The Glacial Geomorphology Around Inverness and the Great Glen

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Abstract

Superimposed on ancient landscape elements, the Inverness region includes a palimpsest of subglacial landforms formed during successive Late Devensian ice movements. It contains a particularly rich and diverse set of sediments and landforms created close to retreating glacier margins, together with the legacy of a major oscillating tidewater outlet glacier. At least five phases of glaciation have been recognised, although they remain poorly constrained temporally. The region includes well-documented buried glacial rafts of arctic shelly clay, two internationally important localities where organic deposits pre-date the last ice sheet, and a good geomorphological record of Late Devensian and Holocene relative sea-level change.

Keywords

Glacial geomorphology • Eskers • Kame terraces • Transverse ridges • Raised beaches • Megagrooves

15.1 Introduction

Situated at the mouth of the Great Glen, the Inverness area is unrivalled in the British Isles for the range of Quaternary landforms and glacigenic deposits it contains. It includes many textbook examples of glacial features, good evidence of Late Devensian and Holocene sea-level change, and the legacy of the punctuated retreat and oscillation of a major outlet glacier that terminated in the Inner Moray Firth, then a glacimarine fjord (Merritt et al. 1995). The Great Glen is a remarkably straight, fault-controlled, steep-sided and glacially overdeepened trench that is clearly visible from space and separates the Northern Highlands and Grampian Highlands geological terranes (Chap. 2). Reaching depths of over 225 m, Loch Ness, the largest freshwater body in Scotland, is located at the north-eastern end of the glen, bounded by remote, mountainous ground mainly between 450 and 900 m above Ordnance Datum (OD). The NE–SW structural trend of the bedrock imparted during the Caledonian Orogeny has a controlling influence on the large-scale topography of the region, particularly the orientation of the Great Glen and Strathglass, and the principal river valleys, those of the Rivers Nairn, Findhorn and Spey (Fig. 15.1a). The uplands to the south of the Inner Moray Firth have been deeply dissected by the River Findhorn, which enters a sinuous, 200–300 m deep open gorge (The Streens) downstream of Tomatin (Fig. 15.2a). The A9 trunk road and railway utilise a glacial breach in the regional Spey/Dulnain-Findhorn divide at Slochd Mòr (401 m). Strathdearn, otherwise known as the Moy Gap (Young 1980), is a major glacial breach in the Findhorn-Nairn divide.

Detailed accounts of the Quaternary landforms and deposits in the Monadhliath, Great Glen and to the east of Inverness are given in Boston et al. (2013) and Merritt et al. (2017a).

15.2 Geology and Landscape Evolution

The rugged mountains of the Northern Highlands and Monadhliath bordering the Great Glen are mostly formed of polydeformed and metamorphosed Neoproterozoic metasedimentary rocks (psammite, semipelite and pelite) intruded locally by granitic rocks, some of which have provided useful indicator erratics (Fig. 15.1a). The Northern Highlands and Grampian Highlands terranes docked left-laterally along the

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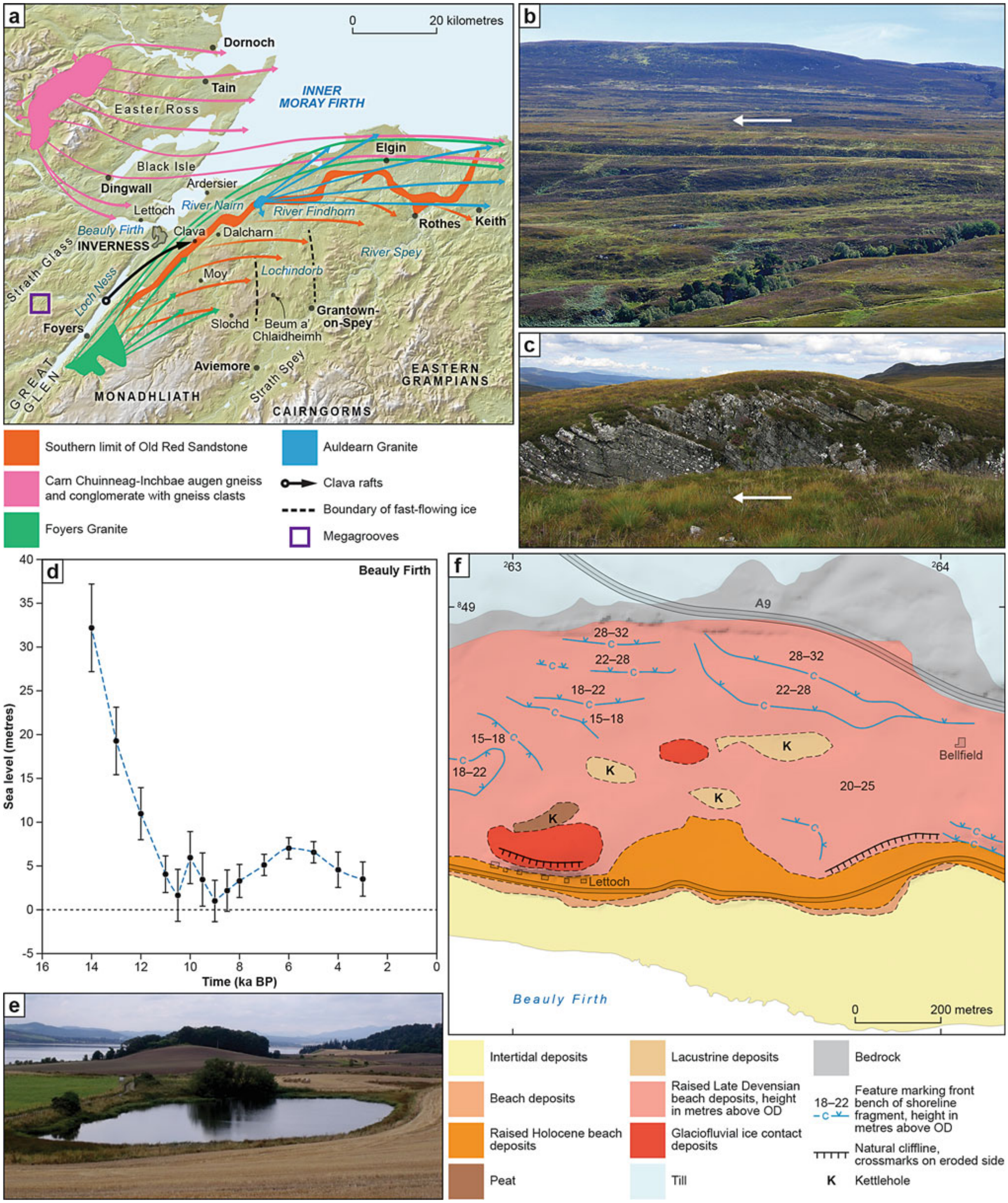

