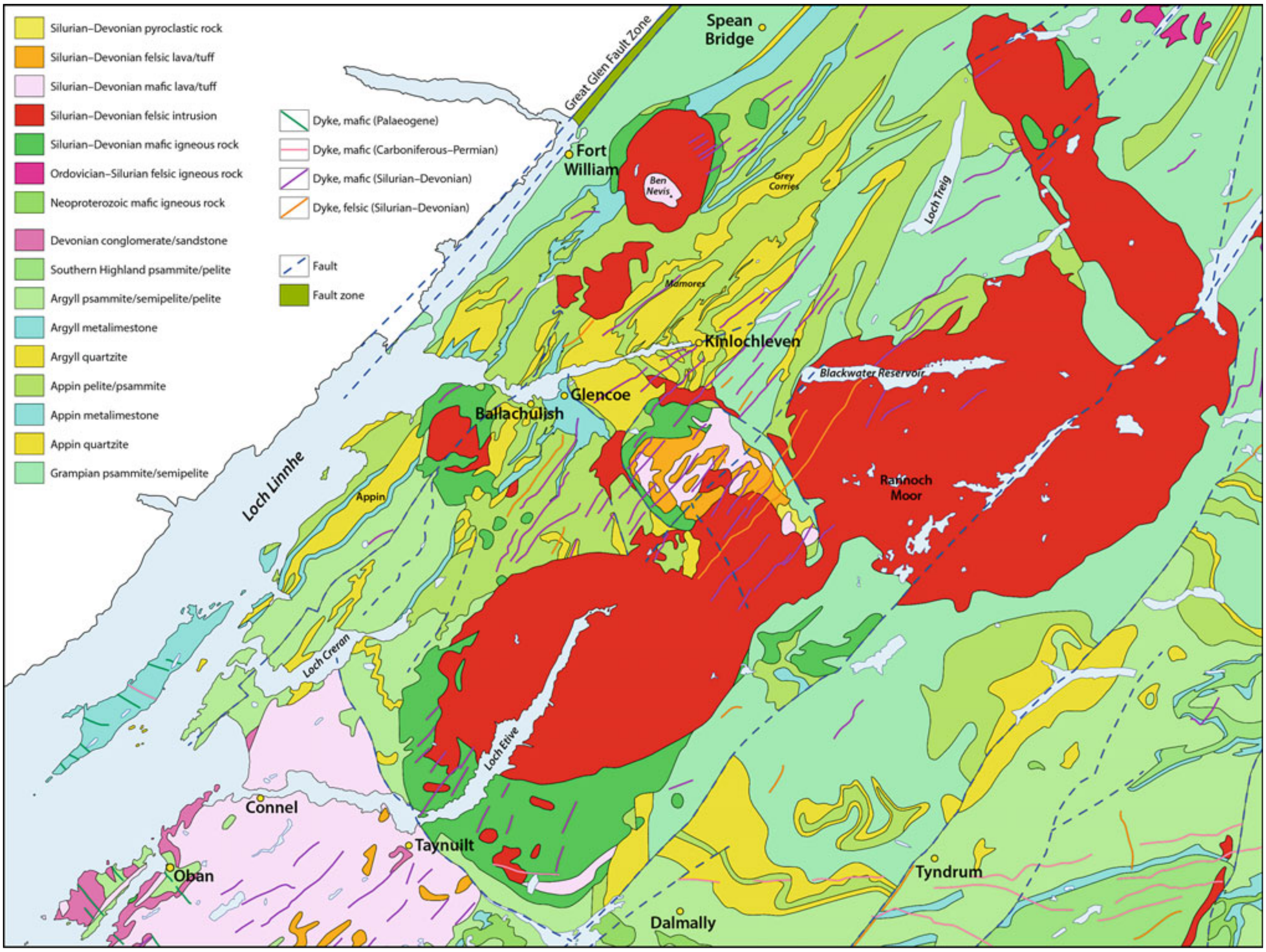

Fig. 17.3 Bedrock geology of the Western Grampian Highlands. (Contains British Geological Survey materials © UKRI 2020)

Large, mainly granitic plutons were emplaced in the Western Grampians from 425 to 410 Ma, including the Etive, Clach Leathad, Ballachulish, Mullach nan Coirean, Ben Nevis and Rannoch Moor intrusions (Fig. 17.3). Major dyke swarms running in a NE–SW direction are associated with the Etive and Ben Nevis igneous complexes. Another episode of dyke injection, in WNW–ESE and E–W directions, occurred in Permian-Carboniferous times.

The Western Grampians are cut by major NE–SW trending faults. Movement on the most significant of these, the Great Glen Fault, was initiated at the close of the Caledonian Orogeny, ~ 430–390 Ma, when significant sinistral strike–slip movement took place. The whole fault zone is ~ 3 km wide and includes shattered rocks that have proved susceptible to erosion and the formation of a major topographic feature, the Great Glen.

The post-Caledonian history of the Western Grampians involved deep and prolonged erosion, and by the end of the Cretaceous the Caledonian mountains had been reduced to a landscape of low relief. Subsequent episodic uplift during the Palaeogene and Neogene accompanied by differential weathering and erosion shaped the broad-scale elements of relief and drainage, resulting in a heavily dissected pre-glacial landscape (Chap. 3). Erosion exploited shatter belts associated with faults and rocks more prone to weathering. Quartzites and the more resistant igneous rocks generally form higher ground: several peaks in the Mamores and the Grey Corries (northeastwards from Sgùrr a' Bhuic to Cruach Innse) bear quartzite caps, while the high summits of Ben Nevis and Glen Coe comprise volcanic rocks. The large (~130 km^2) upland basin of Rannoch Moor (Fig. 17.2c) is a product of differential weathering and erosion of biotite granite that is less resistant than the metamorphic and volcanic rocks underlying the surrounding mountains. The more erodible dykes form gullies, or where more resistant, occasionally stand proud as ridges. A fine example of erosion along two different dykes occurs on the floor of Glen Coe (Sect. 17.8).

