16 Glen Roy and Glen Spean

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Abstract

The landscape around Glen Roy and Glen Spean is dominated by the effects of glacial processes that operated during the Quaternary. The area has been widely studied over the last two hundred years. It was one of the first locations in Britain where the role of glaciation was recognised and remains an important focus of research today. Glen Roy and Glen Spean lie adjacent to the main ice accumulation areas in the Western Grampian Highlands, and geomorphic evidence for processes that operated during the Loch Lomond Stade (~12.9–11.7 ka) is especially well preserved. Particular highlights are the shorelines ('Parallel Roads') and associated landforms of the famous glacilacustrine systems that existed for 518 years between 12,135 and 11,618 cal a BP. The remarkable assemblage of geomorphic features includes terminal and lateral moraine complexes, kames, eskers, kame terraces, kettle holes, shorelines of glacial lakes, subaerial and subaqueous fans, deltas and a cluster of rock-slope failures that were activated before, during and after the glacilacustrine systems. After the demise of the ice-dammed lakes there is evidence for the evolution to fluvial drainage systems of the present day. The geomorphological importance of the area is highlighted by its recognition as a flagship locality within Lochaber Geopark.

Keywords

Ice-dammed lakes • Lake shorelines • Lake deltas • Jökulhlaup • Varve chronology • Alluvial fans • Rock-slope failures • Palaeoseismicity

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16.1 Introduction

Glen Roy and Glen Spean, in Lochaber, provide geomorphological evidence of international significance for Late Quaternary glaciation in the British Isles. This global recognition primarily stems from the distinctive glacial lake shorelines preserved on the hillsides of both valleys and neighbouring Glen Gloy. These shorelines were formed by a glacilacustrine system that developed between ~12.1 ka and ~11.6 ka during the Loch Lomond Stade (equivalent to the Younger Dryas of ~12.9–11.7 ka). In Glen Roy, the shorelines are referred to as 'Parallel Roads' and represent former lake levels at altitudes of 260 m, 325 m and 350 m OD (Ordnance Datum; Fig. 16.1), whereas only fragments of a single shoreline at 260 m are present in Glen Spean and only a single shoreline at 355 m occurs in Glen Gloy. The Parallel Roads represent the focal point of interest, but the shorelines are linked to fine examples of glacial, fluvial and mass-movement landforms that provide important evidence for the Lateglacial evolution of the landscape in the three valleys. These include ice contact subaqueous fans, subaqueous fans, deltas, moraines, kame and esker systems, fluvial terraces and rock slope failures.

The landforms and landscape of Glen Roy and Glen Spean have stimulated debate from the time of the emergence of modern geological principles in the nineteenth century to the present day. After 1840, when the true significance of the lake shorelines was first appreciated, the area was fundamental in establishing the role of glaciers in shaping the Scottish Highlands, and research on its landforms and sediments over the past 50 years has proved critical in determining the extent and chronology of the Loch Lomond Readvance (Younger Dryas) icefield in the Western Highlands. Moreover, Glen Roy and Glen Spean remain at the forefront of research in the UK, through the analysis of annually resolved lake sediment (varve) records to understand glacier dynamics at decadal scales using high-precision chronologies. The discovery within the varve

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Fig. 16.1 **a** 'Parallel Roads' of Glen Roy, looking north from the Viewpoint with the 'Massive Drift Accumulation' in the foreground and showing the three shorelines at 260 m, 325 m and 350 m OD. **b** Detail of the three distinctive shoreline benches eroded into the valley side. **c** Upper Glen Roy, with the 350 m and 325 m shorelines in the foreground and the Burn of Agie fan surface in the background. (Images: **a**, **b** Adrian Palmer; **c** Colin Ballantyne)

sediments of the Vedde Ash, a key Icelandic cryptotephra horizon of Loch Lomond Stadial age, highlights the area's continuing significant role in refining our understanding of Lateglacial environmental and climatic change.

16.2 Topography

Glen Roy and Glen Spean are located in the Western Grampian Highlands, ~20 km northeast of Fort William and ~15 km east of the Great Glen (Fig. 16.2). The area is dominated by mountainous terrain rising to over 900 m OD, which includes some of the highest peaks in the Scottish Highlands. The main valley is the Spean, which trends east–west. Drainage through the Spean valley is fed by the River Pattack, which rises in the east and enters Loch Laggan, which is drained westwards by the River Spean, which in turn flows into the River Lochy in the Great Glen. The River Roy (~25 km long) is a north-bank tributary of the Spean that flows initially westwards from the Roy–Spey watershed at 350 m, then southwards to join the River Spean at Roybridge (Fig. 16.2a).

A number of tributary valleys to Glen Roy and Glen Spean supplied high sediment loads during the Lateglacial period and are thus important to our understanding on the evolution of the landscape (Fig. 16.2). The Burn of Agie enters the River Roy in upper Glen Roy as a south-bank tributary, and Glen Turret is a major valley entering upper Glen Roy from the northwest; the valley of the Allt a' Chòmhlain, a tributary of the River Turret, connects upper Glen Roy with the head of Glen Gloy via a col at 355 m (Fig. 16.3a). A series of small streams through upper and middle Glen Roy have steep catchments (those of the Canal Burn, West and East Allt Dearg, Allt Na Reinich, Allt Brunachain and Allt Bhreac Achaidh; Fig. 16.3a, b). To the west of lower Glen Roy, beyond Bohuntine Hill, lies the valley of Caol Lairig; to the east of lower Glen Roy, Gleann Glas Dhoire connects to the Spean valley via a col at 325 m. The lower Spean valley is flanked by the Nevis range to the south, forms a wide valley west of Roybridge but narrows eastwards. Two deep and narrow valleys enter Glen Spean from the south (the Laire and Treig valleys) and the River Ossian flows into Loch Laggan (Fig. 16.2a).

The cols between and at the heads of valleys played an important role in the evolution of the Lateglacial lake sequence in Glen Roy and Glen Spean (Fig. 16.2b). At the eastern end of the Spean valley a long, low-lying area at 260 m between the River Pattack (Spean catchment) and River Mashie (Spey catchment) forms the lowest col between the Spean and Spey catchments. The 325 m col at the head of Gleann Glas Dhoire connects the Roy and Spean catchments via a valley that joins the Spean valley at Roughburn. On the western side of middle Glen Roy a col at 300 m connects Caol Lairig and Glen Roy, and a col at 350 m at the head of upper Glen Roy connects the Roy catchment with the Spey catchment. Finally, as noted above, Glen Gloy and Glen Turret are connected by a col at 355 m.

16.3 Geology

The bedrock geology of the area is dominated by Dalradian psammites, pelites and mica-schists that strike towards the northeast (Key et al. 1997). The area on the western flanks of Glen Roy and into Glen Turret is composed of psammites, semipelites and quartzites of the Grampian Group, but lower Glen Roy, the western flanks of middle Glen Roy and upper Glen Roy are underlain by pelites and calc-silicate rocks of the Leven Schist Formation (Appin Group). The head of Glen Roy is underlain by granodiorite of the Corrieyairick Pluton. Middle Glen Spean is underlain by psammites and feldspathic quartzites of the Grampian Group and, farther east, by the Strath Ossian granodiorite intrusion. Surficial deposits from the last glaciation are present across much of the landscape and are recorded as sandy tills or gravelly diamictons that mantle the lower slopes of the area. Large faults are also recorded within both Glen Roy and Glen Spean.

16.4 Historical Context and the Formation and Drainage of the Glacial Lakes

Glen Roy has been a focus of geological research since the emergence of modern geological and glaciological thinking in the nineteenth century. The enigmatic shorelines on the valley sides and their altitudinal relationship to the overspill cols led to the suggestion that they represented former lake systems, although the lack of obvious impounding barriers or dams caused some to doubt this theory. For example, Darwin (1839) argued that the features were marine shorelines of an inland sea, comparable to features he had observed in southern South America. Agassiz (1840) was the first to propose ice as a competent barrier to river drainage and so enabled the lakes to form. Indeed, the landforms around the mouth of the Treig valley, in combination with the shorelines, were a crucial line of evidence used by Agassiz to suggest glacial ice was prominent in the development of the landscape. Jamieson (1863, 1892) developed this idea using Ordnance Survey data to develop a model of lake evolution that remained established for nearly a century. The different nineteenth-century interpretations of the formation of the Parallel Roads are summarised in Rudwick (2017).