Fig. 15.1 **a** Location map and transport paths of some indicator glacial erratics (after Merritt et al. 2019). **b** Megagrooves on the western flank of Suidhe Ghuirmain in the Endrick valley, Strath Glass, looking SE. **c** Rock drumlin associated with the megagrooves. Ice flowed NE towards the Moray Firth. **d** Relative sea-level curve for the Beauly Firth (after Firth 1989, modified by Lambeck 1995). **e** Kettle hole in Late Devensian raised shorelines near Lettoch, on the northern shore of the Beauly Firth. Ice-contact sands and gravels form the wooded ridge in the distance. **f** Map of the kettled Late Devensian shoreline fragments between Lettoch and Bellfield, on the northern shore of the Beauly Firth. (Images: **b** BGS registered photo P698979; **c** BGS registered photo P698980; **e** Clive Auton)

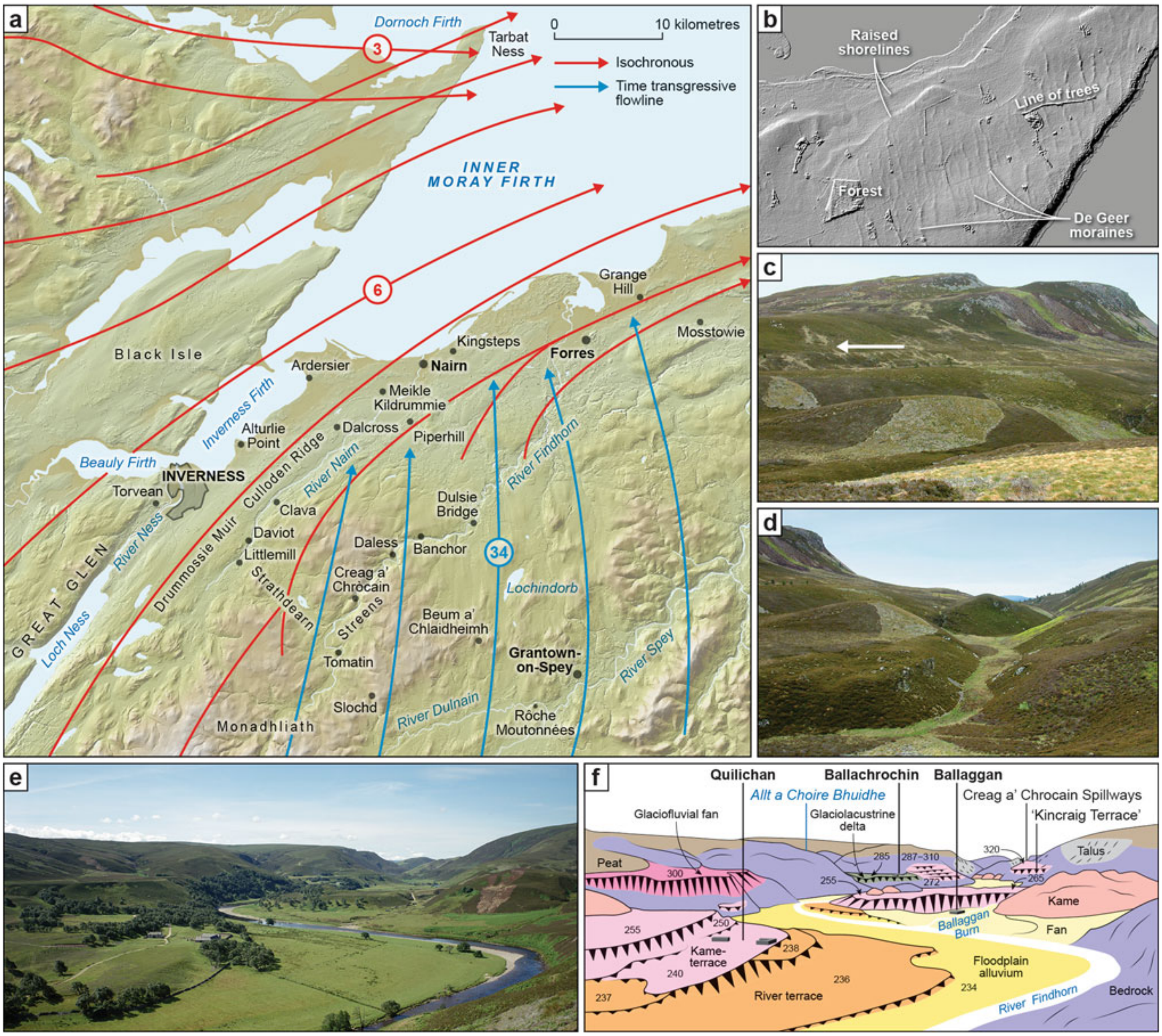

Fig. 15.2 **a** Topography with numbered flowsets identified by Hughes et al. (2014). **b** Transverse till ridges and raised shorelines on Tarbat Ness. **c** Crag-and-tail features at Beum a' Chlaidheimh, looking SE. **d** Glacial spillway at Beum a' Chlaidheimh, looking S towards the breach. **e** The middle Findhorn valley looking SW from Daless. **f** Geomorphological interpretation with elevations in metres above OD (after Fletcher et al. 1996). (Images: **b** Hill-shaded surface model built from NEXTMap™ Britain elevation data © Intermap Technologies with illumination from NW; **c**, **d** Jon Merritt; **e** BGS registered photo P008519)

Great Glen Fault Zone towards the end of the Caledonian Orogeny (430–400 Ma), with lateral displacement of at least 200–300 km (Strachan et al. 2002). This 3 km wide fault zone, formed of relatively weak, intensively sheared and fractured rock, subsequently, experienced 25–30 km of right-lateral strike-slip movement from the Late Palaeozoic, followed by downthrow to the south-east. The ground flanking the mouth of the Great Glen, including the Black Isle and around the Inner Moray Firth, is mostly underlain by sedimentary rocks of the Devonian Old Red Sandstone Supergroup (conglomerate, sandstone and siltstone), which also occur within a narrow graben, bounded on its southern side by the Sron Lairg Fault (British Geological Survey 2012a).