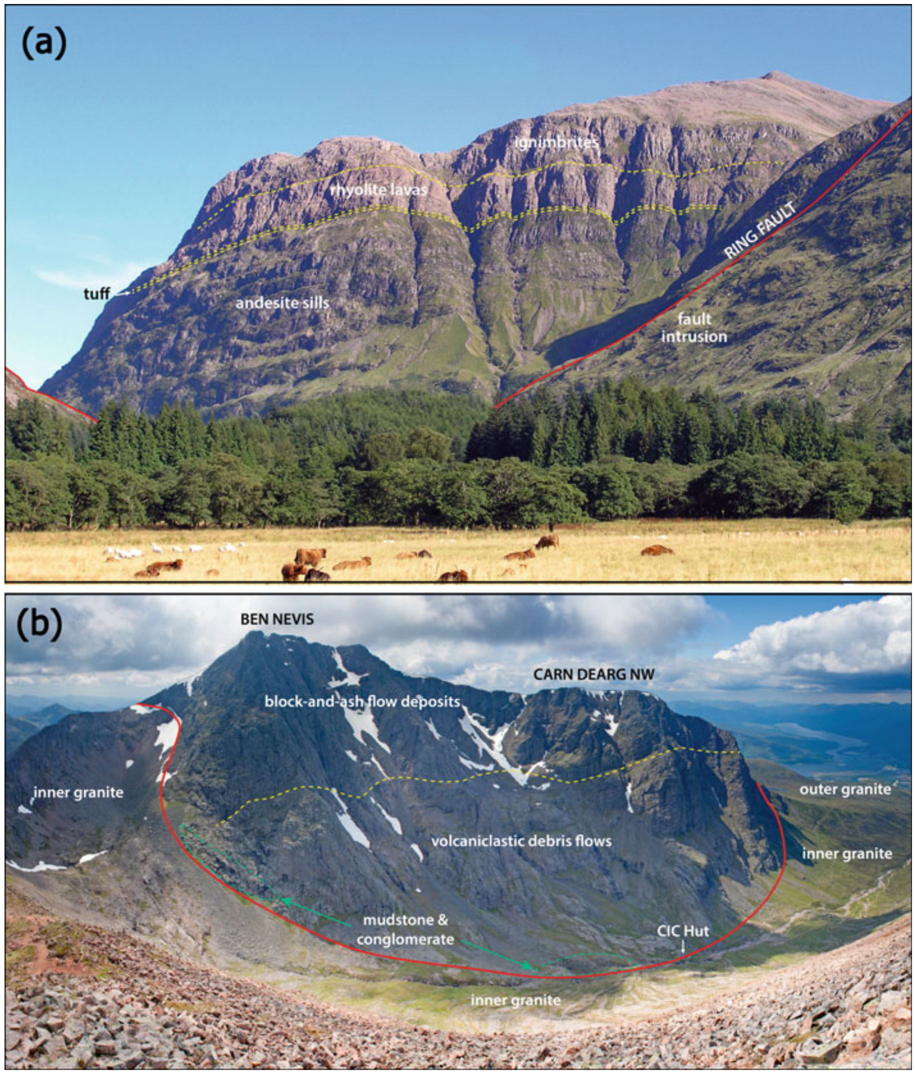

Fig. 17.4 **a** West face of Aonach Dubh, Glen Coe, showing a stack of shallow-level sills that were originally intruded in unlithified wet sediments, overlain by rhyolite lavas and ignimbrites, which indicate a change to more explosive volcanic activity. **b** The 700 m high North Face of Ben Nevis comprises a pile of volcaniclastic rocks set within a granite intrusion. (Images: **a** Noel Williams; **b** © Nick Landells, Lakeland Photo Walks)

17.3 Glaciation History and Patterns

Lochaber played a significant part in the early development of the glacial theory through the observations of Louis Agassiz in 1840, which provided evidence for the former existence glaciers in Scotland (Agassiz 1841, 1842; Chap. 1). Agassiz highlighted the similarity of 'terraced mounds of blocks' at the north end of Loch Treig to moraines in the Chamonix valley in Switzerland and noted the occurrence of polished rock surfaces and moraines at the foot of Ben Nevis and roches moutonnées and polished and striated bedrock at Loch Treig and along the shores of Loch Leven near Ballachulish (Boylan 1998). He also interpreted the Parallel Roads of Glen Roy (Chap. 16) as the shorelines of former ice-dammed lakes.

The landscape of Lochaber reflects the cumulative effects of multiple glaciations during the Pleistocene, involving ice sheets, ice caps and mountain glaciers (Hall et al. 2019; Merritt et al. 2019; Chap. 4). Stratigraphic evidence for glacial episodes pre-dating the Late Devensian is absent, however, having been removed by later glaciations. Favoured by topography and high precipitation, glaciers likely built up repeatedly in the mountains to the west of Rannoch Moor and flowed into the Rannoch basin, which then became a major ice dispersal centre (Bailey and Maufe 1916; Sissons 1967; Payne and Sugden 1990). It is probable that all summits were covered by the last Scottish Ice Sheet during the Late Devensian glacial maximum and also during earlier episodes of ice-sheet glaciation; erratics of Rannoch granite occur up to ~900 m on the Glen Coe hills and 1100 m on Ben Nevis. The patterns of striae and erratic dispersal indicate that the position of the ice divide likely migrated, at times lying across the western side of Rannoch Moor and running northwards towards Ben Nevis, and at other times, over Rannoch Moor itself (Thorp 1987; Hughes et al. 2014).

Later, Rannoch Moor and the mountains to the west were major centres of ice accumulation for the glaciers of the

LLR. Empirical evidence and numerical modelling indicate growth of a domed ice cap with a maximum surface elevation of ~900 m OD, transitional to an icefield system with outlet glaciers confined within the main glens (Golledge and Hubbard 2005; Golledge et al. 2008, 2009; Bickerdike et al. 2018; Fig. 17.1 inset). Outlet glaciers drained west along Glen Nevis, the Loch Leven trough and Glen Coe, merging with a glacier in Loch Linnhe. To the northeast, ice in Glen Spean originating west of the Great Glen merged with glaciers emerging from the cirques of the Ben Nevis range and with ice flowing through the Treig breach and extended eastwards to a limit formed by a large, multiple moraine loop near the western end of the present Loch Laggan (Chap. 16). To the east, an outlet glacier reached the eastern end of Loch Rannoch. Other prominent glaciers flowed along Glen Creran and Glen Etive to the southwest, terminating at the coast. Geomorphological evidence at Loch Etive, Loch Creran and Loch Linnhe demonstrates that glaciers retreated from their maximum limits and stabilised at topographic pinning points. Subsequent active retreat is indicated by recessional moraines on the floor of the inner basin of Loch Etive (Audsley et al. 2016) and by hummocky recessional moraines on Rannoch Moor (Sect. 17.5.2).

