4 The Quaternary in Scotland

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Abstract

The Quaternary Period in Scotland was characterized by major climatic shifts and the alternation of glacial and temperate conditions over a wide range of timescales. The extent of multiple glaciations prior to the Mid-Pleistocene Transition (1.25–0.70 Ma) is uncertain, but thereafter up to ten major episodes of ice-sheet expansion occurred. Glacial erosion by successive glaciers and ice sheets created a range of terrain types: glaciated mountains, zones of areal scouring, landscapes of selective linear erosion, drift-mantled terrain of differential erosion and areas of limited glacial modification. The last ice sheet (~35–14 ka) extended to the shelf edge in the west and was confluent with the Fennoscandian Ice Sheet in the North Sea Basin; during its existence, it experienced marked changes in configuration, in part driven by the development of major ice streams. Subsequent glaciation during the Loch Lomond Stade (~12.9–11.7 ka) was restricted to a major icefield in the western Highlands and smaller glaciers in peripheral mountain areas. Contrasting glacial landsystems occupy terrain inside and outside the limits of the Loch Lomond Stadial glaciers. Postglacial landscape changes have been characterized by Lateglacial periglaciation and paraglacial landscape modification, mainly in the form of rock-slope failure and the accumulation (then later erosion) of paraglacial sediment stores and incision and terracing of glacigenic valley fills. Shore platforms of various ages formed around rock coastlines during the Quaternary, glacio-isostatic uplift has resulted in the formation of Lateglacial and Holocene raised beaches, and reworking of glacigenic deposits has provided sediments for present-day beach and dune systems.

Keywords

Pleistocene • Holocene • Late Devensian • Loch Lomond Stade • Glaciation • Ice streams • Periglaciation • Glacial erosion • Glacial landsystems • Permafrost • Paraglacial landscape modification • Rock-slope failure • Fluvial landforms • Sea-level change • Rock platforms • Raised beaches • Beach and dune systems

4.1 Introduction

The Quaternary Period comprises the Pleistocene Epoch (2.59 Ma to 11.7 ka) and Holocene Epoch (11.7 ka to the present). The Pleistocene is conventionally subdivided into the Early (2.59–0.78 Ma), Middle (0.78–0.13 Ma) and Late (130–11.7 ka) Pleistocene.

The Quaternary was characterized by dramatic and rapid climatic shifts. These resulted in alternation of glacial stages (stadial episodes), when Scotland experienced a climate of arctic severity, with interglacial stages (and interstadial episodes), when more temperate conditions prevailed. Cold periods were dominated by the effects of glaciation and periglaciation, whereas each return to temperate conditions was characterized by paraglacial landscape response and the operation of weathering, slope, fluvial, coastal and aeolian processes. These changes occurred against a backdrop of fluctuations in local relative sea level (from about −130 to +40 m compared to present sea level) and changes in biome, from tundra and cold desert to boreal forest and,

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C. K. Ballantyne and J. E. Gordon (eds.), *Landscapes and Landforms of Scotland*, World Geomorphological Landscapes, https://doi.org/10.1007/978-3-030-71246-4_4

during interglacials, temperate deciduous forest. Although the major relief elements of Scotland were established before the Pleistocene (Chap. 3), the effects of successive glacial cycles transformed much of the Scottish landscape.

Our understanding of the chronology and nature of landscape changes in Scotland during much of the Quaternary is limited, because successive ice sheets covered all of the present land area, removing most of the terrestrial stratigraphic record of earlier events and environmental conditions. There is consequently a considerably greater body of published literature concerning the last ice sheet and its aftermath (the last ~35 ka) than all of the earlier Quaternary. Conversely, however, our growing understanding of the extent and dynamics of the last ice sheet provides insights into earlier periods of ice-sheet glaciation. Similarly, the brief return to cold conditions after the retreat of the last ice sheet during the Loch Lomond (≈Younger Dryas) Stade of ~12.9–11.7 ka provides an analogue for periods of more restricted mountain glaciation and the Holocene (present interglacial) yields insights into the nature of landscape evolution during earlier interglacial periods.

Throughout the Quaternary, erosion by glacier ice during successive cold periods operated in synergy with nonglacial processes during intervening interglacial and interstadial periods. Glacial erosion steepened slopes and deepened valleys, glacial deposition mantled low ground with sediment and loading by glacier ice depressed the lithosphere and stressed the near-surface crust. Every subsequent deglaciation was accompanied and followed by isostatic rebound and paraglacial landscape adjustment in the form of rockfall activity, rock-slope failures and reworking of glacigenic sediment by hillslope, fluvial and coastal processes. During interglacials, much of the resulting paraglacial sediment was stored on the land surface or in nearshore locations. Such sediment and the products of interglacial weathering were then reworked by later glaciers or ice sheets, often being transported to offshore depocentres on the adjacent shelf or shelf edge. The Quaternary landscapes of Scotland are therefore not simply the outcome of successive episodes of glacial and glacifluvial erosion and deposition, but the product of landscape evolution during multiple glacial-interglacial cycles. Moreover, cumulative mass losses from eroded areas and corresponding mass gains in peripheral sediment sinks progressively influenced regional patterns of uplift and subsidence by redistributing overburden loading on the lithosphere.

This chapter focuses first on the nature of landscape evolution during the Early and Middle Pleistocene, before addressing: (i) the dynamics and chronology of the last ice sheet; (ii) glaciation during the Loch Lomond Stade; then (iii) the characteristics of Late Devensian glacial landsystems. The final parts of the chapter consider the trajectories of landscape evolution during both the Lateglacial period (between final local deglaciation and the onset of the Holocene) and the Holocene itself. Key locations are depicted in Fig. 4.1.

4.2 Early and Middle Pleistocene

4.2.1 Introduction

Although the main topographic features of Scotland were established before the Quaternary (Chap. 3), the end-Neogene landscapes of Scotland differed fundamentally from those of the present. The North Sea coastline lay seaward from its present location (Huuse 2002) and many indentations of the Scottish coastline (firths, fjords, sounds and inner seas) did not exist in their present form; some islands, such as Skye and Mull, were still part of the Scottish mainland. The end-Neogene landscape was dominated by dendritic river systems flowing towards extensive coastal lowlands and mantled by thick covers of soil, sediment and saprolite. Much of the modification of this landscape was accomplished by successive Pleistocene glaciers and ice sheets, but weathering, slope, fluvial and coastal processes continued to operate over long periods, particularly during the Early Pleistocene. The rapid tempo of environmental changes over comparatively brief timescales, coupled with changing vegetation cover and shifts in sea level, is likely to have enhanced rates of erosion by nonglacial processes, contributing to landscape transformation. The extraordinary dynamism of Pleistocene environments in Scotland typified that of glaciated areas along the North Atlantic passive margin.