A series of papers by Sissons (1978, 1979a, b, c) and Sissons and Cornish (1982a, b, 1983) presented geomorphic

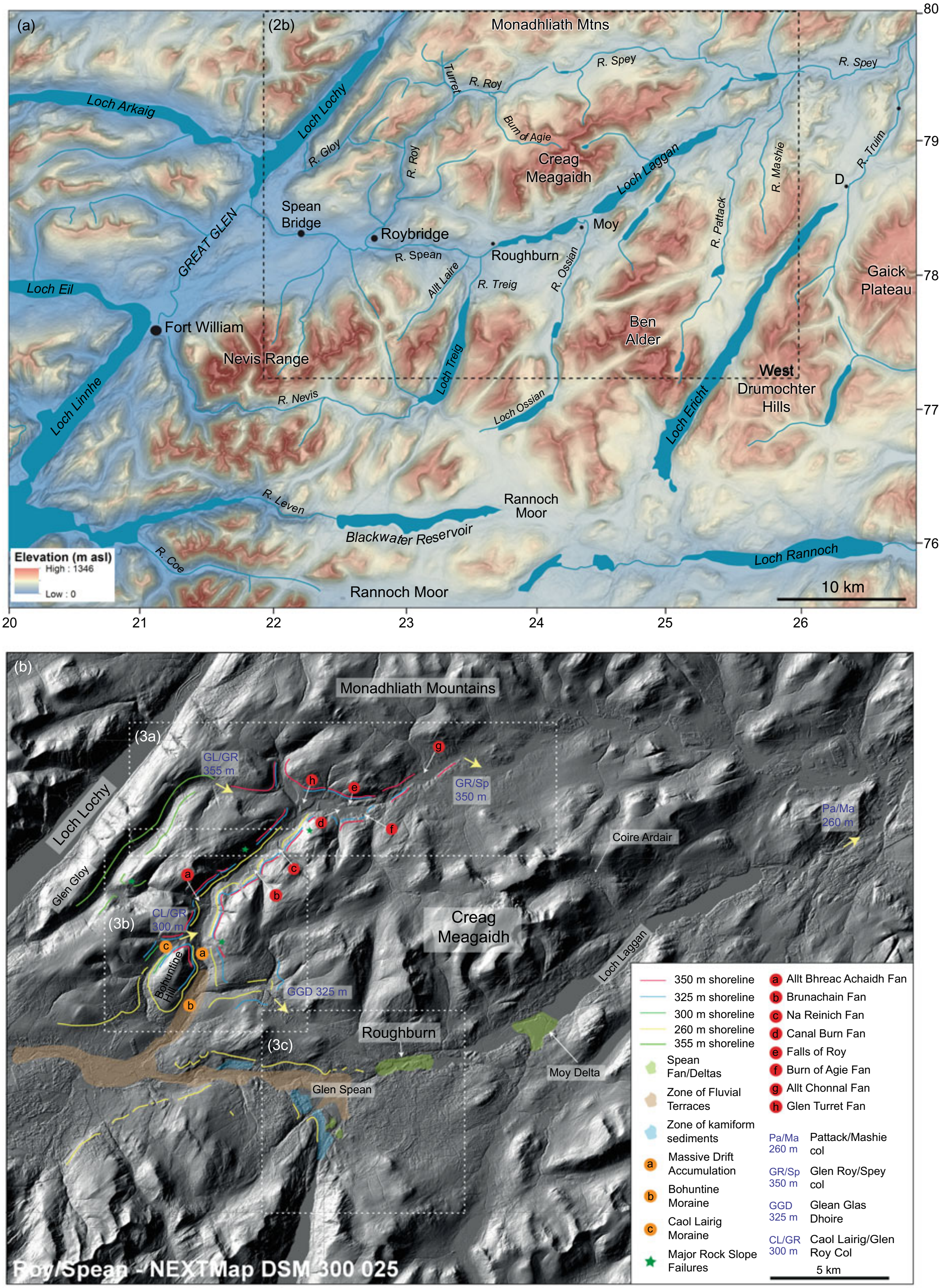

Fig. 16.2 **a** Regional topography and river systems in the area of Glen Roy and Glen Spean (Base map uses OS Terrains5 DTM data available and downloaded from Digimap.edina.ac.uk. © Crown copyright and database rights (2017) Ordnance Survey (100025252)). **b** Digital surface model of Glen Roy and Glen Spean highlighting the distribution of the shorelines and other geomorphological features discussed in the text. (DSM data supplied through Intermap Technologies Ltd)

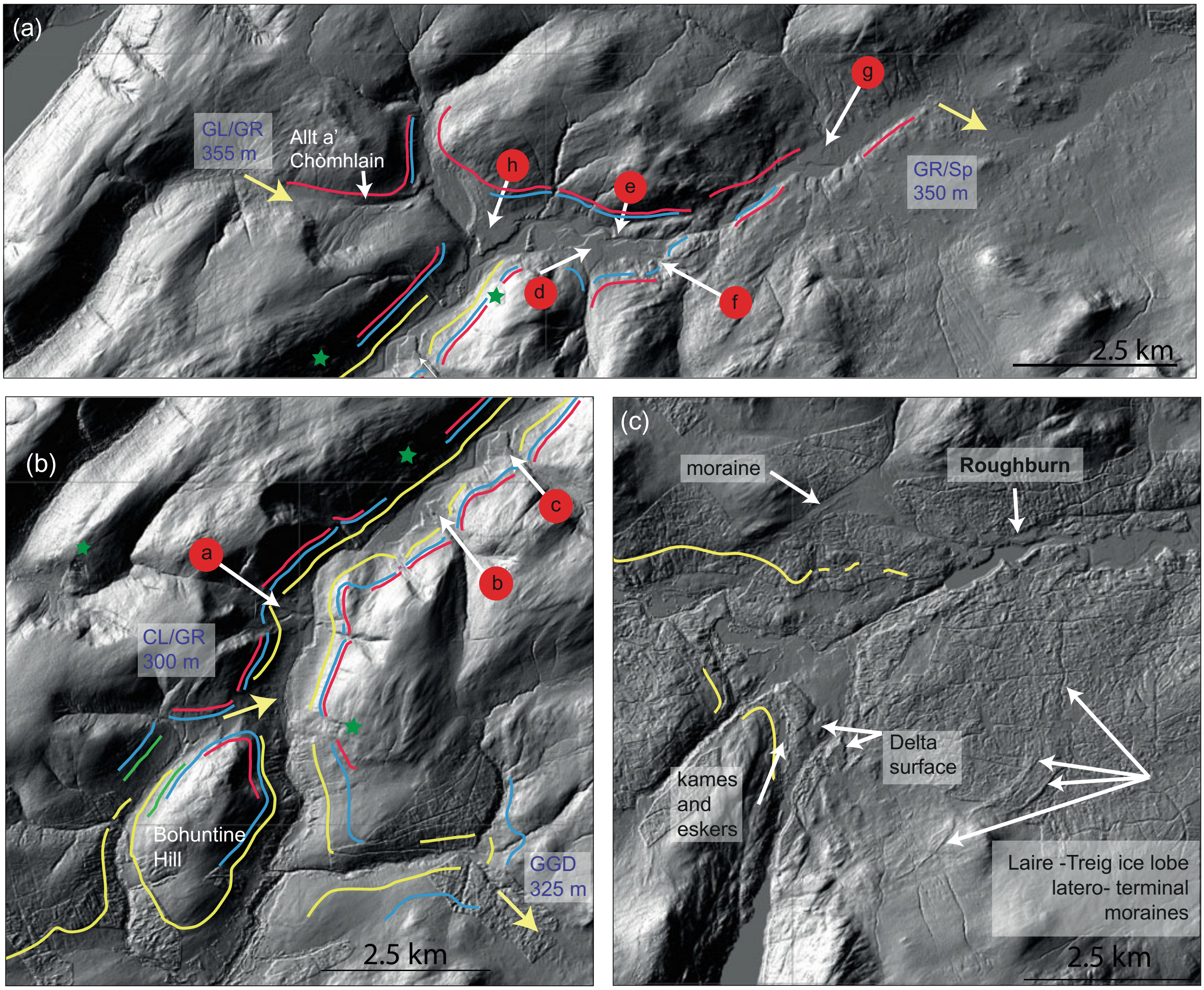

Fig. 16.3 **a** DSM of upper Glen Roy. **b** DSM of middle and lower Glen Roy in the vicinity of the viewpoint. **c** DSM of middle Glen Spean in the area of the mouth of the Treig valley and Roughburn. Key as for Fig. 16.2b. (DSM data supplied through Intermap Technologies Ltd)

mapping of the Spean and Roy catchments and the results of detailed instrumental levelling of the lake shorelines and river terraces. These data and the model for the development of the landscape that emerged from this work are still fundamental to our understanding of the glacial limits, the extent and form of the shorelines, the impact of glacio-isostatic adjustment on the shorelines and the identification of later, lower lake levels and fluvial terrace aggradation after the demise of the main lakes.