Evidence from the area occupied by the West Highland Icefield is critical for establishing the chronology of the LLR ice maximum and subsequent ice recession (Chap. 4). Scotland occupies a key geographical position on the Atlantic seaboard of Europe, and its glacial chronology is important for understanding the driving mechanisms of abrupt climate change in the North Atlantic region during the Younger Dryas, and particularly the influence of sea-surface temperatures and seasonality on terrestrial glacier responses (Golledge 2010; Bromley et al. 2014, 2018). The balance of available evidence (Chaps 4 and 16) indicates that the West Highland Icefield and some of its outlet glaciers survived until the end of the Loch Lomond Stade (~11.7 ka), although some smaller glaciers probably retreated from their maximum positions in mid-stade. Radiocarbon dates on plant macrofossils retrieved from the base of cores from peat-filled basins within the hummocky moraines on Rannoch Moor provide crucial limiting ages for the final disappearance of ice from the main centre of ice dispersal (Sect. 17.5.2), although glaciers likely survived longer in the cirques of the adjacent mountains.

17.4 Landscapes and Landforms of Glacial Erosion

Glacial erosion has had a profound influence in shaping the landscape of the Western Grampians. High snow accumulation fed by Atlantic airmasses and steep pre-glacial glens favoured the development of fast-flowing, warm-based glaciers, particularly during ice-cap and ice-sheet build-up stages. Numerical modelling of the LLR ice cap shows that Glen Nevis, Glen Coe and Glen Etive coincided with corridors of highest subglacial erosion potential (Golledge et al. 2009). Lochaber is a spectacular example of a 'composite' landscape of glacial erosion (Sugden and John 1976), shaped by multiple phases of cirque, valley-glacier and ice-sheet erosion. Much of the pre-glacial valley network has been comprehensively modified, compartmentalising the relief into distinct mountain massifs (Clayton 1974; Haynes 1977, 1983). Contrasting with the extensive plateau palaeosurfaces of the Eastern Grampian Highlands and the Cairngorm Mountains (Chaps 18 and 20), the high density of glacial troughs, breached watersheds, cirques and over-deepened valleys dominates the scenery of the Western Grampians (Fig. 17.2a, b).

Glacial troughs form a distinctive radial pattern centred on Rannoch Moor (Linton 1957). They mostly follow pre-existing valleys exploiting the NE–SW Caledonian structural lineaments, although some glaciers breached pre-existing watersheds (Linton 1951). Examples of the latter include the fault-controlled trough of Loch Treig to the north of Rannoch Moor, which involved ~550 m of glacial incision, Glen Coe to the west and Glen Etive to the southwest (Fig. 17.5a). Glen Coe exhibits truncated spurs and the hanging valley of Coire Gabhail (the 'Lost Valley') along its south side (see Fig. 17.9b below). Glen Nevis is a fine example of a glacial trough, with ice-moulded bedrock at Polldubh crags, roches moutonnées on the nearby valley floor and a spectacular meltwater gorge separating the lower and upper sections of the glen. Above the gorge, the Steall waterfall plunges in a single drop of 120 m from the hanging valley of Coire a' Mhàil (Fig. 17.5b).

Intermediate slopes, valley shoulders, cols and summits up to ~800 m are frequently ice-scoured, with frost-weathered regolith covering summits at higher elevations (Figs. 17.2a and 17.5c). The distal parts of western troughs were drowned by relative sea-level rise during the Early Holocene (Chap. 4), forming the fjords and sea lochs of Loch Linnhe, Loch Leven and Loch Creran (McIntyre and Howe 2010; Fig. 17.1). Glen Etive, and its continuation as Loch Etive, is partly fault controlled. The loch occupies a glacially over-deepened trough comprising several basins, the deepest reaching a maximum water depth of 145 m (Howe et al. 2001; Audsley et al. 2016). A rock bar at the mouth of the loch is the site of a tidal overfall, the Falls of Lora. Loch Laidon, on Rannoch Moor, occupies a rock basin excavated along the line of the Ericht-Laidon fault.

Numerous cirques fret the main ridges and mountain massifs (Figs. 17.2a and 17.5c). They are predominantly but not exclusively developed on the northern flanks of the mountains, with further asymmetry present in the strong northeasterly and northerly orientations of their headwalls.