Although deeply ice-scoured during successive Pleistocene glaciations, the Great Glen first emerged as a major landscape element in the Devonian, during the degradation of the mountains formed during the Caledonian Orogeny, but before much of the sinistral transcurrent faulting. Most other major landscape elements in the region had become established by the end of the Mesozoic and continued to develop in response to tectonic uplift and differential chemical weathering under warm, humid climates through the Palaeogene and Neogene (Hall 1991; Chap. 3).

15.3 Key Quaternary Sites

This region includes one of the few sites in Scotland where organic material lying beneath glacial till has been assigned to the Last (Ipswichian) Interglacial (Marine Isotope Stage 5e; Walker et al. 1992; Merritt et al. 2019). At Dalcharn, 15 km east of Inverness (Fig. 15.1a), the Dalcharn Palaeosol contains compressed and disseminated organic material that includes pollen of full interglacial affinity. The pollen record indicates that closed pine forest with birch, alder and holly was succeeded by pine-heathland, which was replaced initially by birch and later by heath and open grassland as the climate deteriorated. As the Dalcharn site lies near to the present northern limit of holly in Britain, the relative abundance of *Ilex* pollen in the profile almost certainly reflects a climate somewhat warmer than that of today. A compressed bed of fibrous peat found beneath till at the nearby Allt Odhar site, near Moy, contains pollen, plant macrofossils and coleopteran remains that reveal climatic deterioration towards the end of a cool interstadial period as reflected in the replacement of birch woodland and willow scrub with grassland and heath, and then by open communities of grass and sedges. An Early Devensian (MIS 5a or 5c) age is most likely on current evidence.

At Clava, in the Nairn valley, there is an important, well-documented site long known for discoveries of enigmatic shelly clay and shelly diamicton (Merritt et al. 2017a, 2019). The Clava Shelly Clay contains well-preserved, high-boreal to low-arctic, shallow-water marine shells, whereas an associated folded body of pebbly diamicton (Clava Shelly Till) contains fragments of *Portlandia arctica*, an indicator of shallow-marine, fully arctic conditions. At elevations of 150 m OD, these sediment bodies are now generally accepted to be glacial rafts transported eastwards from the Loch Ness Basin (Fig. 15.1a), which was probably a marine fjord during the Middle Devensian (Merritt et al. 2019).