The centrepiece of this work is the paper by Sissons (1979a), which presented a reconstruction of the limits of the Loch Lomond Readvance (LLR) in the area and a model for glacilacustrine evolution in Glen Roy and Spean (Fig. 16.4). Sissons proposed that ice built up initially from the Nevis Range and the mountains farther west, coalescing in the Great Glen, and eventually damming the westwards-flowing River Spean and its Roy tributary. As a result, the lake waters rose to the height of the lowest available col, at 260 m at the eastern end of the Spean valley between the Spean and Spey catchments (Fig. 16.4a). Further ice advance saw the merging of the ice in the lower Spean with the Laire-Treig ice lobe (an outlet glacier of the West Highland Icefield), which advanced northwards into the middle Spean valley. Advance of the Spean glacier eventually severed the connection between the lakes in Glen Roy and Glen Spean, causing the lake level in Glen Roy to rise to the next lowest available outlet col, at 325 m at the head of Gleann Glas Dhoire. At this stage (Fig. 16.4b), Sissons envisaged that drainage of the 325 m lake in Glen Roy overspilled into the 260 m lake in Glen Spean, although drainage was diverted around the northern margins of the Laire-Treig ice lobe at Roughburn. He argued that thereafter the ice margin remained stationary in Glen Spean, but ice continued to advance farther into lower Glen Roy to the vicinity of the Viewpoint, as well as into Caol Lairig and Glen Gloy to the west. Eventually, this ice advance in Glen Roy prevented drainage across the Gleann Glas Dhoire col, and the lake level rose to 350 m, the altitude of the outlet at the head of Glen Roy (Fig. 16.4c). This progressive increase in lake level in Glen Roy is referred to as the 'rising' sequence.

Sissons (1979a) considered that initial ice retreat in Glen Roy resulted in a glacial lake outburst flood passing across the Gleann Glas Dhoire col into the Spean at Roughburn, causing the Glen Roy lake level to drop from 350 to 325 m (Fig. 16.4d), though he depicted the coeval margin of the

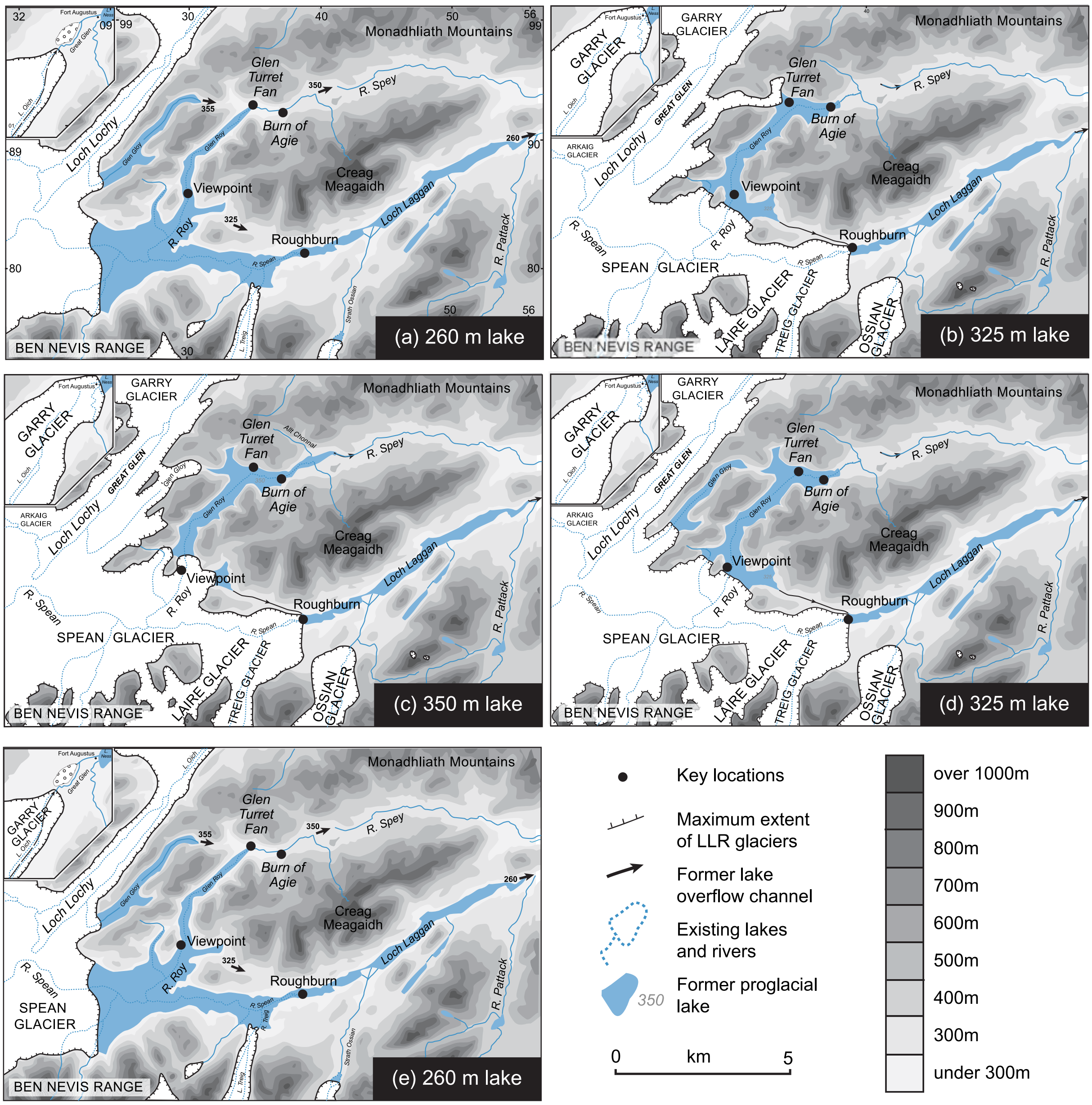

Fig. 16.4 Changing extent of LLR glaciers and evolution of the ice-dammed lakes in Glen Roy and Glen Gloy as proposed by Sissons (1979a). Stage 1 depicts ice advancing from the west and south causing the formation of the unified 260 m lake system in Glen Spean and Glen Roy. Subsequent ice advance blocked lake drainage routes, enabling the water level to rise in Glen Roy (stages 2 and 3) but to fall during ice retreat (stages 4 and 5). The extent of the glacier and timing of ice advance and retreat in Glen Gloy are debatable. Depicted here is the interpretation of Sissons and Cornish (1983), Sissons (2017) and Cornish (2017), which shows ice from Glen Gloy and the Great Glen terminating in Glen Turret (stage 2); Peacock (1986) envisaged a more restricted glacier advance in Glen Gloy at this time. More recently, the configuration of ice prior to, and during, ice advance in lower Glen Spean has also been questioned by Palmer et al. (2020). (Creative Commons CC-BY licence)

Laire-Treig lobe as remaining close to its maximum position at Roughburn. Subsequent ice retreat, he argued, resulted in severance of the Glen Roy lobe and Spean glacier from the Laire-Treig lobe, with continued retreat of the former eventually permitting lowering of the Glen Roy lake level to 260 m (Fig. 16.4e). This sequence of events is referred to as the 'falling' sequence. Sissons (1979b) argued that final drainage of the lake system was effected via catastrophic subglacial drainage of ~ 5 km^3 of water northwards along the Great Glen, with associated jökulhlaup sediments being deposited both as a massive terrace of coarse sediment at Fort Augustus (Russell and Marren 1998) and an extensive spread of subaqueous gravels in the Beauly Firth at the northern end of the Great Glen, near Inverness. Further transient, lower-altitude, ice-contact lakes continued to be dammed by the retreating ice in Glen Spean and the Great Glen as the fluvial network became re-established (Sissons and Cornish 1983).

16.5 Glacial Geomorphology

Glacially streamlined bedrock outcrops extend upslope to the summit crests (up to an altitude of 900 m) that flank Glen Spean (Fig. 16.5a). Often these outcrops are asymmetric, with steep, smoothed stoss sides and shallower, irregular lee sides and have elongation ratios averaging 5:1 (Turner et al. 2014). Most streamlined outcrops are oriented SW–NE or WSW–ENE, parallel to the trend of the valley and indicate that these hilltops were overtopped by the last and probably earlier ice sheets. Both Glen Roy and Glen Spean have a classic glacial trough profile, and the Treig valley is one of the best examples in Scotland of a glacial breach. These features reflect glacial erosion over multiple glacial cycles. The bedrock in the valley floors and lower flanks is also glacially smoothed and locally striated, although striae are rarely observed beyond the limits of the LLR.