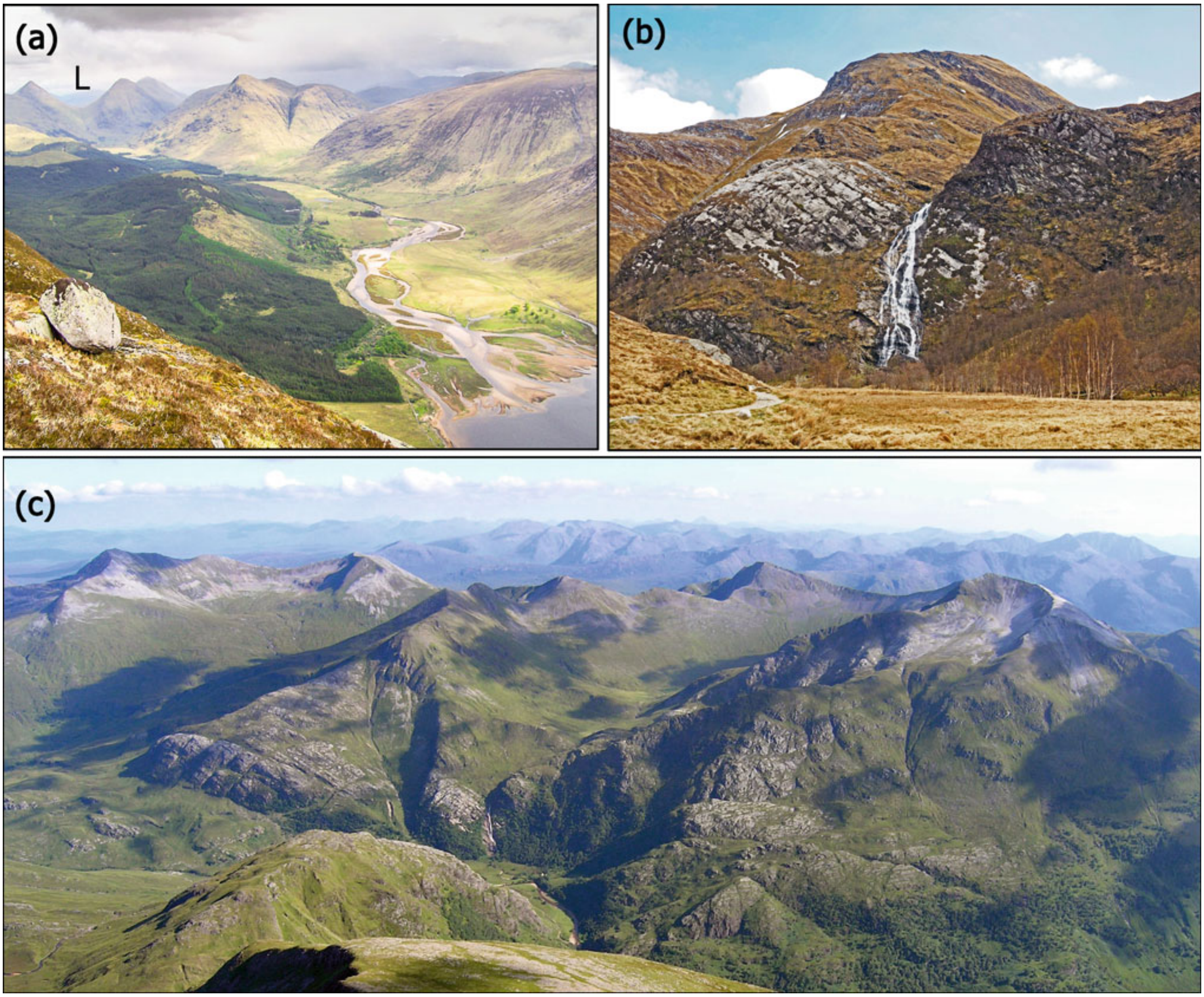

Fig. 17.5 **a** The partly fault-aligned glacial trough of Glen Etive is the product of multiple episodes of glacial and fluvial erosion. The Lairig Gartain (L) is a prominent, glacially breached watershed. The River Etive transitions from a rocky upper reach to a wandering gravel-bed and then to a low-angle gravel delta as it enters Loch Etive. **b** Upper Glen Nevis gorge and the Steall waterfall. **c** The Mamore range displays frost-weathered quartzite summit ridges and screes, with ice-scoured slopes below. (Images: **a** Adrian Hall; **b**, **c** Noel Williams)

Cirque headward erosion has contributed to the formation of the arêtes of Aonach Eagach and Càrn Mòr Dearg.

17.5 Landscapes and Landforms of Glacial and Glacifluvial Deposition

LLR glaciers removed or reworked much of the earlier glacial deposits, and thick accumulations of glacial deposits are rare within the area apart from Rannoch Moor (Thorp 1991). This contrasts with the area immediately to the south of Rannoch Moor, where extensive glacial deposits emplaced by the last ice sheet were only slightly modified during the LLR (Golledge 2006, 2007). Two distinctive assemblages of deposits are associated with the LLR glaciers: valley sandar and recessional moraines.

17.5.1 Valley Sandar and Ice Limits

Several outlet glaciers draining the LLR ice cap terminated at the west coast producing a series of striking landforms, including ice-contact features and glacial outwash deposits. The maximum extent of these glaciers was probably determined by tidewater calving and their patterns of recession by the positions of topographic constrictions or pinning points where the glacier fronts stabilised, so that outwash spreads or valley sandar occur inside the maximum glacier limits (Peacock 1971; Gray 1975; Greene 1992).

At its maximum, the Etive glacier probably extended to a large accumulation of glacial deposits 2 km west of Connel, at the westernmost extent of Loch Etive. Within this limit, on the north side of the loch, a ~4 km^2 outwash plain at Moss of Achnacree (Gray 1975, 1993, 1995; Fig. 17.6) formed across a bedrock threshold that constricts the mouth of the loch. Kettle holes and a meltwater channel occur on the outwash surface. A narrow channel, possibly cut by outflow from a freshwater ice-contact lake during glacier retreat, forms the exit of the loch. The margins of the outwash plain were later trimmed by the sea at ~13 m OD (Ordnance Datum), and a spit formed along its western margin. As relative sea level fell, Holocene raised beach deposits formed along the margins of the outwash plain. Smaller outwash terraces occur on the south side of the loch, and kame terraces, kame and kettle topography and eskers extend eastwards along both its sides (Fig. 17.6), together with the Moss of Achnacree forming perhaps the finest outwash and kame terrace system in Britain (Gray 1993).

An end moraine complex at the mouth of Loch Creran (Peacock 1971, 1993; Gray 1975; Peacock et al. 1989) comprises reworked marine clay with sand and gravel and runs for ~2.5 km southeast from South Shian parallel to the shore of the loch, with a peat-covered outwash plain beyond. On its distal side, mounds of ice-contact sediments surrounded by outwash suggest that the Creran glacier extended ~2 km further south and west. The glacier advanced over fossiliferous Lateglacial marine and glacimarine silts and clays (Clyde Beds), including high-arctic molluscan shells, laid down on the loch floor. Exposures at South Shian and Balure of Shian show contorted clay laminae and crushed shells, and at Balure of Shian the clay is glacitectonically folded into ice-contact silts overlain by gravel (Peacock 1971, 1993). Deposits at Balure of Shian are less glacitectonised and overconsolidated than those at South Shian, suggesting proximity to the ice-maximum position (Peacock et al. 1989). After reaching its maximum extent, the glacier retreated and stabilised at the South Shian moraine, possibly controlled by a rock bar. The outwash and moraines were later trimmed by the sea, and raised gravel beaches occur at ~13–14 m OD.