Neotectonic movements of the crust operated throughout the Pleistocene in Scotland, driven by the far-field effects of intra-plate stresses generated by mid-Atlantic ridge push and the Alpine orogeny, the transfer of large volumes of sediment onto adjacent offshore shelves and basins, and glacio-isostatic loading and unloading of the crust by the growth and shrinkage of successive ice sheets (Stewart et al. 2000). The long-term effects of such movements are illustrated by evidence for vertical movement of fault blocks in Orkney, Moray and the Hebrides, and by uplift of a low-level Pliocene planation surface that formed around the margins of the Highlands to elevations of up to 150 m in eastern Lewis, Caithness and Buchan (Chap. 3). Similarly, high-level (10–40 m OD) shore platforms, often buried under till, are preserved on coastlines peripheral to the centres of ice accumulation (Smith et al. 2019; Sect. 4.9.2). Fault scarps provide evidence of minor faulting since the retreat of the last ice sheet (Firth and Stewart 2000; Smith et al. 2009) and significant seismic activity ($M_L \geq 4$) continues to affect the western Highlands, Inner Hebrides and Midland Valley at present (Musson 2007).

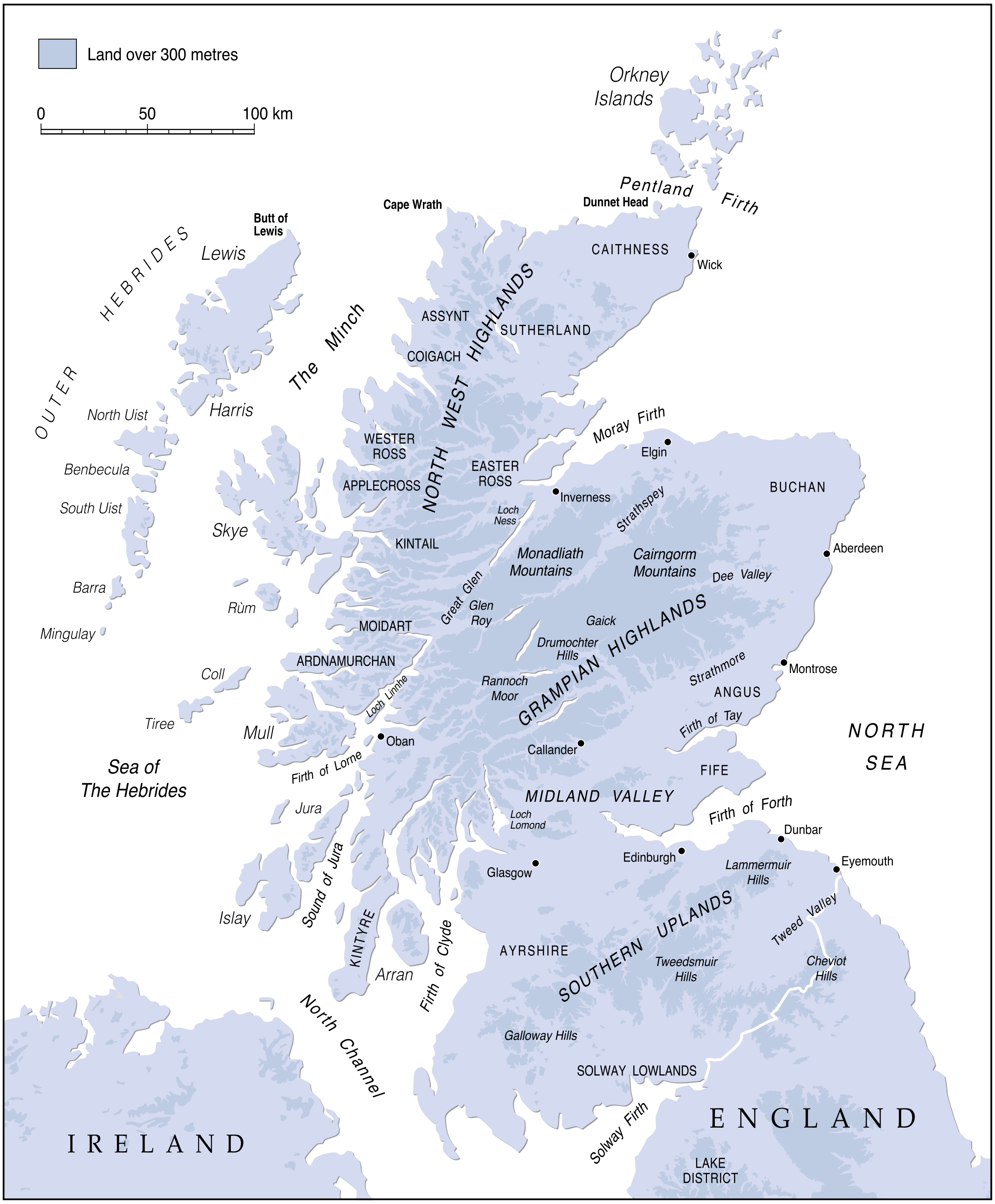

Fig. 4.1 Key locations mentioned in the text. The Shetland Islands (not shown) are located ~170 km north of the Scottish mainland

The $\delta^{18}0$ record for North Atlantic marine sediments constrains the first-order timing and intensity of Pleistocene environmental change in Scotland (Fig. 4.2). In the Early Pleistocene, global climate forcing was driven by 41 ka orbital cycles, but during the Mid-Pleistocene Transition (MPT) at ~1.25–0.70 Ma there was a shift towards forcing driven by 100 ka cyclicity (Head and Gibbard 2005; Willeit et al. 2019) that initiated the growth of extensive ice sheets. In the Early Pleistocene, global sea level reached a few metres higher than present during brief interglacial periods and declined no lower than −60 m during glacial stages. After the MPT, sea-level lowstand reached −130 m during glacial maxima due to the huge volumes of water sequestered in ice sheets (Spratt and Lisiecki 2016).