15.4 Late Devensian Glacial History

Although the area was glaciated repeatedly during the Pleistocene (Hall et al. 2019), the last (Late Devensian) Scottish Ice Sheet expanded at ~32 ka BP and probably reached its maximum extent before the global Last Glacial Maximum (LGM) at ~24 ka (Clark et al. 2012; Ballantyne and Small 2019; Chap. 4). Several distinct flowsets of subglacially streamlined landforms have been recognised (Fig. 15.2a) and cross-cutting relationships indicate that major switches in flow occurred during the last glaciation (Hughes et al. 2010, 2014). Evidence suggests that there were at least five distinct phases during the last glaciation (Merritt et al. 2017a, 2019), as described below.

15.4.1 Phase 1: Early Eastward Ice Flow

Few, if any, landforms may be assigned with confidence to this phase, but the distribution of indicator erratics and the composition and lithostratigraphy of tills indicate that ice flowed eastwards from the Great Glen across the middle to lower reaches of the Nairn, Findhorn and Spey valleys (Fletcher et al. 1996; Fig. 15.1a). The timing of this early phase of ice-sheet glaciation is uncertain but was influenced by a relatively thick build-up of ice to the north-west. Dated organic beds and ice-rafted shelly material found locally within glacigenic sequences indicate that this flow mainly occurred after MIS 5a and possibly during MIS 3 (Merritt et al. 2017b, 2019).

15.4.2 Phase 2: Last Glacial Maximum (LGM)

The distributions of crag-and-tail features, roches moutonnées and glacial striations indicate that the ice sheet subsequently buried the entire region (Ballantyne and Small 2019). However, a narrow swathe of ground around Lochindorb (Fig. 15.1a) containing streamlined subglacial landforms suggests that a corridor of relatively fast-flowing ice (an ice stream) flowed northwards from the Cairngorms and upper Strath Spey across the lower Findhorn valley and into the Inner Moray Firth Basin (Hughes et al. 2010, 2014; Merritt et al. 2017a). Flow was concentrated through the Beum a' Chlaidheimh breach (flowset 34 in Fig. 15.2a). The presence of interlocking spurs and decomposed regolith within The Streens Gorge upstream of Daless suggests that the middle Findhorn valley has experienced relatively little cumulative glacial erosion, like most of the north-eastern Grampians (Hall et al. 2019). By contrast, the mountains to the north of the Great Glen are heavily ice-scoured. For example, a swathe of splendid glacially streamlined megagrooves (Newton et al. 2018), whalebacks and rock drumlins occurs in the upper reaches of Strath Glass (British Geological Survey 2012b; Boston et al. 2013; Fig. 15.1b, c). These features probably are the legacy of an ice stream within the last ice sheet that flowed directly through Strath Glass towards the Moray Firth.

15.4.3 Phase 3: Early Upland Deglaciation

Following the LGM, the ice sheet eventually became too thin for ice to be driven northwards over the Spey-Findhorn divide, and a major glacial reorganisation ensued after 21.3 ka (Merritt et al. 2019). Ice flowing from the Cairngorms and from upper Strath Spey gradually parted from ice that flowed north-eastwards into the Moray Firth from the Monadhliath and Great Glen. A substantial outlet glacier became established within Strath Spey upstream of Grantown-on-Spey between 18 and 15 ka (Hall et al. 2016), and an ice-free enclave opened up that included the middle Findhorn valley, within which there was widespread deltaic and glacilacustrine sedimentation (Merritt et al. 2017a; Fig. 15.2e, f).

15.4.4 Phase 4: Establishment of the Moray Firth Ice Stream (MFIS)

The presence of widespread, well-preserved and relatively elongate subglacial landforms across the Black Isle indicates that a vast ice stream drew down ice from the west towards the Moray Firth Basin (Hughes et al. 2010, 2014; flowset 6 in Fig. 15.2a). The MFIS possibly became established during the Elgin Oscillation at ~15 ka when ice re-advanced into lower Strath Spey from offshore (Peacock et al. 1968; Clark et al. 2012; Merritt et al. 2017b). The subglacial landforms of flowset 6 clearly truncate, and are younger than those of flowset 34, a temporal relationship that is corroborated by the lithostratigraphy (Merritt et al. 2017a, 2019). The MFIS was pinned against opposing slopes to the northeast of Inverness, where it also blocked the lower reaches of the Findhorn valley causing ponding upstream.