Radiocarbon dates on shells from the fossiliferous sediments incorporated in till at South Shian and North Shian

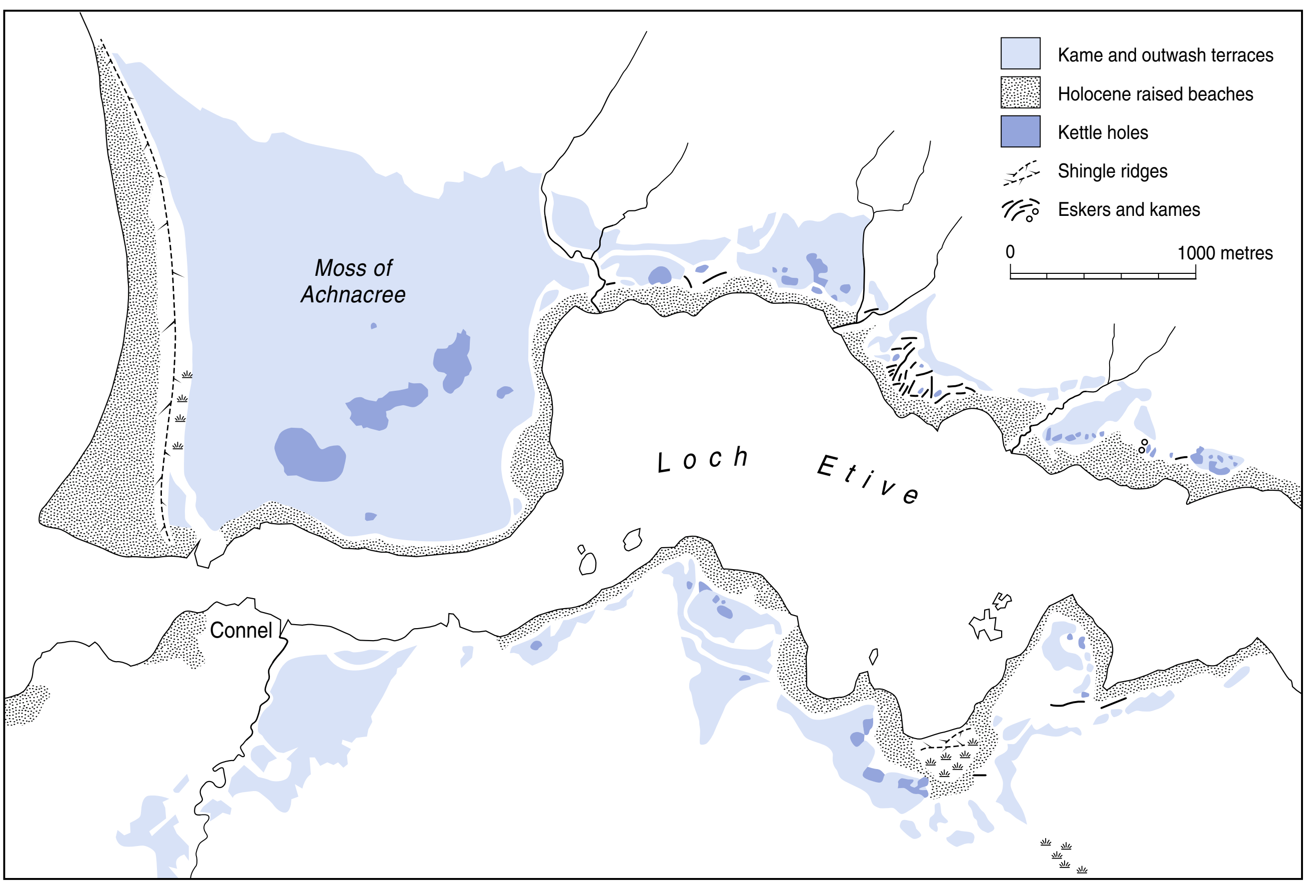

Fig. 17.6 Glacifluvial landforms at the mouth of Loch Etive. (After Gray JM (1975) The Loch Lomond Readvance and contemporaneous sea-levels in Loch Etive and neighbouring areas of western Scotland. Proc Geol Assoc 86:227–238, as adapted by Ballantyne 2019b. Reproduced with permission from the Geologists' Association)

provide a maximum age of 12.6–12.8 cal ka BP for the advance of the Creran glacier (Bromley et al. 2018). Dates obtained from the deposits at Balure of Shian suggest that the glacier remained relatively advanced until the middle or near the end of the Loch Lomond Stade (Peacock et al. 1989).

Thorp (1986) considered that the LLR limit in Loch Linnhe is marked by a small outwash fan at Kentallen, an interpretation supported by seismic evidence for the presence of ice-contact and ice-proximal sediments on the adjacent loch floor (Greene 1995). However, compacted marine sediments at the base of a vibrocore from the Shuna basin, ~14 km farther south, indicate that the Loch Linnhe glacier was possibly more extensive (McIntyre and Howe 2010), consistent with the numerical simulation of Golledge et al. (2008). Subsequently, retreat of the Linnhe glacier was interrupted by stabilisation at pinning points, indicated by a large kettled outwash terrace at Corran and a marine-reworked outwash fan at the mouth of Loch Leven (McCann 1961, 1966; Fig. 17.2b).

17.5.2 Recessional Moraines

Extensive recessional moraines are particularly well displayed on Rannoch Moor, with concentrations in the Bà valley in the southwest of the Moor, and around and to the north of Lochan Gaineamhach (Horsfield 1983; Thorp 1986; Wilson 2005; Bromley et al. 2014; Turner et al. 2014; Fig. 17.7). They are often described as 'hummocky moraine', comprising generally steep-sided mounds and ridges with numerous surface boulders of granite and a variety of constituents ranging from water-sorted silts, sands and gravels to coarse, rubbly till. Clasts are predominantly of local granite, but igneous erratics from the mountains to the west occur in the Bà valley. At ground level, the ridges and mounds appear chaotic, but many display nested alignments when mapped or viewed from the air. Such moraines occur extensively in the Highlands and are now considered to represent the successive ice-margin positions of actively retreating glaciers (Bennett and Boulton 1993; Lukas and Benn 2006). Moraine patterns on Rannoch Moor demonstrate that the last glaciers retreated actively into valley heads in adjacent mountains (Horsfield 1983; Boulton 1992; Wilson 2005). Cross-valley moraines on the north side of Blackwater Reservoir and east of Loch Bà (Turner et al. 2014) similarly indicate active glacier retreat, as do recessional moraines on the floor of Loch Etive partly controlled by topographic pinning points (Audsley et al. 2016). Possibly the extent and complex pattern of hummocky moraines on Rannoch Moor reflect the presence of earlier Late Devensian ice-sheet moraines partially preserved and reworked under the LLR ice cap (Bickerdike et al. 2018), while some ridges may represent glacial streamlining by ice flowing onto the Moor from the west (Wilson 2005).