The Early Pleistocene was dominated by two climate types (Hall et al. 2019; Fig. 4.2): an interglacial or

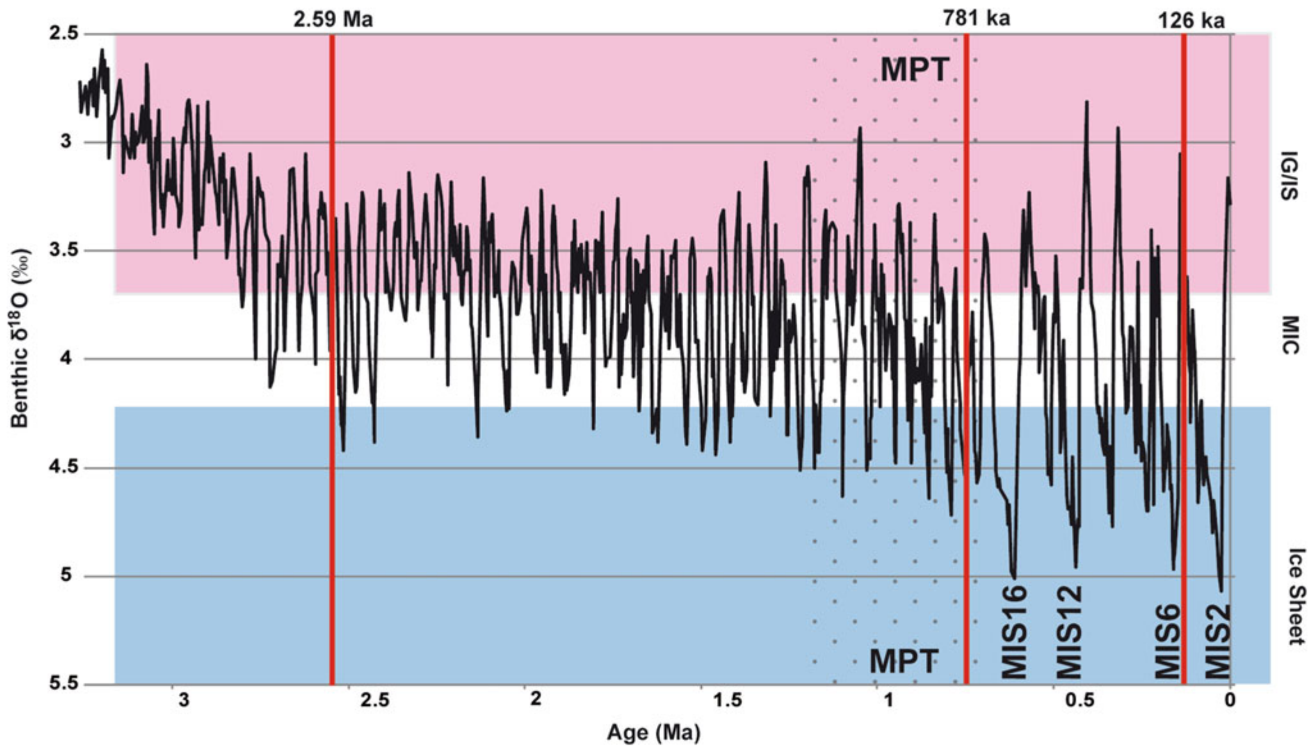

Fig. 4.2 The δ^{18}O record for benthic foraminifera from marine core DSDP 607, interpreted as a proxy for glacier extent in Scotland. Values of $<3.7^{0}/_{00}$ δ^{18}O are interpreted as indicating interglacial (IG) or interstadial (IS) conditions in Scotland; 3.7–$4.2^{0}/_{00}$ δ^{18}O as indicating periods of mountain ice caps (MIC) and limited glacier cover; $>4.2^{0}/_{00}$ δ^{18}O as indicating development of extensive ice sheets. MPT: Mid-Pleistocene Transition. MIS: Marine Isotope Stage. (Modified from Hall et al. 2019 Earth Env Sci Trans R Soc Edinb 110:537 © The Royal Society of Edinburgh)

interstadial regime, when temperate conditions prevailed and glaciers were absent in Scotland; and a stadial regime, when glaciers developed in mountain areas and periglacial conditions affected lower, peripheral locations (Murton and Ballantyne 2017). Owing to their position on the leeward margin of the North Atlantic Ocean, Scotland's mountains provided near-optimal conditions for the rapid development of icefields, ice caps and valley glaciers in response to moderate (~3–6 °C) falls in summer temperature, as evidenced by the formation of such glaciers during the Loch Lomond Stade (Golledge et al. 2008; Sect. 4.5). The maximum extent of glacier ice during the Early Pleistocene is uncertain. Evidence provided by iceberg scour marks in stacked marine sediments suggests repeated extension of grounded ice margins into the western North Sea Basin after 2.53 Ma and the central North Sea Basin after 1.87 Ma, implying that ice sheets developed over Scotland from the earliest Pleistocene (Rea et al. 2018). These may, however, have been of limited extent and duration, as Early Pleistocene sediments on the edge of the East Shetland Platform appear to lack a glacial component until 1.1–1.0 Ma (Buckley 2017). In the west-central North Sea Basin, the Early Pleistocene Aberdeen Ground Formation is truncated by an extensive erosional unconformity, the Upper Regional Unconformity (URU), which formed at ~1.2 Ma and probably represents the earliest expansion of the Fennoscandian Ice Sheet into the central North Sea area (Reinardy et al. 2017).

The increased intensity and duration of cooling events after the beginning of the Middle Pleistocene implies that up to ten subsequent episodes of ice-sheet expansion occurred in Scotland (Fig. 4.2). By analogy with the extent and thickness of the last ice sheet (Sect. 4.4), it is likely that the ice sheets that developed in marine isotope stages (MIS) 16, 12 and 8–6 had maximum surface elevations of 1.5–2.0 km or more and extended far across the adjacent shelves to, or close to, the Atlantic shelf break in the west (Stoker et al. 1993). Eastwards extension of successive Middle Pleistocene ice sheets across the North Sea Basin is indicated by increasing influx of sediment of Scottish origin over the URU, seven generations of tunnel valleys within these sediments and several sets of mega-scale glacial lineations within the Middle to Late Pleistocene sequence (Stewart et al. 2013). During successive Middle Pleistocene glacial maxima, the Scottish and Fennoscandian Ice Sheets were probably confluent across a shifting, broad zone in the North Sea Basin (Bendixen et al. 2017; Sect. 4.4.1). Extension of Scottish ice as far south as East Anglia during the Middle

Pleistocene is demonstrated by the presence of indicator heavy minerals and erratics of Scottish provenance in coeval till deposits (Lee et al. 2015).