15.4.5 Phase 5: Punctuated Retreat of the MFIS

Ice-marginal drainage was concentrated at progressively lower elevations along Strath Nairn during deglaciation. Staircases of glacifluvial (kame) terraces and fans formed sequentially, whilst the lateral margin of the MFIS withdrew towards the Inverness Firth. Numerous sets of low transverse till ridges were formed at its westward-retreating frontal margin on the coastal lowland as far east as Elgin. The Inverness Firth was occupied by a receding tidewater outlet glacier that progressively uncoupled from adjacent, stagnating land-based ice and ice-cored glacifluvial deposits (Alturlie Gravels; Merritt et al. 1995). A significant glacial readvance (the Ardersier Readvance) subsequently deformed glacimarine deposits (Ardersier Silts) within the firth to create a push moraine stretching between Castle Stuart and the Ardersier peninsula (Fig. 15.3a). This undated event followed an oscillation of the ice front at Grange Hill (Fig. 15.2a) and preceded a minor readvance from the Beauly Firth, during which a large fan-delta formed at Alturlie Point (Bothyhill Gravels; Merritt et al. 1995, 2017a). The Great Glen glacier had a lightly grounded, or potentially floating ice shelf at the mouth of the glen, but subsequently retreated to a more grounded position at Foyers, where a major end moraine beneath the loch was created during a stillstand or glacial readvance (Turner et al. 2012; Boston et al. 2013). The entire region became deglaciated during the Lateglacial Interstade, a period of ameliorated climate between ~ 14.7 and 12.9 ka (Chap.4).

15.4.6 The Loch Lomond Stade

Although glaciers developed in the Monadhliath, Cairngorms and Western Highlands during the Loch Lomond (≈Younger Dryas) Stade of ~12.9 to 11.7 ka, none extended onto the lower ground of the region (Boston et al. 2013). However, cobble gravels underlying an extensive, low-lying raised marine terrace adjacent to the Kessock Bridge (Fig. 15.3a) represent the top of a marine delta that formed during successive flood events of the River Ness (Merritt et al. 1995; British Geological Survey 1997; Boston et al. 2013). Sissons (1981) proposed that the delta resulted from an enormous glacial outburst flood when the 260 m ice-dammed lake in Glen Roy and Glen Spean drained catastrophically towards the end of the Loch Lomond Stade (Chap. 16).

15.5 Sea-Level Change and Raised Shorelines

A flight of up to ten raised shorelines of Late Devensian age has been identified around the Inner Moray Firth, indicating there was a progressive fall in relative sea level (RSL) from at least 35 m OD whilst ice retreated westwards into the Beauly Firth and south-westwards into the Great Glen (Firth 1989; Fig. 15.1d). Each shoreline is tilted north-eastwards at progressively gentler gradients down the sequence; this occurred as a result of diminishing glacio-isostatic rebound whilst the glaciers retreated. RSL in the Beauly Firth fell to a minimum of +2 m OD early in the Loch Lomond Stade, before rising to create a prominent abandoned cliffline around the Beauly and Inverness Firths later in the Stade. The period of marine erosion was replaced by deposition and falling relative sea level during the Early Holocene when