Rannoch Moor provides critical evidence for dating the demise of the LLR glaciers in Scotland and more widely for understanding abrupt climate change and glacier responses in the North Atlantic region during the Younger Dryas (Golledge 2010; Bromley et al. 2018). A recent interpretation proposing an ice maximum early during the Loch Lomond Stade and deglaciation of Rannoch Moor by ~12.6–12.2 ka (Bromley et al. 2014, 2018) is at variance with other evidence that Rannoch Moor was not completely deglaciated until the end of the stade or the beginning of the Holocene (Small and Fabel 2016; Peacock and Rose 2017; Lowe et al. 2019; Chaps 4 and 16).

17.6 Periglacial Landforms

Periglacial features formed on exposed mountain summits and slopes as the latter became exposed to intensely cold conditions during ice-sheet deglaciation and the Loch Lomond Stade. Blockfields and frost-weathered debris, probably of pre-Late Devensian age (Fabel et al. 2012), occur on many summits, notably on Ben Nevis, Ben Starav and the quartzite ridges of the Grey Corries and the Mamores. Relict, stone-banked solifluction sheets and lobes formed where the debris moved downslope, as on the upper slopes of Aonach Beag and on Leum Uilleim (Thorp 1986). On some summits, this debris displays a clear lower limit, or 'trimline', below which the bedrock is ice scoured (Thorp 1981, 1986; Fig. 17.5c). Postglacial scree slopes are also well developed on the quartzites of the Mamores and Grey Corries (Fig. 17.5c).

In winter, high snowfall and heavy drifting from the summit plateau of Ben Nevis generate substantial snowbeds that survive late into the summer and provide important nival habitats (Manley 1971; Watson and Cameron 2010; Watson 2011; Fig. 17.4b). Below the 600-m-high cliffs on the north face of Ben Nevis a rampart of angular boulders, ~3 m high, ~75 m long and with a distal apron of avalanche run-out debris, impounds a small loch at ~910 m OD. These features are interpreted as a rare example of snow avalanche impact landforms in Britain (Ballantyne 1989). A good example of an avalanche boulder tongue also occurs below Tower Gully on Ben Nevis.

17.7 Mass-Movement Landforms

As the last ice sheet decayed, unloading of steep rock slopes resulted in propagation of stress-release joints, leading to deformation or local catastrophic collapse of mountain-side slopes. A seismic trigger associated with fault reactivation caused by differential glacio-isostatic rebound is possible (Ballantyne et al. 2014; Chap. 14). A cluster of such

Fig. 17.7 Hummocky recessional moraines, Rannoch Moor. (Image: John Gordon)

rock-slope failures (RSFs) occurs in Lochaber (Jarman 2006). They include the failure scars of Lateglacial RSFs where the run-out debris was removed by LLR glaciers; examples include Coire Sgreamhach on Beinn a' Bheithir and Stob Bàn in the Mamores (Ballantyne 2013; Fig. 17.2a). Many are arrested slides where the displaced rock mass has retained its integrity (Fig. 17.8a). Although most catastrophic RSFs in Scotland occurred during the Lateglacial period, prior to ~11.7 ka, some are of Holocene age. A striking example occurs near the mouth of Coire Gabhail in Glen Coe, where a rock avalanche involving some 0.6 Mt of rhyolitic ignimbrite has formed a massive cone of boulders that block the entrance to the hanging valley (Ballantyne 2007; Fig. 17.8b). This event occurred ~1700 years ago (Ballantyne et al. 2014), damming the glen so that floodplain deposits accumulated upvalley from the landslide debris. Except during periods of high discharge, run-off within Coire Gabhail now sinks into the floodplain and emerges below the avalanche debris.

Steep, drift-mantled slopes and talus slopes have been extensively modified during the Holocene by debris flows triggered by high-intensity rainfall events, although other factors such as land-use changes during the last few centuries may have contributed to increased slope-failure susceptibility (Ballantyne 2019a). Hillslope and valley-confined debris flows scar the flanks of many glacial troughs, while repeated debris flows along the same tracks have deposited some of the largest postglacial debris cones in Scotland, notably in Glen Etive and Glen Coe. These two glens display some of the finest examples of both active and fluvially modified debris cones in Britain (Brazier et al. 1988; McEwen 1997; Werritty and McEwen 1997). Often these are fed from deep gullies eroded along porphyritic dykes. They include the Chancellor cone, the largest debris cone in Britain, below Aonach Eagach on the north side of Glen Coe (Fig. 17.9a) and the Eas na Broige cone in Glen Etive. Lichenometric dating suggests increased debris-flow activity during the last ~250 years associated with land-use changes (Innes 1983). However, burial of older debris by later events skews the lichenometric record towards recent activity (Ballantyne 2019a). Debris cones are often polygenetic; for example, that below Coire nan Lochan (Glen Coe) has been modified by mountain torrents and comprises coarse, bouldery deposits with abandoned channels on its surface (McEwen 1997; Fig. 17.9b). At the Eas na Broige cone below Dalness Chasm, exposures have provided evidence for successive phases of Holocene debris-flow and alluvial fan development (Brazier et al. 1988; Werritty and McEwen 1997). The landform comprises a debris cone with an inset alluvial fan. Radiocarbon dating of buried palaeosols indicates an earlier, active phase during the Early-to-Middle Holocene when glacial debris was available for reworking, and a later, recent phase initiated by climatic deterioration or grazing pressure. Debris cone aggradation ceased prior to ~5.2 ka, possibly as a result of sediment exhaustion. This was followed by a prolonged period of relative slope stability and soil development until ~0.6 ka, after which fluvial reworking of debris cone sediments produced the inset alluvial fan. Pollen and charcoal evidence indicates that fluvial incision was in part triggered by burning for arable and pastoral agriculture (Brazier et al. 1988). Evidence of human impacts on the landscape is also present in lake-floor sediments in Loch Etive. Accelerated rates of sedimentation during the last thousand years (Nørgaard-Pedersen et al. 2006; Cundill and Austin 2010) likely record enhanced soil erosion arising from anthropogenic deforestation. This was part of a wider pattern of landscape transformation during the last millennium (Macklin et al. 2000) and in particular during the eighteenth and nineteenth centuries when there was extensive woodland removal to produce charcoal for the Bonawe iron furnace at Taynuilt.