Excellent examples of moraines are present within Glen Roy and Glen Spean. The most spectacular of these is the LLR latero-terminal moraine complex deposited by the Laire-Treig outlet glacier (Figs. 16.3c and 16.5a, b). The limit of this glacier in middle Glen Spean is marked by an almost continuous moraine, 15 km long, that descends eastwards from 500 m at the northern outlet of the Treig gap to 400 m along the southern slopes of the glen, then loops northwards across Glen Spean in the form of three massive ridges up to 20 m high. The moraine then descends to a fan-delta complex at 250 m on the valley floor at Roughburn and then rises westwards to 400 m. Shorter recessional moraine fragments within the outer moraine ridge suggest active ice retreat. Further moraines occur in Glen Spean to the west of the Laire valley at around 400 m.

A distinct, 5 m high terminal moraine in Caol Lairig occurs close to the col (Fig. 16.5c) and has a crest that runs transverse to the valley axis and then rises up the valley sides to merge with a delta associated with the 350 m shoreline on the northern valley side. This feature has been interpreted as a subaqueous moraine ridge that formed as the LLR glacier advancing northeastwards up Caol Lairig reached its maximum extent when the lake level was at 350 m (Tye and Palmer 2017).

In lower Glen Roy, two former ice limits are defined by morainic debris although they have distinctly different geomorphological expressions. The first is at Bohuntine, where a ~ 2–3 m high ridge rises from 150 to 250 m on either side of the River Roy, close to the most southerly extent of the 325 m shoreline (Fig. 16.5d). The second, about 1 km north of this point, is a so-called Massive Drift Accumulation; this extends upvalley for 1.5 km and is composed of superficial deposits up to 80 m thick containing glacial diamictons and sandy gravels that are concentrated below the 260 m contour (Fig. 16.1a). This accumulation of material is now extensively gullied by valley-side streams and therefore appears to have ridge-like forms transverse to the valley axis. It is not clear whether these gully features were initiated during glacial lake drainage or as a result of paraglacial incision after the demise of the lake systems. Sissons (1978) observed that a poorly defined ridge at the outer limit of the deposit extends up the valley sides to around 370 m on the eastern flanks of the glen, close to the entrance to Gleann Glas Dhoire.

As well as the large regional ice lobes described in Sect. 16.4, local ice masses have also been identified in the vicinity. Finlayson (2006) identified evidence for an icefield of probable LLR age over the Creag Meagaidh massif, including hummocky moraine in the lower reaches of the Burn of Agie valley to the south of upper Glen Roy. Boston et al. (2015) mapped LLR ice limits across the Monadhliath Mountains, including those on the northern margins of Glen Roy. Their reconstruction suggests that ice accumulated on the high plateau areas of the Monadhliath and flowed into the heads of some valleys, notably Glen Chonnal at the head of Glen Roy and the high-level tributary valleys feeding Glen Turret, but terminated short of the 350 m shoreline. The presence of an ice-contact slope and moraines at the proximal end of the Glen Turret fan in upper Glen Roy (Fig. 16.5e) adds a complication to our understanding of the landsystem since it indicates that either ice formerly extended to a much lower altitude during the LLR than in other areas of upper Glen Roy or that these landforms represent evidence for an earlier ice margin at the time of ice sheet retreat (Boston and Lukas 2017). The age of these features is considered in further detail in Sect. 16.6.

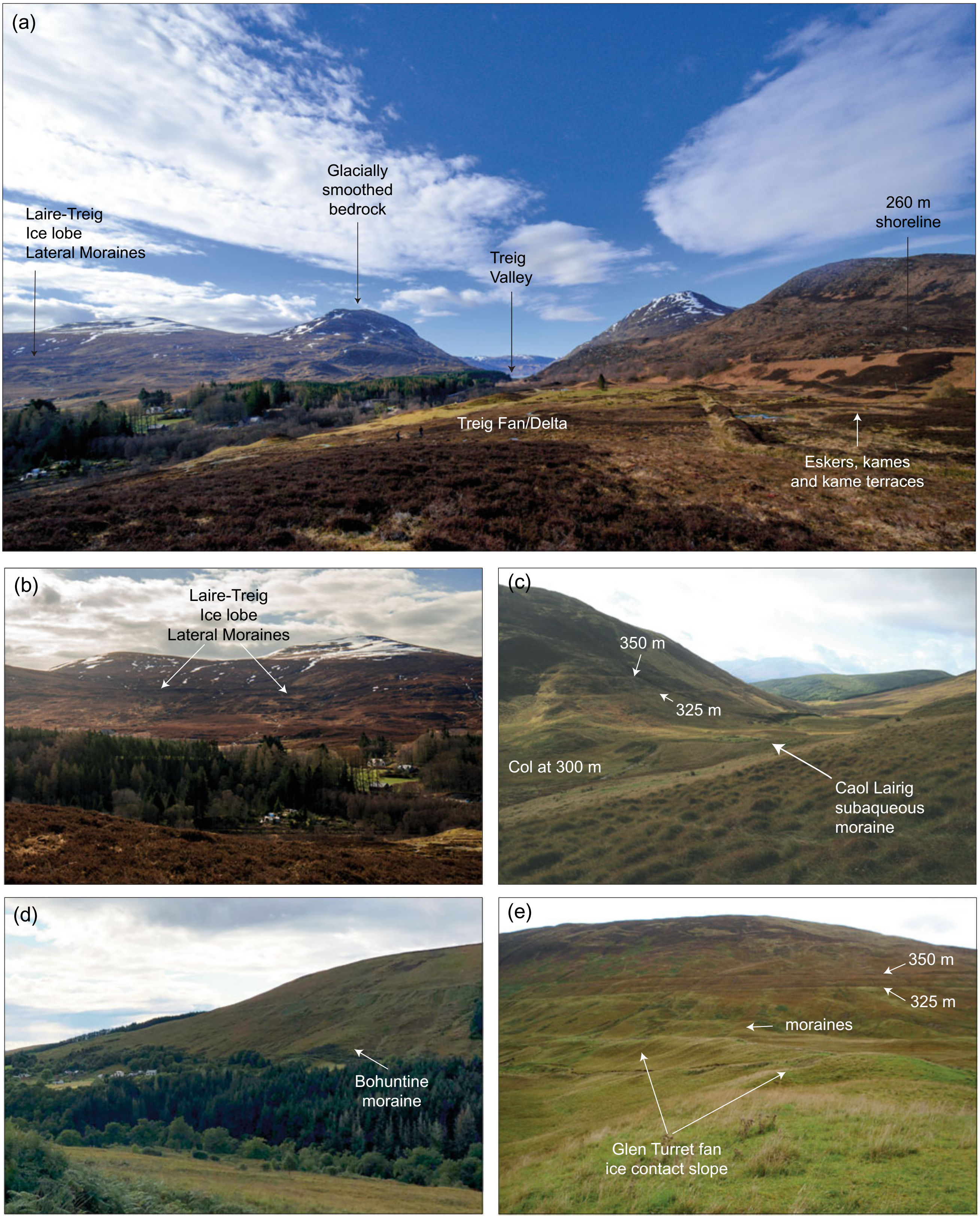

Fig. 16.5 Landforms at the mouth of the Treig valley, looking south towards the Treig glacial breach. **b** View southeast to the lateral moraines on the southern side of Glen Spean; these loops across the valley floor as the end moraine of Laire-Treig ice lobe. **c** Subaqueous moraine ridge in Caol Lairig looking southwest. **d** Bohuntine moraine in lower Glen Roy looking southeast. **e** Ice contact slope on the Glen Turret fan in upper Glen Roy looking north. (Images: **a**, **b**, **e** Christopher Francis; **c**, **d** Adrian Palmer)

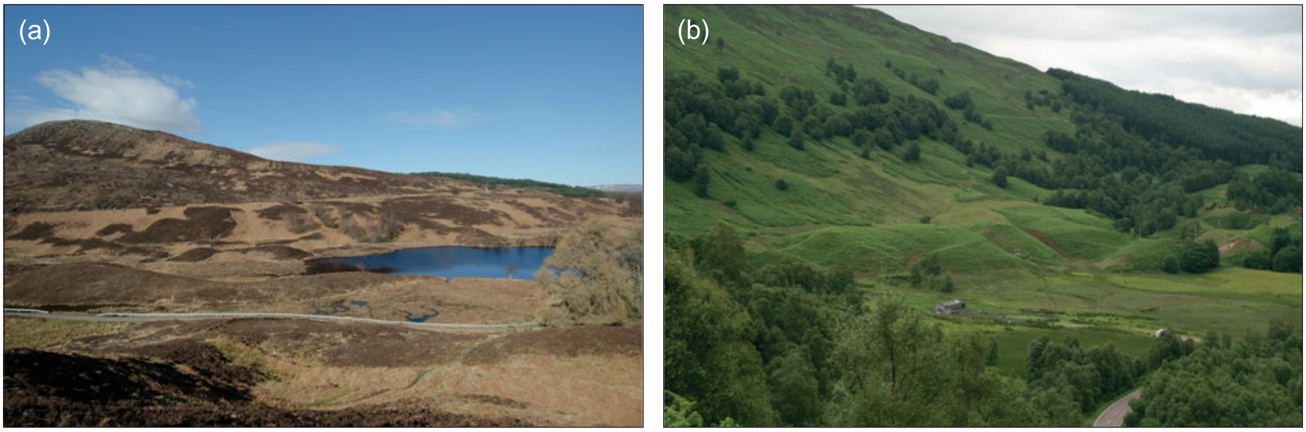

Fig. 16.6 **a** Kame and esker landscape assemblage on the western margins of the mouth of the Treig valley. A series of kame terraces occupies the foreground, and kettle depressions are either completely infilled with sediment or remain as lakes. In the centre is the end of an esker; the 260 m shoreline is cut halfway up the opposite hillside. **b** Gullied kames and kame terrace complex on the northern side of the Spean valley east of Roybridge. (Images: **a** Christopher Francis; **b** Adrian Palmer)