It is likely that the patterns of ice flow during periods of Middle Pleistocene ice-sheet glaciation were similar to those of the last ice sheet, with primary centres of ice dispersal located over the Scottish Highlands and Southern Uplands and persistent local ice divides over the Outer Hebrides, the Orkney-Shetland Platform, Skye, Mull, the Cairngorm Mountains and the Galloway Hills (Sect. 4.4.1). Similarly, the locations of the main ice divides and flow paths are likely to have migrated during the lifetimes of Middle Pleistocene ice sheets (Hughes et al. 2014). As with the last ice sheet, successive Middle Pleistocene ice sheets probably exhibited 'binge and purge' cycles, with build-up of cold-based ice over upland areas alternating with drawdown of ice evacuated by persistent or transient ice streams (Hubbard et al. 2009).

4.2.2 Early and Middle Pleistocene Terrestrial Stratigraphy

In Scotland, no Early Pleistocene sediments have been confirmed onshore. In a few locations in Buchan and Caithness, however, sediments or fossils of probable Early Pleistocene age have been reworked into Late Pleistocene glacigenic sequences (Merritt et al. 2003).

The Middle Pleistocene stratigraphic record in Scotland includes glacigenic deposits and periglacial features that represent cold stages back at least to MIS 8, together with terrestrial sediments with a floral, faunal or pedological record of interstadial and interglacial conditions. The most complete stratigraphic record of Middle Devensian events is preserved in the Kirkhill area of Buchan, where at least three stadial-interstadial-interglacial cycles are represented (Hall et al. 2019). The lowermost cycle probably pre-dates MIS 7 and includes glacial and glacifluvial material deposited at different times by ice moving either towards or away from the North Sea coast; these sediments are overlain in turn by a periglacial gelifluctate (solifluction deposit) then a podzolic palaeosol that formed under humid-temperate conditions. The overlying sediments of the second cycle, assigned to MIS 6–5e, record an initial return to permafrost conditions (represented by ice-wedge pseudomorphs and gelifluctate), followed by glaciation (represented by a till) and development of a palaeosol of inferred last interglacial age. The final cycle, of Devensian (MIS 5d–2) age, is represented by ice-wedge pseudomorphs indicating the return of permafrost, tills deposited by the last ice sheet, then Lateglacial gelifluctate.

At a few other sites, glacigenic deposits of Middle Devensian age underlie organic deposits of probable last interglacial (MIS 5e) age. On the NW coast of Shetland, for example, a till indicating SE–NW ice movement underlies a peat layer of probable last interglacial age, suggesting that during MIS 6 ice flowed radially outwards from the Orkney-Shetland Platform (Hall et al. 2002; Chap. 7). Across Moray and Buchan, and into lower Strathspey, tills of probable MIS 6 age that locally underlie last interglacial palaeosols and organic deposits contain erratics and exhibit fabrics that suggest directions of ice flow similar to those of the last ice sheet (Merritt et al. 2003). In Caithness, lower till units of uncertain age record both former ice flow from the mountains to the west and northeastward flow of ice from the Moray Firth (Hall and Riding 2016). Collectively, these and other sites suggest that the pattern of flow of the MIS 6 ice sheet was broadly similar to that associated with the last ice sheet.

4.2.3 Long-Term Glacial Erosion

Given the frequency of glacial episodes in Scotland after ~2.6 Ma (Fig. 4.2) and the growth and demise of successive ice sheets after ~0.78 Ma, it is likely that all large-scale glacial erosional landforms in Scotland had formed before the last interglacial and that Late Pleistocene (~130–11.7 ka) glacial erosion accomplished only limited landscape modification. This is evident in the preservation of older bedrock landforms, such as shore platforms, sea cliffs, meltwater gorges and the scars of major rock-slope failures. Moreover, the geomorphological legacy of successive episodes of Pleistocene glaciation was markedly non-uniform across the country. Topographic asymmetry and exposure to dominantly westerly airmasses produced strong longitudinal climatic gradients across Scotland. Snowfall and air temperature were highest on the Atlantic margins (Barr et al. 2017) and consequently the glaciers in western Scotland had high ice discharges and were predominantly warm-based (Hubbard et al. 2009). The overall duration of Pleistocene ice cover was also greater near western centres of ice dispersal, particularly during periods of limited glaciation similar to that of the Loch Lomond Stade, when marine-terminating icefields developed in the western Highlands, but only small cirque and valley glaciers occupied the comparatively snow-starved eastern Highlands (Sect. 4.5). Glacial dissection of mountain areas is consequently most strongly developed in the Hebrides, western Highlands and SW Southern Uplands (Chaps. 10, 13, 17 and 27).

Farther east, as across the Eastern Grampians, Cairngorm Mountains, the lowlands of Buchan and much of the Southern Uplands, successive ice sheets were predominantly slow-moving and cold-based, and consequently accomplished very limited modification of palaeosurfaces (Hall and Sugden 1987; Chaps. 18, 20, 21 and 27). In such areas, effective glacial erosion was confined to corridors of fast-flowing ice within glacial troughs and landscapes of selective linear glacial erosion evolved (Rea 1998).

The effect of glacial erosion across lowlands was conditioned by the underlying lithology. Across the resistant gneisses of NW Scotland and the Outer Hebrides, for example, glacial abrasion and plucking predominated, forming knock-and-lochan landscapes of low, ice-scoured bedrock hillocks and intervening depressions, typically with patchy drift cover (Krabbendam and Bradwell 2014; Chaps. 9 and 12). In the Midland Valley, differential glacial erosion created a landscape of drift-covered lowlands underlain by sedimentary rocks, interspersed with higher ground formed of resistant lavas, sills and volcanic plugs that have commonly been streamlined in the direction of ice flow and shaped into crag-and-tail forms (Chap. 26).