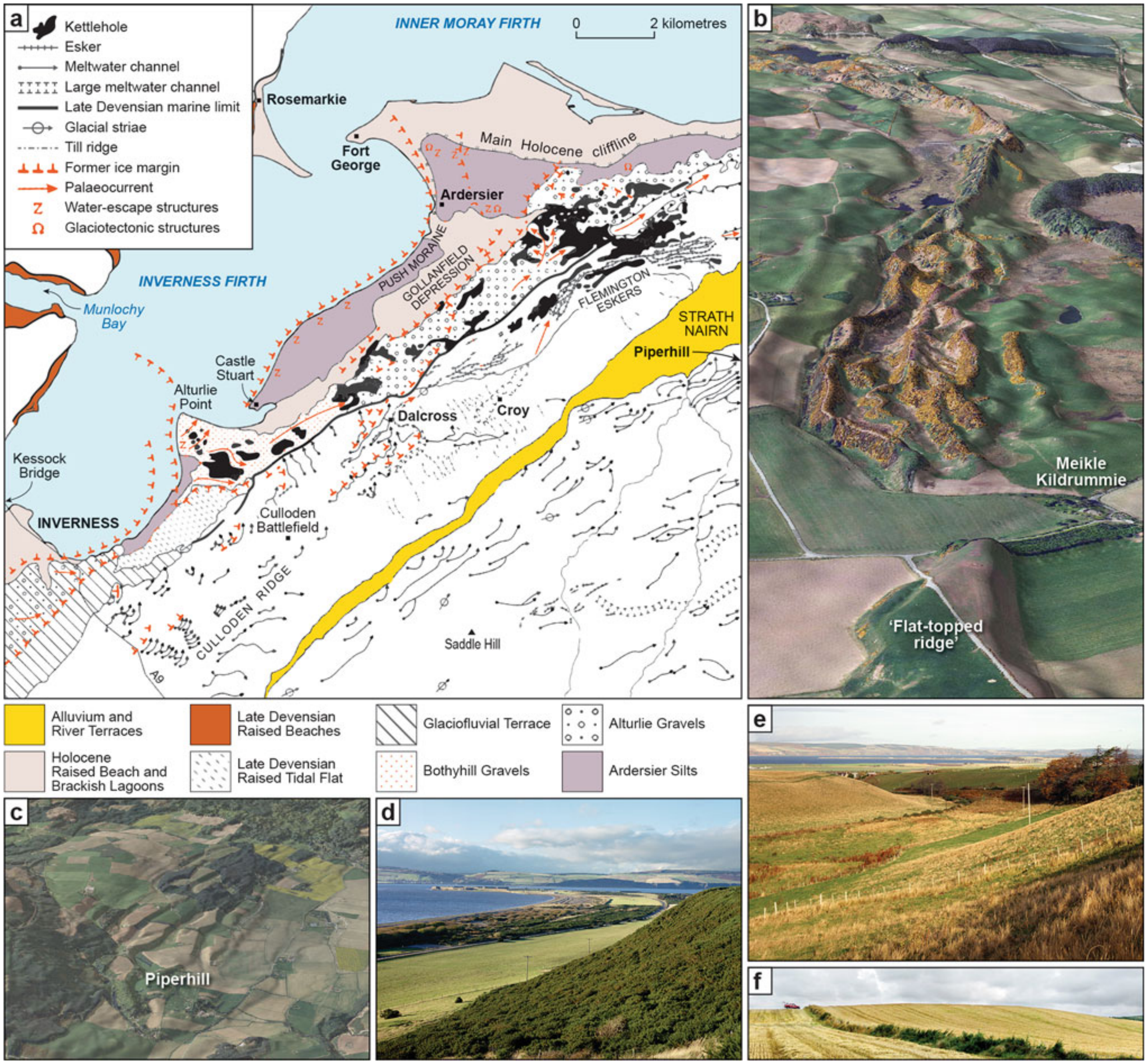

Fig. 15.3 **a** Geomorphological features and deposits associated with deglaciation of the Inverness Firth (after Merritt et al. 1995). **b** The Flemington Esker system looking WSW; ×4 vertical exaggeration. **c** Ice-marginal benches, lateral moraines, glacifluvial terraces and glacial drainage channels in lower Strath Nairn, looking SW towards Piperhill; ×3 vertical exaggeration. **d** View looking NW towards Fort George on the Ardersier peninsula. Mid-Holocene raised beach abutting a slope formed principally during the Ardersier Readvance. **e** Subglacial meltwater channel near Dalcross, looking NNW. **f** Transverse till ridge near Mosstowie, looking E. (Images: **b**, **c** NEXTMap™ Britain elevation data © Intermap Technologies. Aerial photography © UKP/Getmapping Licence No. UKP2006/0.1; **d** BGS registered photo P002879; **e** BGS registered photo P008543; **f** Clive Auton)

estuarine features, now buried, developed at the head of the Beauly Firth (Firth and Haggart 1989). Subsequently, RSL rose and extensive estuarine mudflats were deposited against the abandoned cliffline. RSL peaked locally during the Middle Holocene, resulting in an extensive raised shoreline that tilts gently north-eastwards, backed by the Main Holocene Cliffline at an altitude of 9 m OD at Inverness (Smith et al. 2019; Fig. 15.3a).

Late Devensian raised beaches at up to ~29 m OD occur around Munlochy Bay, whereas others pass laterally at similar elevations into extensive glacifluvial outwash fan-deltas and raised tidal flats beneath eastern Inverness (Fig. 15.3a). The elevations and juxtaposition of shorelines and raised fan-deltas indicate that a relative fall in sea level occurred from 28 to ~22 m OD whilst the outlet glacier retreated westwards through the Beauly Firth (Firth 1989).

A notable feature of the coastal lowlands, particularly between Inverness and Forres, is that raised shingle beaches commonly lie at higher elevations than adjoining large kettle holes within outwash deposits immediately inland. This indicates that the outwash was locally ice-cored and that ice remained buried during the fall in sea level. Kettle holes also occur within raised beaches, notably around the Beauly Firth (Fig. 15.1e, f), indicating that sea-level changes were occurring whilst the outlet glacier was retreating.

15.6 Glacial and Glacifluvial Landforms

15.6.1 The Beum a' Chlaidheimh Breach

The Beum a' Chlaidheimh ('cleft of the sword') at ~360 m OD is the lowest of several breaches in the Dulnain/Spey-Findhorn divide where large crag-and-tail features provide evidence for strong northward flow of ice during the local LGM (Hughes et al. 2010, 2014; Merritt et al. 2017a; Fig. 15.2c). The breaches lead towards a relatively featureless plain underlain by till around Lochindorb. During deglaciation, meltwaters flowed northwards through the Beum a' Chlaidheimh and higher breaches to the west, cutting deep, winding, lee-side drainage channels and spillways (Fig. 15.2d). These features start at the watershed and descend with interlocking spurs, suggesting that they were functioning when ground to the north of the watershed was largely ice free. The main channel links with an esker on the southern side of the breach amidst a suite of ice-marginal channels, benches and block-strewn lateral moraines that arc around the mountain rim, formed at the northern margin of a huge outlet glacier that occupied Strath Spey (Young 1977; British Geological Survey 2013; Merritt et al. 2017a).

15.6.2 The Middle Findhorn Valley

The middle Findhorn, downstream of Tomatin, contains a particularly fine assemblage of glacial features and deposits that can be viewed from Daless (Fletcher et al. 1996; Merritt et al. 2017a; Fig. 15.2e, f). Here, the NE–SW trend of the middle Findhorn is influenced by the NNE–SSW alignment of a pair of faults that form a graben within which Middle Old Red Sandstone strata occur. The higher of two splendid glacial spillways cutting Creag a' Chròcain follows a zone of shattering along the northern of the graben-margin faults (Fletcher et al. 1996).