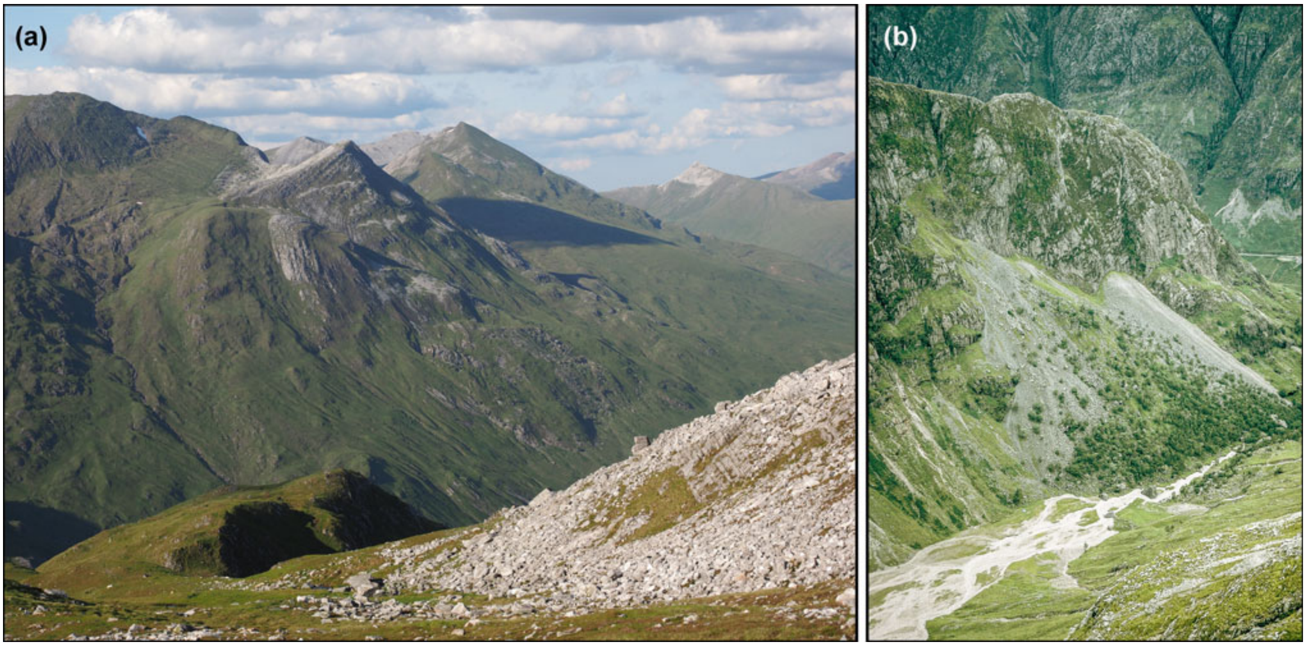

Fig. 17.8 Rock-slope failures. **a** Arrested slide (centre) in folded quartzite bedrock, Sgùrr a' Bhuic, Glen Nevis. **b** Catastrophic rock-slope failure, Coire Gabhail, Glen Coe. The height of the slope from the valley floor to the top of the rock ridge is ~300 m. (Images: **a** Noel Williams; **b** John Gordon)

17.8 Fluvial Landforms

The fluvial geomorphology of the area is characterised by steep mountain torrents in the upper reaches of many catchments and gravel-bed rivers in the lower reaches. Tributaries from higher valleys and cirques form steep alluvial fans at their junctions (e.g. below Stob Coire nam Beithe in Glen Coe). The River Coe provides an excellent example of a high-energy fluvial system with an unusually rapid transition in channel form downstream (McEwen 1994, 1997). The upper reach of the river at the head of Glen Coe is a steep boulder-bed mountain torrent incised into a gorge excavated along porphyritic dykes (Bailey and Maufe 1916; Fig. 17.9b); the River Coe and two tributary streams converge at the 'Meeting of Three Waters', where a NE–SW Caledonian dyke which runs the length of Coire Gabhail intersects a WNE–ESE Carboniferous dyke running along the floor of the main glen. Within a distance of 1.5 km the River Coe transitions to a sinuous, wandering gravel-bed channel with adjacent palaeochannels of different ages, then to a low-angle gravel delta where it enters a small loch (Chap. 4). The post-nineteenth century history of channel adjustment reveals a complex record of braiding and channel shifting across the valley floor (McEwen 1994). This dynamism reflects high discharges, together with sediment inputs from mountain-torrent tributaries, from undercutting of adjacent alluvial fans and debris cones and from paraglacial sediment stores on the floodplain. The River Etive displays a similar change in character from a bedrock river in its upper reaches to a wandering gravel-bed river in its lower reaches (Fig. 17.5a). The Allt Coire Gabhail, a tributary of the River Coe, is unique in Scotland as the location of an alluvial basin that has developed upstream of the rock avalanche that dammed the mouth of the glen (Werritty 1997; Fig. 17.8b).

17.9 Coastal Landforms

The Lateglacial Main Rock Platform (Chap. 4) is well displayed along the fjordic southeast coastline and adjacent islands of Loch Linnhe and the Firth of Lorn. The raised platform and its cliffline fringe much of the Isle of Lismore, carved in predominantly limestone bedrock. Uranium-series disequilibrium dates on speleothems from several of the many caves and undercut notches raise the possibility that the origins of the platform may pre-date the Late Devensian and that it is polycyclic in origin (Gray and Ivanovich 1988), though cosmogenic ^{36}Cl exposure dating of the platform on Lismore is consistent with its formation under periglacial conditions during the Loch Lomond Stade (Stone et al. 1996). An excellent example of a raised sea-arch occurs along a steeply dipping fault at the rear of the platform at Clach Toll on the adjacent mainland.