The western Highlands and mountainous parts of Skye, Rùm, Mull and Arran are characterized by a glacial landscape of deep troughs, cirques, rock basins, fjords, arêtes and areas of glacially roughened bedrock (Fig. 4.3a–c). In this region, successive episodes of glacial erosion operating on a fluvially dissected landscape removed all but small fragments of pre-Quaternary palaeosurfaces. A repeatedly established, former mountain ice-cap zone in the western Highlands is marked by lake-filled rock basins in a 15–30 km wide zone on both sides of the former main Highland ice shed. In the NW Highlands, eastward migration of the former ice divide (Hughes et al. 2014) resulted in the formation of numerous glacial breaches that cut through the present north–south watershed. Equally conspicuous are the glacial breaches, troughs and rock basins that radiate from the Rannoch Moor basin in the Grampian Highlands, suggesting that this area formed a major centre of ice dispersal during successive glaciations (Chap. 17). Despite the pervasive effects of glacial erosion, however, some summits and plateaux in the western Highlands retain a cover of little-modified blockfields that pre-dates at least the last ice sheet (Fabel et al. 2012; Hopkinson and Ballantyne 2014). The preservation of such blockfields implies that the last ice sheet was polythermal, with cold-based ice occupying the highest ground whilst warm-based, erosive ice flowed through adjacent troughs (Fame et al. 2018) and it is likely that this was also true of Early and Middle Pleistocene ice caps and ice sheets. Along the western seaboard from Knoydart to Argyll, however, summit blockfields are absent and glacially moulded bedrock often extends to mountain summits.

Across much of the eastern Highlands the polythermal nature of the last and earlier ice sheets is manifest in the striking contrast between deep glacial troughs and well-preserved, extensive plateau palaeosurfaces such as those of the Cairngorms, Monadhliath, Gaick and Eastern Grampians (Chaps. 3, 18 and 20; Fig. 4.4a–c). Similar undulating tablelands dissected by glacial troughs also form high ground in the Southern Uplands (Chap. 27), though here the effects of glacial erosion are more muted (Fig. 4.4 d, e). Such topographic contrasts imply that during successive glaciations cold-based ice that was frozen to the underlying substrate persisted on high ground, feeding fast-moving, warm-based glaciers that occupied (and progressively eroded) adjacent and intervening troughs (Sugden 1968; Glasser 1995; Rea 1998). Some plateau margins in the eastern Highlands, such as the Cairngorms, are extensively scalloped by cirques. Others, such as the Gaick plateau, are almost devoid of cirques, but flanked by steep trough heads.

Blockfields and other forms of frost-weathered regolith (gelifractate) mantle most plateaux in the eastern Highlands, and on the Cairngorms plateau numerous granite tors have survived burial by the last and earlier ice sheets, though some have been modified by glacial erosion (Hall and Phillips 2006; Phillips et al. 2006). Across the Highlands as a whole, the lower limit of blockfields declines away from the centres of ice dispersal, indicating the fundamental importance of englacial thermal boundaries in dictating upper limits to effective glacial erosion (Hall and Glasser 2003). There is, for example, a consistent decline in the lower limit of blockfields away from former ice-shed locations in the northern Highlands (Ballantyne et al. 1998; Ballantyne and Hall 2008) and the upper limit of effective glacial erosion also declines eastwards across much of the Grampians (Hall et al. 2019), such that even the low palaeosurface of the Buchan plain exhibits negligible evidence of erosion (Hall and Sugden 1987; Chap. 21).

During major glaciations, major pre-glacial valleys such as the Great Glen, Strathspey, Strathmore and the Tweed valley formed important arteries for the evacuation of ice from upland sources and guided ice flow towards major ice streams that developed mainly on relatively weak sedimentary rocks or deformable unconsolidated sediments (Bradwell et al. 2019). Activation of ice streams led to draw-down of ice towards the offshore Mesozoic basins of the Moray Firth, Minch, Sea of the Hebrides and North Sea Basin, where ice flowing across weak substrates during Middle Pleistocene glaciations excavated deep basins. Glacial overdeepening over multiple glacial cycles reshaped the Scottish coastline, causing it to recede landwards and severing islands such as Mull, Skye and Orkney from the mainland (Chaps. 8, 9 and 10).

The spatial pattern and depths of cumulative Pleistocene glacial erosion can be estimated by using nonglacial landforms and landsurfaces as reference points. In general, depths of glacial erosion increase westwards across the Grampians. In eastern Buchan, where Tertiary gravel deposits survive on ridges, total erosion has locally been of the order of metres (Hall and Sugden 1987). In the Cairngorms, glacial deepening of pre-glacial valleys probably did not exceed 200–350 m (Hall and Gillespie 2016) and glacial