Kame topography is well preserved in a zone on the south side of Glen Spean and into the mouth of the Treig valley (Sissons 1978; Figs. 16.3c and 16.6a). This area contains the remnants of kettle holes that are either completely open, infilled with ~10 m of sediments (Kelly et al. 2017) or impound small, shallow lakes. Closer to the River Treig, there are more distinct sinuous, irregular ridges with crest-lines up to 10 m high parallel to the valley axis, which are likely to be eskers. A series of kame terraces that formed against a bedrock step in the centre of the valley suggest that ice downwasted during the final stages of ice retreat and that dead ice was prevalent to form the kettle holes on this side of the valley. In the areas of lower relief, continuous, sinuous, sharp-crested ridges that run parallel to the Treig valley axis on the western side of the valley are interpreted as eskers (Sissons 1979b). Gullied kame terraces and kames up to 10 m high are also present on the north side of Glen Spean to the east of Roybridge (Figs. 16.2b and 16.6b). Gullying of the terraces is probably related to the drainage of the 260 m lake system and suggests that the 260 m lake may have submerged parts of the glacier margin as it retreated.

16.6 Lake Shorelines

The shorelines were originally surveyed by the Ordnance Survey in the nineteenth century, and the resulting maps formed the basis for early reconstructions of the lake sequence. Further mapping of the features by Sissons (1978) revised the distribution of the shoreline fragments (Fig. 16.2b). The 260 m shoreline occurs throughout lower and middle Glen Roy and extends to the vicinity of the Glen Turret fan, but is absent in the lower part of the Turret valley. It is also preserved in the lower (southern) part of Caol Lairig and on the northern flank of lower and middle Glen Spean (Fig. 16.3). The 325 m shoreline extends northwards from Bohuntine in lower Glen Roy, around Bohuntine Hill into Caol Lairig and then into upper Glen Roy to the vicinity of the Burn of Agie in the east and into Glen Turret to the west. Crucially, the 325 m shoreline also extends into Glean Glas Dhoire where the 325 m col is present. The 350 m shoreline occurs in the vicinity of the ‘Viewpoint’ in lower Glen Roy and extends into the upper parts of Caol Lairig and through middle and upper Glen Roy and parts of Glen Turret and up to the 350 m col on the watershed to the Spey. Very short fragments of other shorelines are preserved at 334 m on the northern sides of the valley overlooking the Glen Turret fan and at 297 m close to the valley floor in Caol Lairig. A single shoreline at 355 m extends up both sides of Glen Gloy, terminating at the 355 m col at the head of the glen.

The distribution of the shorelines can be linked to land-forms delimiting the former ice margin positions. The southern limit of the 325 m shoreline in lower Glen Roy coincides with the distinctive, subaqueous terminal moraine preserved on the valley floor and flanks at Bohuntine (Figs. 16.3c and 16.5d). The 350 m shoreline, however, extends southwards of the ‘massive drift accumulation’ that marks the LLR limit in Glen Roy, suggesting that ice retreat was initiated during the existence of the 350 m lake, enabling shorelines to be cut south of the ice limit prior to lake drainage to the 325 m level. Shorelines are also present within the limits of other former ice margins, such as the 260 m shoreline present in the lower and middle Spean and the 325 m and 350 m shorelines within the area of lower Glen Turret (Fig. 16.2b).

Sissons (1978) carried out detailed instrumental levelling of all the three main shorelines in Glen Roy and recorded their width, aspect and implied volume of material removed at regular intervals along his survey transects. There are several key points from his analysis: (i) the shorelines are mainly cut in bedrock, although fragments of rock have often accumulated on the front edge of the notch; (ii) the widest shorelines occur close to tributary streams where material from the streams accumulated as a beach on the front edge of the shoreline, particularly on the upvalley side; (iii) shoreline width is negatively related to hillslope gradient and (iv) the volume of material removed from the shorelines correlates with the length of the fetch from the southwest. He proposed that the shorelines formed through a combination of wave action, frost shattering of bedrock associated with slight fluctuations in lake level and removal of coarse debris on lake ice.

The rate of shoreline formation was also considered by Sissons (1978) using measurements of the shoreline widths inside and outside the associated LLR glacier limits. Average widths of 11.3 m, 10.6 m and 10.1 m were found outside the glacier limits for the 350 m, 325 m and 260 m shorelines, respectively, and 9.4 m, 9.4 m and 11.7 m for the shorelines inside the limits. On the assumption that glacial erosion would have removed or modified shorelines during periods of ice advance, he inferred that the shorelines initially formed rapidly to enable similar widths to be achieved during different durations of lake existence during ice advance and retreat.

16.7 Deltas and Fans

16.7.1 Deltas and Fan–Deltas in Glen Spean

Both Glen Roy and Glen Spean contain fine examples of deltas and fans associated with the glacial lake systems. In Glen Spean, the Moy Delta is a large (1.52 km^2) body of sediment that accumulated in the 260 m lake, fed by the northwards-flowing meltwaters draining the Ossian glacier terminus (Fig. 16.2b). The apex of the delta lies at 265 m with the toe at an altitude of 259 m. The feature is 8–10 m high and composed of sand and gravel facies, although exposures of the sediment architecture are poor and have not been examined in detail.

Also within Glen Spean, two ice-contact fan–deltas at Roughburn and the mouth of the Treig valley occur with surface altitudes of $\sim$260 m (Fig. 16.3c). The Roughburn fan–delta has been fragmented by erosion during the final drainage of the 260 m lake. It had an estimated extent of 1.94 km^2 and is mainly composed of sands and gravels that spread along approximately 1.5 km of the narrow western end of the present Loch Laggan. These sands and gravels display both horizontal bedding that probably represents bottomsets and topsets, and steep foreset bedding dipping towards the east and southeast, evident in exposures on the south side of the valley. On the eastern margins of the landform and distal delta bottomset varves overlie thick massive sand beds (Palmer et al. 2020). The Roughburn fan–delta is located close to three terminal moraines of the Laire-Treig ice lobe that cross Glen Spean at this point. On the northern side of Glen Spean, the surface of the fan–delta is incised by an 8-m-deep channel containing many large boulders, and, farther to the east, large boulders are distributed over an area of 800 m^2 across the fan surface; some are perched on braid bars and show imbrication indicating flow from the northwest. These bouldery deposits were deposited by glacial outburst floods that occurred when retreat of the ice margin in Glen Roy permitted drainage of the 350 m lake across the 325 m col at the head of Gleann Glas Dhoire, reducing the lake level to 325 m. These boulders comprise material washed down the valley and reworked morainic debris deposited at the margins of the Laire-Treig ice lobe. The outburst flood was directed around the northern margins of the Laire-Treig ice lobe and into the Spean glacial lake. This complex feature may reflect ice contact, subaqueous fan deposition in combination with a glacilacustrine delta complex as the ice margin actively retreated.

The Treig delta is a complex landform at the mouth of the Treig valley close to its confluence with the Spean (Figs. 16.3c and 16.5a). It is a gently sloping landform with a surface altitude of 260 m in the central and eastern parts of the valley, and is separated from the kamiform and esker deposits to the west by a bedrock step. The extant delta surface has an area of 0.9 km^2 and slopes down gradually northwards, but has been eroded to the south and east by the River Treig and originally extended farther eastwards. Sediment exposures are limited, although horizontally bedded and massive gravels occur towards the top of this feature. The size and position of this delta at the mouth of the Treig valley and its association with nearby stagnant ice features suggest that it was deposited by proglacial outwash rivers at the margins of the 260 m lake during the initial retreat of the Laire-Treig glacier (Peacock and Cornish 1989).