Topographical benches may be observed at up to twelve levels from Daless. Glacifluvial terrace fragments and benches rise above the floodplain and river terraces. Sections in a bench at 285 m OD on the eastern side of the valley reveal that the feature comprises gravel fining downwards into interlaminated sandy silt and clay with dropstone cobbles, indicating a glacilacustrine origin. The succeeding benches at between 287 and 310 m OD are underlain by gravel, with one including a kettle hole 5 m deep. The sequence terminates with a small outwash fan at 365 m OD. The Kincraig Terrace lies at the foot of the Creag a' Chrocain spillways and is underlain by about 25 m stratified sand and gravel. Many of the benches are probably kame terraces laid down in contact with downwasting ice within the valley, whereas the large sloping terraced feature at 300 m OD south of Quillichan is a glacifluvial fan.

A river cliff section 4.5 km downstream, at Banchor, displays particularly good evidence of glacilacustrine sedimentation (laminated sand and silt with dropstones). This supports traditional views that an ice-dam formed by Moray Firth ice blocked drainage lower in the Findhorn valley, near Dulsie Bridge (Fig. 15.2a), leading to the ponding of Glacial Lake Findhorn (Merritt et al. 2017a).

15.6.3 Piperhill and Lower Strath Nairn

Flights of ice-marginal features extend along the south-eastern flank of Strath Nairn, downstream from Daviot (Fletcher et al. 1996; British Geological Survey 1997; Fig. 15.2a). The anastomosing channels and terraces of this suite formed when the middle Findhorn valley was choked with ice, causing meltwater from the upper Findhorn valley to flow through Strathdearn and into Strath Nairn near Daviot. The features are well displayed around Piperhill (Fig. 15.3a, c), where glacifluvial terraces and moraines either form contiguous staircases, or are bound on their uphill sides by arcuate, steep-sided, glacial meltwater channels up to 15 m deep (Merritt et al. 2017a). Some terraces pass upstream into channels eroded into till and separated by lateral moraine ridges with steep scarps (ice-contact slopes) facing the main valley. An age of 14.5 ± 1.4 ka BP has been determined from the mean of four cosmogenic ^{10}Be exposure ages derived from large glacially transported boulders embedded in the moraine ridges. These hitherto unpublished ages were calculated using CRONUScalc v.2.0 (Marrero et al. 2016).

15.6.4 The Flemington Eskers

The Flemington Eskers form one of the best-preserved braided esker systems in Britain (Merritt et al. 1995, 2017a; Fig. 15.3b). The eskers are mainly aligned with the final north-eastward direction of ice flow (flowset 6) and were created whilst the ice front retreated south-westwards towards the Great Glen. The main system includes at least eight braided ridges, 5–10 m high, with intervening kettle holes infilled by peat. The braided forms occur in three distinct groups, linked together by a single discontinuous ridge (Fig. 15.3b). At the south-western end of the system, a single ridge curves around into the bottom of a deep subglacial drainage channel at Dalcross (Fig. 15.3a). Debate continues as to whether the eskers were deposited within subglacial or englacial conduits within the ice, or within open channels cut into the ice and ice-cored outwash at the front of the receding ice margin (Auton 1992; Merritt et al. 2017a).

The main esker system terminates north-eastwards in a broad, flat-topped and steep-sided ridge near Meikle Kildrummie (Fig. 15.3b). This feature slopes gently towards the east from ∼38 m OD and is pitted by small kettle holes. It has been interpreted either as a glacimarine delta laid down at the mouth of a subglacial conduit at the retreating ice front, or as a glacifluvial deposit formed within a large open crevasse, or cleft, at the ice margin, unmodified by marine processes (Merritt et al. 1995). The ridge was initially contiguous with the esker system but has been separated from it by subsequent glacifluvial erosion.

The Flemington Eskers form part of an extensive belt of glacifluvial deposits, including eskers, kames, plateaux and terraces, that lie between Daviot (Fig. 15.2a), in the upper Nairn valley, and Elgin (Merritt et al. 2017a). The features formed sequentially, probably along a suture or shear margin that divided stagnating Monadhliath ice within Strath Nairn from more active ice that issued from the Great Glen during deglaciation. A splendid assemblage of glacifluvial features straddles the valley of the River Ness around Torvean (Fig. 15.2a), on the western fringe of Inverness, where ice retreating back into the Great Glen formed a 68 m high esker, one of the tallest in Great Britain (Gordon 1993).

15.6.5 The Drummossie Muir-Culloden Ridge

A broad, elongate, gently convex and drumlinoid ridge lies between Strath Nairn and Inverness (Fig. 15.2a). The feature was sculptured beneath ice that flowed north-eastwards (flowset 6) from the Loch Ness Basin (Hughes et al. 2010, 2014). The ridge extends past the Culloden Battlefield visitor centre towards Croy (Fig. 15.3a); it has been modified by glacial meltwaters that carved channels of contrasting origin and is surmounted by two distinct suites of low ridges (Fletcher et al. 1996).