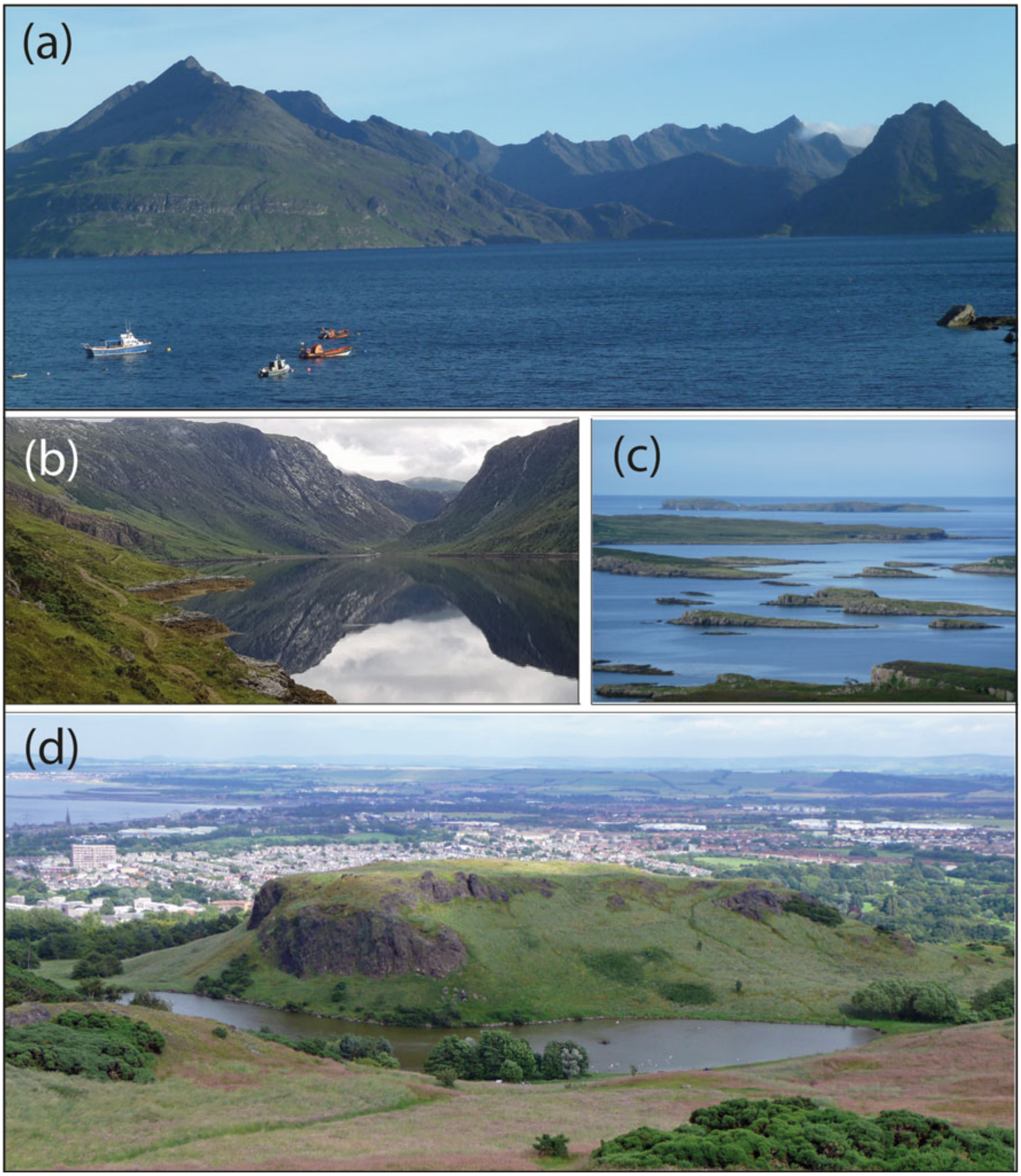

Fig. 4.3 Landscapes of high-intensity glacial erosion. **a** The Black Cuillin, Skye: an alpine glacial landscape fashioned mainly in Palaeogene gabbros by Pleistocene cirque and valley glaciers. **b** Gleann Dubh, Assynt: a mountain glacial landscape and fjord cut mainly in Archaean gneisses. **c** Ulva, Mull: glacially roughened surface of gently inclined Palaeocene basalt lavas; ice movement was left to right. **d** Dunsapie Hill, Edinburgh: part of a resistant Carboniferous basic igneous vent picked out by glacial erosion and standing ~100 m above the adjacent Carboniferous sedimentary rocks. (Images: Adrian Hall)

erosion of plateaux was extremely limited. Average Pleistocene erosion depths across the Dee catchment south of the Cairngorms have been estimated at 30–60 m, with a substantial contribution from the removal of saprock and saprolite (Glasser and Hall 1997). An eastward decline in the intensity of cumulative glacial erosion is also indicated by landform evidence. Glacially streamlined terrain across much of Caithness and along the lower Dee valley merges eastwards with non-streamlined terrain with similar ridge-top elevations, where glacial erosion has been restricted mainly to the excavation of valleys and depressions.

Along the western seaboard, focusing of glacial erosion is also evident. On the open Lewisian gneiss terrain of the

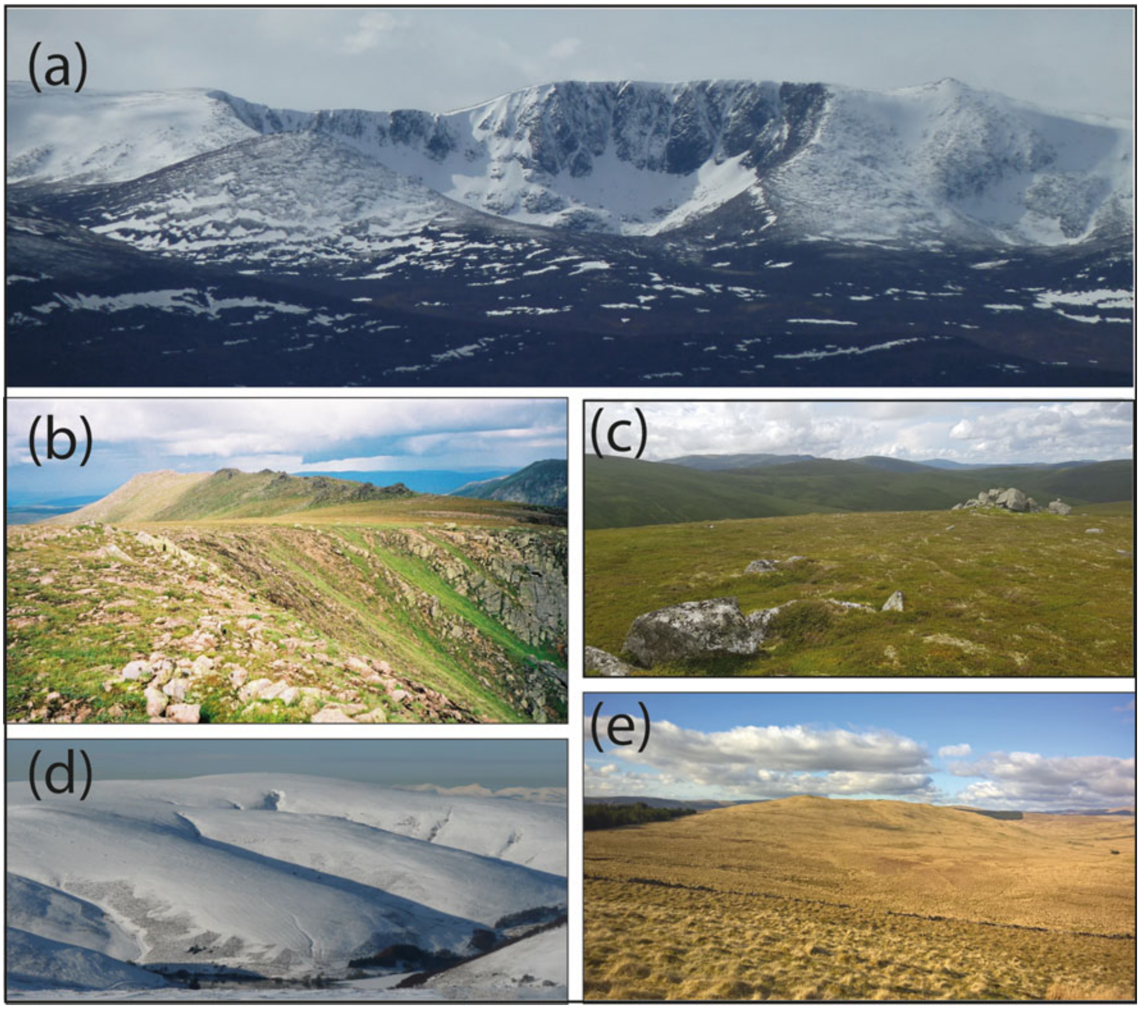

Fig. 4.4 Landscapes of relatively low-intensity glacial erosion. **a** Selective glacial erosion on the north flank of Lochnagar, Grampian Highlands, showing cirques cut into the granite plateau; Meikle Pap on the left is festooned with bouldery solifluction lobes. **b** Mountain-top regolith and granite tor landscape on Beinn a' Bhuird, Cairngorms. **c** Ridge-top tors and fluvial valleys in upper Strathdon. **d** The eastern Lammermuir Hills, Southern Uplands: smooth slopes and fluvial valleys cut in Silurian metasediments. **e** Undulating tableland of Silurian metasediments on the Tweed watershed, Southern Uplands. (Images: Adrian Hall)