16.7.2 The Gravel Fans of Glen Roy

Glen Roy contains some of the most spectacular gravel fans in Scotland, rivalled only by Lateglacial alluvial and outwash fans in the Spey valley catchment (Chap. 19). All are relict landforms, perched above the level of the River Roy floodplain, truncated at their distal ends and deeply incised and terraced by their parent streams. The age and origin of these fans have proved contentious (Sissons and Cornish 1983; Peacock 1986; Boston and Lukas 2017; Lowe et al. 2017; Palmer and Lowe 2017), and some aspects of their formation remain controversial. Cornish (2017) has provided a detailed account of fan morphology and lithostratigraphy and the debates concerning their interpretation.

The most extensive fan is the Allt Chonnal fan, deposited by the river of that name at the head of Glen Roy (Fig. 16.3a). This remarkable landform consists of distinctive upper and lower fan fragments separated by a steep bluff. Although now extensively terraced, the surviving fragments of this fan indicate that it had impressive dimensions: collectively the upper and lower fans occupied an area of at least 0.8 km^2, and Cornish (2017) estimated that together they originally contained $\sim 6 \times 10^6$ m^3 of sediment, mainly coarse gravels. The upper fan has its apex at 360 m, and most of its surface lies at the altitude of the highest shoreline (350 m); the lower fan apex is at 335 m, and its surface lies around or just below the altitude of the middle shoreline (325 m).

Equally impressive are the remnants of three merging fans in upper Glen Roy, deposited by the north-flowing Canal Burn (Fig. 16.7b) and Burn of Agie (Fig. 16.7c) and linked by a fan deposited by the River Roy. The apices of the Canal Burn and Burn of Agie fans lie at similar altitudes (286 m and 288 m), and the former descends to 261 m, where it is truncated by a frontal bluff that may in part represent the former 260 m shoreline.

In middle Glen Roy, the two most spectacular gravel fans are those deposited on the valley floor by the Allt Brunachain and Allt na Reinich, which flow northwestwards from small, steep catchments. Both fans are deeply incised and terraced by their parent streams and terminate at steep frontal bluffs (Fig. 16.7d, e), and the Allt na Reinich fan consists of upper and lower surfaces separated by a 5 m high bluff at 259 m, suggesting a relationship with the lower lake shoreline (260 m).

The fans described above (and other tributary fans in Glen Roy) were initially interpreted by Peacock (1986) as paraglacial landforms deposited during the Lateglacial Interstade (~14.7–12.9 ka). Cornish (2017), however, demonstrated that the fans of upper Glen Roy (Canal Burn, Burn of Agie and Allt Chonnal) comprise a consistent tripartite stratigraphy consisting of a lower unit of coarse gravel or diamicton, in places up to 20 m thick, overlain in turn by lacustrine sediments, usually no more than 2 m thick, of laminated silts and clays (varves) or locally by stratified sands, then by an upper gravel unit typically 1–2 m thick. He proposed that the lower gravels represent deposition in shallow water during the rising lake sequence, followed by deposition of lacustrine sediments as lake levels rose higher, and finally subaerial deposition of gravels as lake levels fell. A feature of this interpretation is that it requires extremely rapid deposition of coarse sediment during the rising lake sequence: in the case of the Allt na Reinich lower fan, which has a catchment area of 2.23 km^2 and originally contained $\sim 2.5 \times 10^6$ m^3 of sediment, an average catchment denudation rate of at least 11 mm a^{-1} is implied (Cornish 2017).

The origins of the Glen Turret fan, located at the confluence of Glen Turret and Glen Roy, have proved singularly controversial. Unlike the fans described above, this fan terminates upvalley at an ice-contact slope, implying deposition when glacier ice occupied Glen Turret (Figs. 16.5e and 16.7a). The Glen Turret fan has an upper surface altitude of ~270 m and slopes down southeastwards to 253 m, towards the River Roy. The bluffs at the toe of the fan are 25 m high. Most of the fan is composed of horizontally bedded and massive, crudely stratified gravel beds or massive diamicton, with a thin (~1.2 m) layer of varved glacilacustrine sediments exposed on the fan surface and locally up to 5 m of lacustrine sediment under the fan gravels. This stratigraphy implies that deposition of the fan both pre-dated and post-dated lacustrine deposition. A series of indistinct mounds in the northwestern sector of the fan surface appear to represent moraines; hollows and channels run across the fan surface parallel to the fan apex, and the 260 m shoreline is absent within Glen Turret (Figs. 16.2b and 16.5e; Cornish 2017).

Interpretation of the Glen Turret fan has polarised around two viewpoints. Peacock (1986) interpreted the fan as a proglacial ice contact fan deposited during retreat of the last ice sheet and subsequently inundated by rising lake levels during the LLR, a view supported by Boston et al. (2013) and Boston and Lukas (2017) on the grounds that morphostratigraphic evidence suggests that lower Glen Turret was ice-free during the LLR. Conversely, Sissons and Cornish (1983) and Cornish (2017) argued that the Glen Turret fan was deposited during the LLR by ice feeding into Glen Turret from Glen Gloy and the Great Glen. The source of the ice that occupied Glen Turret at the time of fan deposition is still open to debate, but Palmer et al. (2020) concluded that the fan accumulated during the early stages of the LLR, and that the subsequent rise of the Glen Roy lakes to 325 m and 350 m destabilised the ice margin and caused the ice to retreat, allowing inundation of the lower Turret valley by lake waters. An implication of this interpretation is that the single lake shoreline at 355 m in Glen Gloy formed after retreat of ice from this glen.

16.8 Fluvial Terraces and Later Lower Lakes

Excellent fluvial terraces are preserved in upper Glen Roy, providing a glimpse of the evolving landscape immediately after the 260 m lake drained. The terraces have been eroded by the River Roy, revealing mainly sand and gravel facies at the toes of the Canal Burn, Burn of Agie, Allt Na Reinich and Allt Brunachain fans. Sissons and Cornish (1983)