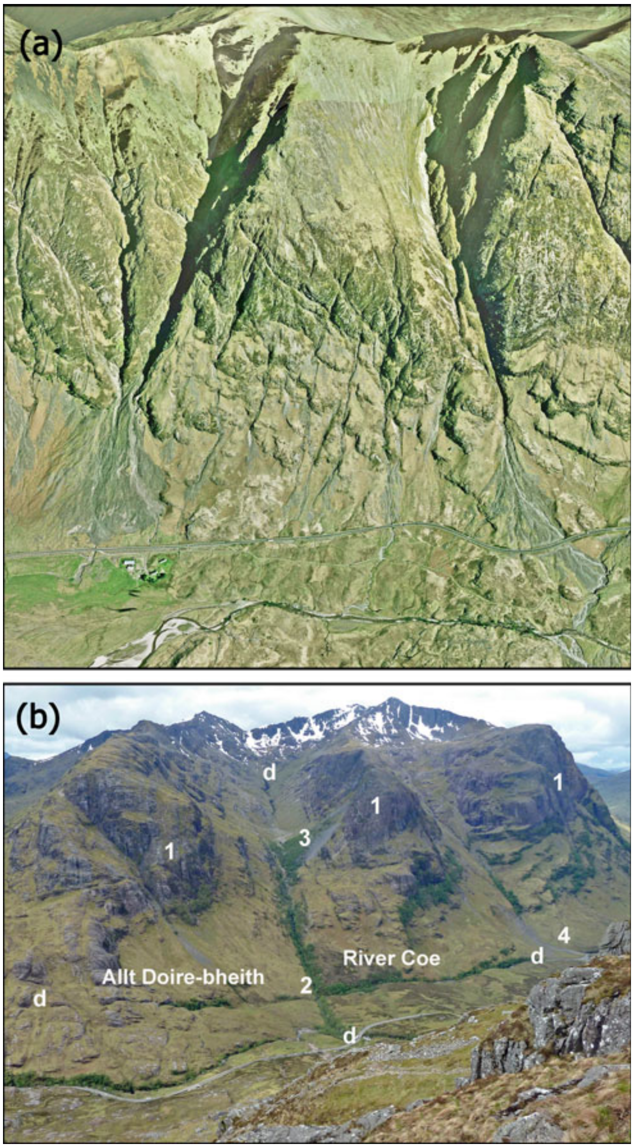

Fig. 17.9 Hillslope and fluvial landforms, Glen Coe. **a** Debris cones below Meall Dearg (953 m) on the Aonach Eagach ridge on the north side of Glen Coe are fed from gullies controlled by porphyritic dykes. The Chancellor cone on the left is named after a prominent rock tower on the ridge. Debris-flow activity periodically blocks the A82 road, and it is recorded that the settlement of Achtriochtan (bottom left) was destroyed by debris flows in the eighteenth century. **b** The Glen Coe glacial trough viewed from the north. 1: Truncated spurs. 2: 'The Meeting of Three Waters' at the intersection of two dykes (d). The middle reach of the River Coe and its headwater, the Allt Doire-bheith, follow a rocky gorge controlled by the ESE-WNW aligned dyke. 3: Catastrophic rock-slope failure, Coire Gabhail. 4: Fluvially modified debris cone below Coire nan Lochan. (Images: **a** Google Earth™ image; **b** Lochaber Geopark)

17.10 Geoheritage and Geoconservation

The natural heritage value of many of the landforms described in this chapter is recognised through a variety of statutory and non-statutory conservation designations. Large parts of Ben Nevis and Glen Coe, together with Moss of Achnacree, South Shian and parts of Rannoch Moor, are protected as Sites of Special Scientific Interest for their geoheritage features. Ben Nevis and Glen Coe are managed by non-governmental organisations, respectively, the John Muir Trust and National Trust for Scotland, which promote landscape conservation, public understanding and enjoyment. Geology and geomorphology underpin the landscape qualities of the Ben Nevis and Glen Coe National Scenic Area. Ben Nevis, Glen Coe, Rannoch Moor and Glen Etive are incorporated within Lochaber Geopark which, *inter alia*, promotes geoconservation, sustainable development, geotourism and educational activities in partnership with local communities. The Geopark has played a significant part in raising wider awareness of the links between geology, geomorphology and landscape through publications, educational activities and public engagement.

The connections between geology, landscape and culture have formed the basis of visitors' appreciation of the West Highland landscape since the latter part of the eighteenth century and were popularised in the journals of early travellers such as Thomas Pennant, Dorothy Wordsworth and Samuel Taylor Coleridge (Crocket 1986). Today, the area is an attractive visitor destination for its scenic qualities and opportunities for outdoor recreation in a variety of landscape settings shaped by the geology and geomorphology. The mountain ridges and rock faces of Ben Nevis and Glen Coe are renowned for their mountaineering and hillwalking challenges, both in summer and winter, and downhill skiing facilities are located on Aonach Mòr and on the slopes of Meall a' Bhùiridh above Rannoch Moor. Glen Coe is a major stopping point for visitors to view the scenic qualities of the huge rock buttresses and truncated spurs formed by glacial erosion. It is has been widely celebrated by artists for its 'sublime' scenery (e.g. in paintings by Horatio MacCulloch and J.W.M. Turner), as well as for its cultural heritage and associations with Celtic mythology, its notorious place in Scottish clan history and as a film-set location (e.g. see https://www.nts.org.uk/visit/places/glencoe).

17.11 Conclusions

The Western Grampians bear a strong imprint of the Caledonian Orogeny and post-orogenic volcanism in terms of lithological and structural influences on the form of the landscape and topographic features at different scales. Rannoch Moor and the adjacent mountains formed the principal ice-accumulation centre in Scotland for repeated ice-cap and ice-sheet growth and dispersal during the Pleistocene. The landscape displays many classic landforms of glacial erosion and excellent examples of LLR outwash plains and hummocky recessional moraines, the latter indicating active glacier recession. Topographic pinning points played an important part in determining the style of glacier retreat within the sea lochs and controlled the positions of large outwash accumulations. The area is particularly important in the context of dating the culmination of the LLR and the final disappearance of the ice, currently a matter of debate, which has a significant bearing on understanding the drivers of abrupt climate change and the response of terrestrial glaciers during the Younger Dryas in the North Atlantic region. The array of rock-slope failures and Holocene debris flows and debris cones is also outstanding. The geodiversity of the region is reflected in numerous conservation designations and the inclusion of a large part of the area within Lochaber Geopark.

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