Outer Hebrides and Assynt, glacial erosion has apparently been largely limited to the removal of pre-glacial regolith cover (Godard 1965), with deep erosion of basement rocks only in fracture-controlled basins and valleys (Krabbendam and Bradwell 2014). In contrast, mega-grooves up to 6 km long, 10–100 m wide and 5–15 m deep on the streamlined bed of a former ice-stream onset zone in Assynt (Bradwell et al. 2008b) and on the floors of The Minch (Bradwell and Stoker 2015a) and the Sea of the Hebrides (Dove et al. 2015) demonstrate highly effective glacial erosion of hard crystalline rock in zones of focused fast ice flow.

On land, depths of cumulative Pleistocene glacial erosion are greatest in the troughs of the western Highlands, particularly where convergent ice flow resulted in the excavation of deep rock basins. More than 50 trough-floor basins over 40 m deep occur in this region and the deepest (those occupied by Lochs Morar, Ness and Lomond) reach depths of 190–310 m. Similarly, several of the fjords that indent the western coastline descend to depths of over 100 m before shallowing at their outlets, and narrow straits (sounds) that focused ice flow (such as the Inner Sound between Skye and the mainland) exceed 200 m in depth. Even in the Midland Valley, where differential erosion of igneous and sedimentary rocks dominates the landscape (Fig. 4.3d), glacially excavated trenches and rock basins extend below valley floors, locally to depths below sea level (Kearsey et al. 2019).

4.2.4 Interglacial and Interstadial Processes

The nonglacial processes of weathering and erosion that operated in Scotland during and after the retreat of the last sheet (Sects. 4.7 and 4.8) can be considered representative of those that operated during interglacials and interstadials following the MPT. Prior to the expansion of the last ice sheet and again during ice-sheet retreat, permafrost developed down to sea level in terrain not occupied by glacier ice and periglacial processes of frost weathering, ice-wedge formation and solifluction affected extensive areas. That such processes also operated during the Early and Middle Devensian is demonstrated by stratigraphic evidence in England (Murton and Ballantyne 2017) and by the stratigraphic record at Kirkhill in Buchan (Sect. 4.2.2).

Retreat of the last ice sheet and its predecessors was accompanied by a range of paraglacial processes: failure or deformation of critically stressed rock slopes, accumulation of rockfall debris as talus, reworking of glacigenic sediment by rivers, debris flows and coastal erosion, and incision and terracing of glacigenic valley fills. Such paraglacial landscape modification was most rapid during the millennia immediately following deglaciation and declined thereafter as rock slopes stabilized and reserves of glacigenic sediment accessible to reworking processes declined (Ballantyne 2002, 2019b; Ballantyne et al. 2014). Paraglacial sediment stores that accumulated following each episode of deglaciation then contributed to the sediment entrained by subsequent glaciers and ice sheets. The only paraglacial landforms known to have survived at least one ice-sheet glaciation are the scars of major rockslides (Cave and Ballantyne 2016). The preservation of such features indicates that paraglacial rock-slope failure has, over multiple glacial-paraglacial cycles, made a major contribution to trough widening and the lateral extension of cirques (Jarman 2009; Ballantyne 2013a, 2019a; Chap. 14).

The role of weathering during successive interglacials in producing readily erodible soils and regolith that contributed to the sediment transported during subsequent periods of glacial expansion may have been considerable, particularly in the long periods of interstadial and interglacial conditions of the Early Pleistocene. In Buchan, where successive ice sheets were mainly cold-based and glacial erosion was minimal, pre-Quaternary and interglacial saprolites were preserved and frost-shattered rock occurs under glacial deposits; similar weathering covers were once widespread elsewhere but have been removed by glacial erosion.

Similarly, the blockfields and other forms of periglacial regolith that mantle summits and high plateaux provide evidence of long-term weathering of bedrock, mainly under periglacial conditions. Since the downwastage of the last ice sheet, only thin, immature covers of frost-weathered debris have accumulated on ice-scoured summits, implying that mature blockfields have evolved over more than a single glacial-interglacial cycle, possibly over timescales of 100 ka (Marquette et al. 2004). Preservation of Scottish blockfields under cold-based ice during at least the last (and probably earlier) ice-sheet glaciation(s) has been demonstrated by cosmogenic ^{10}Be exposure dating of erratics resting on blockfield surfaces (Fabel et al. 2012). Some periglacial regolith covers may have evolved throughout the Quaternary, with formation of detritus by weathering being balanced by gradual nonglacial erosion (Ballantyne 2010), though the most recent generation of extant blockfields probably formed during the Late Pleistocene (Hopkinson and Ballantyne 2014). Although the blockfields on Scottish mountains represent mainly breakdown of well-jointed rock by frost weathering, they contain assemblages of clay minerals, including gibbsite and kaolinite, that indicate long-term chemical alteration of blockfield debris (Ballantyne 1998a).

The most specular evidence for long-term subaerial weathering and erosion during the Quaternary is provided by the emergence of tors through preferential weathering and erosion of the surrounding surfaces. Terrestrial cosmogenic nuclide (TCN) data indicate that the granite tors of the Cairngorms and conglomerate tors in Caithness pre-date the last interglacial (Phillips et al. 2006; Ballantyne and Hall 2008); the oldest dated tor surface in the Cairngorms has a minimum modelled (exposure and burial) age of ~675 ka. Collectively, the TCN data obtained for the tors on the Cairngorms indicate that nonglacial denudation of rock surfaces and regolith covers operated at rates of 2.8–12.0 m Ma^{-1} during successive interglacials. Palaeosurfaces and high plateaux in Scotland are therefore not pristine pre-Quaternary landforms but experienced up to a few tens of metres of surface lowering under nonglacial conditions during the Quaternary.