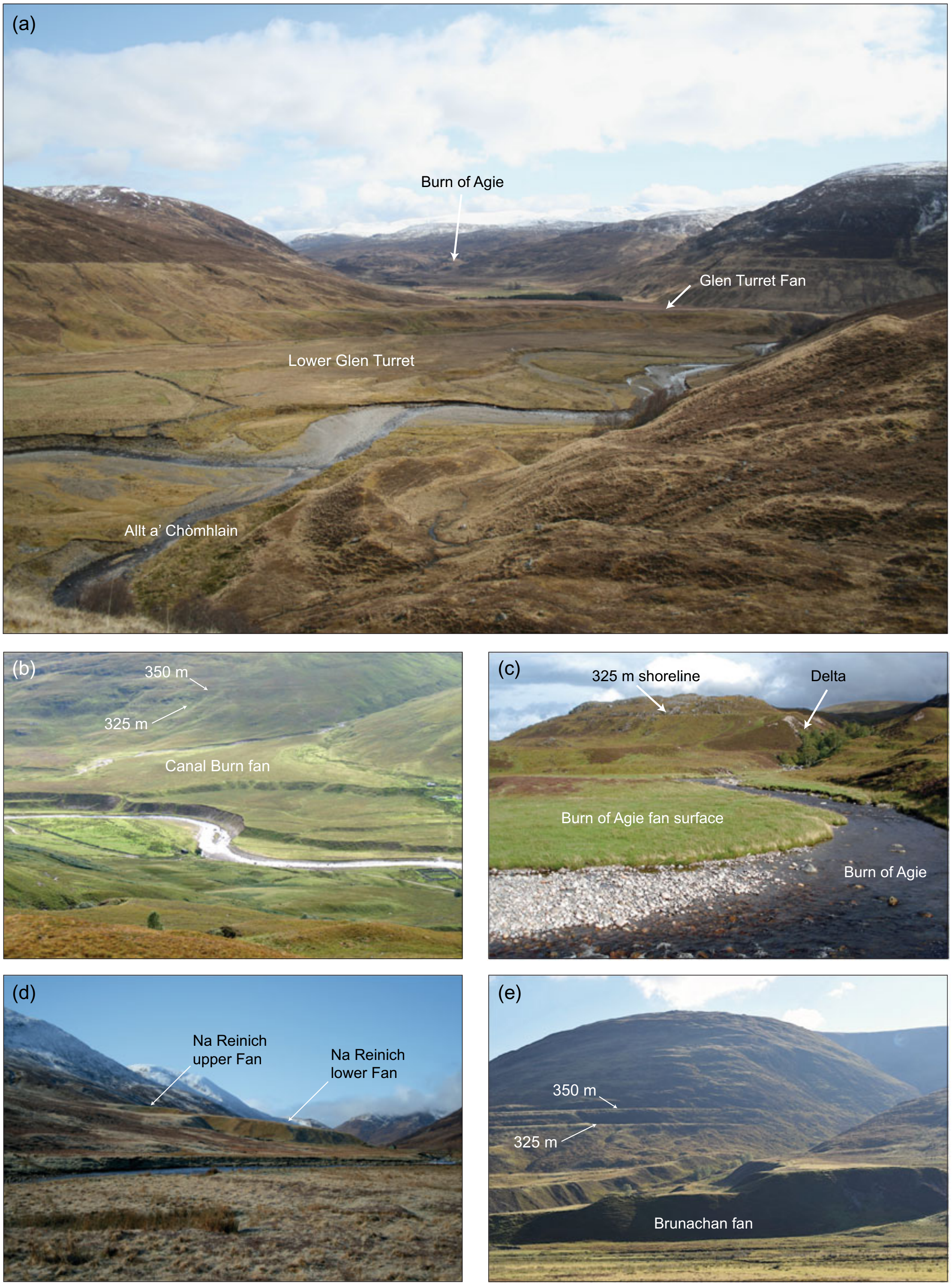

Fig. 16.7 Fan and delta landforms in Glen Roy. **a** Looking east from the Allt a' Chòmhlain towards lower Glen Turret and upper Glen Roy. The Glen Turret fan lies at the confluence of the two glens, with the proximal, ice contact slope facing northwest. **b** The Canal Burn fan with the River Roy flowing around the toe of the fan. **c** The Burn of Agie delta associated with the 325 m lake system lies above the surface of the Burn of Agie fan at 272 m altitude. **d** The Na Reinich fan in middle Glen Roy: the apex of the upper fan is at 260 m, suggesting an association with the 260 m lake. **e** The Allt Brunachain fan in middle Glen Roy, which has been dissected and terraced by its parent stream. (Images: **a**, **c**, **d** Adrian Palmer; **b**, **e** Colin Ballantyne)

projected the surface form of the surviving fan fragments across the Glen Roy valley floor, proposing that, after 260 m lake drainage, the valley floor had an undulating surface with small lakes persisting in depressions between the fans. The River Roy transformed this landscape through incision of the fan toes, causing drainage of these small lakes and the deposition of material close to the valley floor.

Both Glen Spean and lower Glen Roy also exhibit good examples of fluvial terraces (Sissons 1979c). These are distributed between the mouth of the Treig valley in the east through lower Glen Spean (Fig. 16.2b) in the west and extend into lower Glen Roy up to the viewpoint. The terrace belts are typically 0.5–1.0 km wide; individual terrace fragments are 10–300 m wide and up to ~1 km long. They are normally present up to 30–40 m above the current rivers, although in lower Glen Roy they rise up to 60 m above the river in the vicinity of the Viewpoint; locally, a suite of more than five terraces is present. Exposures in the terraces exhibit sandy gravel facies in the west close to the Treig and Laire valleys, whilst in lower Glen Spean sandier facies are exposed and in lower Glen Roy sandy facies locally overlie laminated sediments (sands, silts and clay) indicating that the terraces post-date the ice-dammed lake sequence.

Through mapping and survey of the terrace surfaces, Sissons (1979c) reached three key conclusions. First, four further lake levels post-dated the 260 m lake and were confined to lower Glen Spean. These lower lakes had altitudes of 113, 99, 96.5 and 90.5 m OD and were fed by outwash from the retreating Treig and Laire ice lobes and from Glen Roy. Second, from the distribution of the terraces in lower Glen Roy, Sissons inferred that a small lake was temporarily impounded behind the 'Massive Drift Accumulation' during the development of the terraces and the associated lower lakes. Third, the lack of fluvial terraces for 2 km in the vicinity of the kame terraces and kames in middle Glen Spean (Fig. 16.6b) is explained by the presence of dead ice at this location whilst the higher terraces formed.

16.9 Rock-Slope Failures and Palaeoseismicity

Glen Roy, Glen Gloy and intervening valleys contain a cluster of about 17 postglacial rock-slope failures (RSFs) that collectively occupy an area of ~5.7 km^2. Most are rock-slope deformations (RSDs), formed by the gradual downslope displacement of mountainside slopes (Chap. 14). These typically exhibit upper-slope tension cracks and trenches, slope bulging and bedrock benches, scarps and/or antiscarps (upslope-facing scarps) with localised superficial collapse of displaced bedrock blocks. Those in the Glen Roy–Glen Gloy area exhibit limited downslope displacement and tend to lack rupture surfaces or clearly defined lateral margins, but their extent is locally defined by springlines where groundwater percolating through fractured rock emerges at the surface. Two RSDs in Glen Roy exhibit partial collapse: a huge (~2.0 km^2) RSD opposite Brunachan on the steep (~38°) eastern slopes of Beinn Iaruinn and the Bohaskey RSD (~0.6 km^2) in the lower glen, where about one-third of the original RSD (informally termed the 'Viewpoint' RSF) has failed as a rockslide that extends to the floor of the glen (Fig. 16.8a). The area contains only two relatively simple rockslides. One of these, the Glen Fintaig RSF (0.17 km^2) represents catastrophic failure along

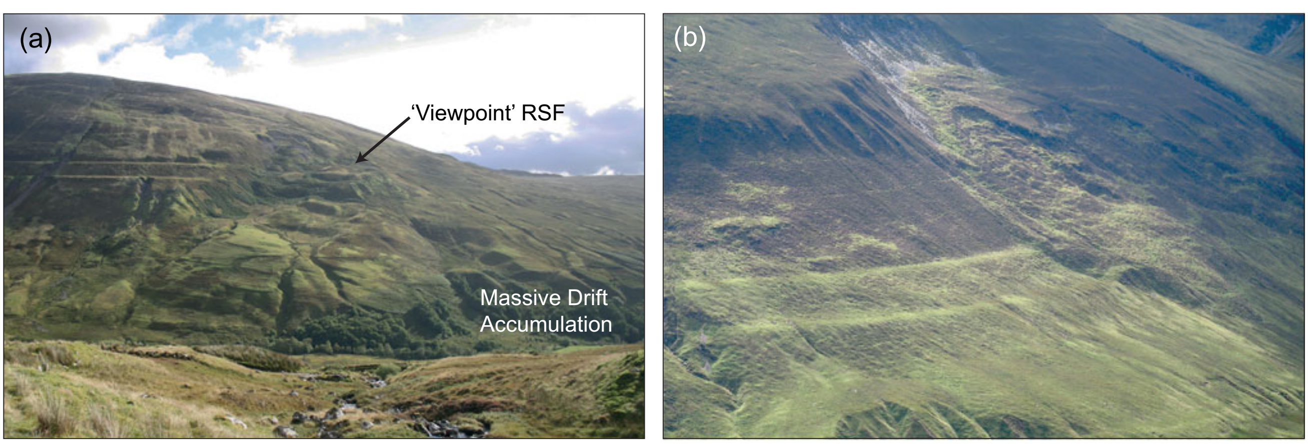

Fig. 16.8 **a** Eastern hillslope of lower Glen Roy opposite the 'Massive Drift Accumulation'. On the left is the Bohaskey rock-slope deformation (RSD), which is cut by the 325 m and 350 m shorelines, indicating that downslope displacement had ceased prior to shoreline formation. In the centre is the 'Viewpoint' RSF, a deep-seated rockslide that represents failure of the southern margin of the original RSD. This rockslide has displaced the same shorelines and therefore occurred during or after lake drainage. **b** The Braeroy arrested slide, which displaced the upper shorelines but failed to reach the 260 m shoreline, although this shoreline is poorly defined in this area. (Images: **a** Adrian Palmer; **b** Colin Ballantyne)

slope-parallel schistosity and extends to the valley floor, where the run-out exhibits brittle folding and thrusting of planar blocks. The other, the Braeroy RSF (0.12 km^2) is a small arrested rockslide on the 35° slope opposite Brae Roy Lodge (Fig. 16.8b).

The Glen Roy–Glen Gloy RSF cluster is of interest because the morphostratigraphic relationships between the RSFs and the lake shorelines permit relative dating of the RSFs (before or after shoreline formation) and also because of evidence that some (possibly many) of the RSFs were triggered or conditioned by earthquakes. At some sites, undisturbed shorelines cut across RSDs (Fig. 16.8a), implying that these developed then stabilised in the interval (~15–12 ka) between ice-sheet deglaciation and shoreline formation, consistent with the timing of RSF response following deglaciation elsewhere in Scotland (Ballantyne et al. 2014; Chap. 4). This was confirmed by Peacock and May (1993), who demonstrated that strata deformed by deep-seated rock-slope deformation in Glen Gloy are cut by the single (~355 m) shoreline in that glen. Other RSFs, including the Glen Fintaig and Braeroy landslides and the collapsed margins of the Brunachan and Bohaskey RSDs, have disturbed, buried or destroyed some or all of the shorelines (Fig. 16.8), demonstrating that they occurred during lake-level lowering or after final lake drainage. Using such evidence, Fenton (1991) concluded that about 30% of the RSFs had stabilised prior to flooding of the glens, a few occurred during lowering of lake levels and the remainder failed (or continued to move) after lake drainage.