Several 15 m deep channels occur around Dalcross and Croy (British Geological Survey 1997; Fig. 15.3a, e). The features were probably incised subglacially as they start and terminate abruptly and are generally aligned with the former north-eastward direction of ice flow. Shallower channels arc around towards Strath Nairn, probably cut when the ice had thinned and the routing of subglacial meltwater was controlled more by the underlying topography being exhumed during deglaciation. A third set of channels occurs only along the north-west-facing slope of the ridge, and cross-cutting relationships indicate that they were cut at progressively lower elevations. They formed at, or close to, the margin of the outlet glacier that retreated into the Great Glen, but some locally have humped longitudinal profiles indicating a subglacial origin. Several flights of 'in–out' channels (Benn and Evans 2010) south-east of Inverness (Fig. 15.3a) were probably cut by meltwater that mostly flowed in conduits within the glacier.

A suite of ridges orientated parallel to the axis of the Drummossie-Culloden Ridge are ubiquitous at the south-western end of the feature, where the land surface has a corrugated form with 2–4 m deep furrows (possibly megagrooves) spaced 10–20 m apart (British Geological Survey 1997). The intervening ridges are formed of sandstone and siltstone rubble derived from the underlying Lower Devonian bedrock. This sediment-landform assemblage was interpreted as fluted moraine by Fletcher et al. (1996), but some of the furrows curve and locally bifurcate suggesting that they were eroded by subglacial meltwater. A contrasting suite of transverse till ridges lies across the distal end of the ridge, where they are typically 2–5 m high, spaced 75–150 m apart, locally coalesce, are generally lobate in plan and have intervening re-entrants (Fletcher et al. 1996; British Geological Survey 1997; Fig. 15.3a). These could have formed at the retreating ice front as winter push ridges, but generally they are not asymmetrical in profile like most such features (Benn and Evans 2010).

15.6.6 Transverse Ridges Between Nairn and Elgin, and on Tarbat Ness Peninsula

Similarly, orientated transverse ridges occur on the coastal lowland as far east as Elgin (Merritt et al. 2017a, b). The features tend to become longer and higher eastwards and are well-developed around Mosstowie (Finlayson et al. 2007; Figs. 15.2a and 15.3f). They are generally 3–7 m high and 50–90 m wide, traversing topographic undulations of up to 20 m amplitude. The major ridges are till-cored, have an average spacing of 190 m and are closely associated with ice-marginal glacial drainage channels that cut across higher ground to the south. Small-scale flutings occur locally between the major ridges. More pristine transverse ridges occur on Tarbat Ness (Fig. 15.2b), beside the Dornoch Firth, where they are up to 6 m high, 40–90 m wide and spaced 80–280 m apart (Finlayson et al. 2007).

Transverse ridges may result from different glacial processes (Benn and Evans 2010). Networks of narrow, locally anastomosing transverse ridges occur in the forelands of modern surging glaciers where they form by water-saturated sediment squeezing up into basal crevasses in highly fractured ice during surging. The sediment subsequently freezes and becomes part of the glacier. However, the straightness, length, height and spacing of the ridges at both Mosstowie and Tarbat Ness are also characteristic of De Geer moraines, especially as the ridges tend to have steeper east-facing ('down-ice') slopes (Finlayson et al. 2007). De Geer moraines are created at, or near, ice margins retreating in water. The features possibly formed during the retreat of the marine-terminating MFIS, but the altitudes of both sets of the ridges (up to 55 m OD) are much higher than predicted by current glacio-isostatic adjustment sea-level modelling for the region (Smith et al. 2019).

15.6.7 Ardersier

The Ardersier peninsula is bordered by a prominent raised beach at ~11 m OD that underlies Fort George (Fig. 15.3a, d). This shingle beach is of Middle Holocene age (Firth and Haggart 1989), but the abandoned cliffline that borders it represents a former ice-contact slope created earlier during a significant, but so far undated, late-stage glacial readvance within the Inverness Firth (Merritt et al. 1995). This so-called Ardersier Readvance formed a push moraine composed of glacitectonized glacimarine sediments (Ardersier Silts) that arcs around from Castle Stuart towards Rosemarkie, on the Black Isle (Merritt et al. 1995, 2017a; Fig. 15.3a). The Ardersier peninsula is also trimmed by fragmentary Late Devensian shorelines at altitudes of 28.5, 26.6, 21.0–21.6 and 18.5 m OD (Firth 1989).

15.7 Conclusions

A key feature of the Inverness region is that it provides a palimpsest of successive Late Devensian ice movements that are clearly recorded in the landscape. It contains a particularly rich and diverse set of sediment and landform assemblages that were mostly created at glacial margins towards the end of the last glaciation. It includes the legacy of a major oscillating tidewater outlet glacier together with Late Devensian and Holocene sea-level changes. At least five phases of glaciation have been recognised, although they remain poorly constrained temporally.

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