The possibility that some or all of the RSFs were seismically triggered was first explored by Sissons and Cornish (1982a, b), who demonstrated that the Glen Roy shorelines exhibit dislocation and tilting. They attributed shoreline dislocation to differential glacio-isostatic uplift of crustal blocks and suggested that such movements were accompanied by RSF-triggering earthquakes. Ringrose (1989) reported further evidence for seismic activity in the form of soft-sediment deformation structures in varved lake sediments. He interpreted these structures as seismites produced by cyclic shaking and sediment liquefaction, showed that at least two deformation events had occurred and found that deformation intensity decreased radially from an inferred earthquake epicentre in Glen Roy. From the maximum epicentral distance (~15 km) of sediment deformation structures, he estimated that they were caused by an earthquake with $M_W = 5.9$, later revised by Fenton (1991) to $M_S = 6.3 \pm 0.5$. More controversially, Ringrose related the earthquake activity to glacio-isostatic reactivation of the Glen Gloy fault, which extends SSW from the head of Glen Gloy but is obscured by the Brunachan RSF in Glen Roy. The fault trace exhibits evidence of sinistral displacement of ~40 m and later dextral displacement of ~0.5 m. The former, however, probably reflects ancient (possibly Caledonian) fault movement (Firth and Stewart 2000), though the later dextral movement is apparently consistent with realignment of the principal horizontal stress field during glacio-isostatic uplift (Fenton 1991).

Stability analyses indicate that most RSF sites in the area are stable under gravitational loading alone (Fenton 1991), suggesting that some, most or all of the Glen Roy–Glen Gloy RSFs were initiated, conditioned or triggered by earthquake activity, including the RSDs that had stabilised prior to shoreline formation. However, the variable ages of the RSFs and the multiple dislocations of the lake shorelines imply that though there may have been a single major earthquake that produced the main suite of deformation structures in lake sediments (Ringrose 1989), it is likely that fault movements and seismic activity occurred over a prolonged period following ice-sheet deglaciation (e.g. Muir-Wood 2000; Stewart et al. 2000; Hampel et al. 2010), both before and after shoreline formation. Fluctuating lake levels (Fenton 1991) and crustal unloading by catastrophic lake drainage (Sissons 1979b; Sissons and Cornish 1982a) may also have promoted localised seismic activity. Because deglacial unloading alone may initiate RSDs (Agliardi et al. 2012; Chap. 14) and RSF response to earthquakes may be delayed (Gischig et al. 2015), establishing a definitive relationship between the Glen Roy–Glen Gloy RSFs and particular seismic events remains elusive.

16.10 The Timing of Ice Advance and Retreat in Lochaber

The reconstruction by Sissons (1979a; Fig. 16.4) provided the framework for the advance, maximum extent and retreat of glaciers in this sector of the West Highland Icefield. The Loch Lomond Stadial age of the readvance is confirmed by palynological evidence, which demonstrates that kettle holes and rock basins that infilled after the demise of the lake systems contain organic sediments no older than Early Holocene in age (Lowe and Cairns 1989). Direct dating of shorelines using cosmogenic radionuclide dating shows that these surfaces were exposed at ~11.9–11.5 ka, and the drainage of the lake systems has been dated to ~11.0–10.7 ka using samples extracted from the surface of the Glen Turret fan; though samples from the Allt Brunachain fan recorded a later age of ~9.9–9.7 ka (Fabel et al. 2010).

Detailed analysis of the record provided by glacilacustrine varves (annually layered sediments) in Glen Roy and Glen Spean has permitted the chronology of Lateglacial events in these glens to be reconstructed with unparalleled accuracy and precision. Palmer et al. (2010, 2012; Palmer and Lowe 2017) employed microfacies analysis of these laminated sediments to establish the first LLR glacilacustrine varve chronology in the UK, demonstrating that the entire lake system existed for a total of 515 years. The duration of specific lake levels was more difficult to estimate by using the varve thicknesses, and it was suggested that the falling 260 m lake system may not be fully represented within the record.

More recent glacilacustrine varve analysis employing data from ten sites within Glen Roy and Glen Spean includes varve sequences from all three lake levels. In upper Glen Roy, one of these sites could have accumulated varves only in the 325 m and 350 m lakes, whilst another site represents varves formed only in the 350 m lake (Palmer et al. 2020). The resulting Lochaber Master Varve Chronology 2019 (LMVC19) implies the following conclusions.

1. The total duration of the 260 m, 325 m and 350 m lake systems was 518 ± 18 varve years.
2. The configuration of ice advance reconstructed using the varve evidence differs from that of Sissons (1978) because it indicates that accumulation of varve sediments within Glen Roy did not commence until the 325 m lake level was reached. This was 188 years after the initiation of varve sedimentation in Glen Spean and suggests that (i) the Laire-Treig ice lobe had advanced to close to its maximum extent prior to the maximum of the Spean-Roy ice lobe; and (ii) Glen Roy was initially free-draining with the ice dam yet to form in lower Glen Spean and, when it did, the waters in Glen Roy rose to 325 m. Consequently, the 260 m lake level in Glen Roy was only created during the falling sequence of the Glen Roy lakes.
3. Ice advance to its maximum extent in Glen Roy occurred within ~300 years from the inception of the 260 m lake in Glen Spean. The interval between the onset of ice retreat in Glen Roy to complete drainage of the main glacial lake systems was less than ~200 years. Average ice advance rates through the lower Spean and into Glen Roy were ~88 m a^{-1}, and retreat rates were up to ~30 m a^{-1}.
4. Shoreline formation rates for the 260 m and 325 m lake levels averaged 0.02–0.13 m a^{-1}, although the 350 m shoreline was excavated in only 47 years at a rate of 0.32 m a^{-1}.
5. The presence of the Vedde Ash, a tephra from Iceland, in the varve sediments dates the lake systems to between 12,135 and 11,618 cal ^{14}C a BP, indicating that glacier ice persisted in the Highlands of Scotland into the Early Holocene.

The new age estimates from the LMVC19 chronology provide the most precise evidence for the timing of LLR glacial activity in Scotland, improving our understanding of how and when different outlet glaciers of the West Highland Icefield advanced and retreated. It also gives unparalleled insights into the rate that geomorphological processes were operating and, with the aid of sub-surface mapping technologies, may allow more detailed estimates of sedimentation rates in the larger fan–delta accumulations within the valleys.

The precision and accuracy of the LMVC19 chronology also permit comparison to other European palaeoclimatic and palaeoenvironmental records at Meerfelder Maar, Germany and Krakenes, Norway. Lane et al. (2013) propose that there was a time-transgressive shift in the pattern of warmer air masses moving across northern parts of Europe during the mid-Younger Dryas (Loch Lomond Stade) . Using the Vedde Ash to align records in Germany and Norway, the warming in Norway would have been delayed by ~140 years. Theoretically, this warming would also have been experienced in Scotland and may have led to the ablation of the ice mass which formed the ice-dammed lakes. However, the initial retreat of the ice in Glen Roy appears to have post-dated the inferred timing of warming in Norway by ~150 years (Palmer et al. 2020). The reason for this delay is still to be resolved and could relate to the sensitivity of the cryospheric response to atmospheric warming and/or the influence of the ice mass on local climates.

16.11 Conclusions

The Parallel Roads and associated landforms of Glen Roy and Glen Spean represent one of the most remarkable landsystems in Scotland and deservedly merit their international geomorphological acclaim. The geomorphological importance of the area was highlighted in the Geological Conservation Review (Gordon 1993; Gordon and McEwen 1997). It has justly been accorded several conservation designations and is one of the key areas for geotourism in Lochaber Geopark (Brazier et al. 2017). From its pivotal contribution in the emergence of the glacial theory in the nineteenth century to the recent reconstruction of one of the most precise and accurate chronologies for the advance and retreat of the LLR glaciers now available, the area has played a major role in our understanding of Lateglacial landscape evolution and environmental change in Scotland (Palmer and Lowe 2017, Palmer et al. 2020). Recent geochronological studies have also greatly elucidated the timing and rates of formation of certain landforms. However, there is still much to learn from the rich geomorphological archive in Glen Roy and Glen Spean. Future refinements may include constraining the spatial and temporal patterns of ice build-up and the later phases of ice retreat in the wider area, the development of glacilacustrine systems in Glen Gloy, the role of icefields on plateaux adjacent to Glen Roy and Glen Spean, the impact of glacio-isostatic adjustment on the shorelines and the rates of paraglacial adjustment after final lake drainage. The answers perhaps lie in the application of technologies such as remote mapping and ground-truthing, to geophysical profiling of sediment accumulations such as the fans, deltas and basins in Glen Roy and Glen Spean. Finally, there is great importance in conserving the landscape for future use by the scientific community and communication of research results to enhance wider public understanding and appreciation of this exceptional area.

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