4.3 Late Pleistocene

The Late Pleistocene comprises the last (Ipswichian) interglacial (MIS 5e; ~130–116 ka) and the last (Devensian) glacial stage, the latter being equivalent to the Weichselian glacial stage in western Europe. The Devensian is subdivided into the Early (MIS 5d–4; ~116–57 ka), Middle (MIS 3; ~57–31 ka) and Late Devensian (MIS 2; ~31–11.7 ka) substages. The Devensian was a period of marked climatic fluctuations. The synchronised Greenland ice-core oxygen isotope records for this period identify 26 stadial events and 25 intervening interstades (Rasmussen et al. 2014), though none of the latter indicate warming equivalent to that of interglacial periods. The most protracted cold periods identified in the ice-core record occurred during MIS 4 (~71–57 ka) and MIS 2; the latter coincided with the expansion of the last Scottish Ice Sheet (Sect. 4.4) and the former was probably also associated with development of an ice sheet in Scotland, though confirmation remains elusive. Briefer stadial events during MIS 5d–5a and MIS 3 were almost certainly accompanied by the development of ice caps and icefields in upland areas, and limited ice cover may have occupied high ground during some Devensian interstades. The total duration of glaciation in peripheral lowlands was comparatively brief, perhaps amounting to less than 25–30 ka of the last 130 ka.

4.3.1 The Last Interglacial and Devensian Interstades

The Late Pleistocene terrestrial stratigraphy of Scotland has been reviewed by Merritt et al. (2019). Stratigraphic evidence of last interglacial age is represented at a few sites where till-covered peat beds or palaeosols contain thermophilous pollen assemblages or other organic material that indicate a climate as warm as, or warmer, than now. These include sites at Fugla Ness in NW Shetland (Hall et al. 2002), Dalcharn east of Inverness (Walker et al. 1992), Teindland near Elgin (Hall et al. 1995) and Kirkhill in Buchan (Hall et al. 2019). Other till-covered palaeosols or peats have been attributed to formation during cool Early Devensian interstades (MIS 5c or 5a), notably at Sel Ayre in west Shetland, Allt Odhar southeast of Inverness and at various sites in Buchan. Weathering of basal tills of probable Middle Devensian age in northern Lewis, the Nairn valley, the central Grampians and Midland Valley has also been attributed to temperate conditions during the last interglacial or Early Devensian interstades (Merritt et al. 2019).

4.3.2 Early and Middle Devensian Glaciations

During the Early Weichselian (Early Devensian), an extensive ice sheet occupied Fennoscandia (Kleman et al. 1997). In areas that remained beneath cold-based ice in the Late Weichselian, Middle Weichselian glacigenic sediments and depositional landforms such as moraine ridges and eskers are widely preserved (Kleman et al. 2020). Similar ice-sheet growth is likely to have occurred in the British Isles, but few landforms and sediments in Scotland can be attributed with confidence to Early and Middle Devensian glaciations. At various sites, there are two or more till units of probable Devensian age. Some of these contain erratics or display fabrics indicating switches in ice-flow direction, and others are separated by periglacial facies or outwash sands and gravels (Merritt et al. 2017, 2019). Given a lack of dating evidence and the paucity of recognized Devensian interstadial organic sediments, it is uncertain whether stacked till units reflect deposition during successive Devensian glaciations, or episodic changes in the extent or direction of flow of the last ice sheet alone. In the Clyde and Ayrshire basins, however, the lowermost till underlies MIS 3 deposits and is possibly of MIS 4 age though probably older (Finlayson et al. 2010).

Some light is cast on the extent of Early and Middle Devensian glaciation by ^{230}Th/^{234}U disequilibrium ages for speleothem formation in limestone caves at the foot of mountains in Assynt (Lawson and Atkinson 1995). Speleothem growth is negligible under ice cover and ceases in permafrost. A cluster of 15 overlapping ages for the period ~95–75 ka (MIS 5c–5a) implies mainly glacier- and permafrost-free conditions within this interval. Conversely, MIS 4 is represented by just two ages, both with large uncertainties (63.6±6 ka and 56±13 ka), suggesting that part or all of Assynt was ice-covered during this period. Lithological evidence for an Early Devensian Scottish ice sheet is also present in a deep-ocean core from the Rockall Trough, 300 km west of Scotland, which appears to indicate expansion of an ice sheet across the Hebrides Shelf during MIS 4 (Hibbert et al. 2010). Much research remains to be done to unravel the terrestrial environmental history of the Early and Middle Devensian in Scotland.

4.3.3 The Late Devensian

The Late Devensian (≈ Late Weichselian) substage is temporally equivalent to MIS 2 (31–11.7 ka) and encompasses Greenland Stadials 1–5 (Rasmussen et al. 2014). In Great Britain, it is subdivided into the Dimlington Stade (~31–14.7 ka), the Lateglacial (or Windermere) Interstade (~14.7–12.9 ka) and the Loch Lomond (≈Younger Dryas) Stade (~12.9–11.7 ka). The Late Devensian incorporates the advance of the last Scottish Ice Sheet to its maximum extent, subsequent shrinkage of the ice sheet, and readvance of glaciers during the Loch Lomond Stade following complete (or nearly complete) disappearance of glacier ice from Scotland during the intervening Lateglacial Interstade.

4.4 The Last Scottish Ice Sheet

The last Scottish Ice Sheet (SIS) was the dominant component of the British-Irish Ice Sheet (BIIS) and for much of its existence reached far beyond the present land area of Scotland. During the Last Glacial Maximum, it extended westward and northwestward across the Atlantic shelf, met the Fennoscandian Ice Sheet (FIS) in the North Sea Basin and was confluent to the south with ice nourished in England, Wales and Ireland

(Fig. 4.5). The ice sheet exhibited highly dynamic behaviour during its lifetime, with radical changes in its configuration and flow patterns, periods of sustained ice streaming and multiple readvances that interrupted its retreat. Ballantyne and Small (2019) have reviewed the pattern and chronology of the expansion and retreat of the SIS and a map and comprehensive database of over 170,000 glacial landforms associated with the BIIS have been published by Clark et al. (2017).

Fig. 4.5 The maximum extent of the last British-Irish Ice Sheet, showing the location of independent centres of ice dispersal and generalized directions of offshore ice movement when the ice sheet reached its maximum extent

4.4.1 Ice-Sheet Expansion and Maximum Extent

The presence of ice-rafted detritus of Scottish provenance in deep-water cores from the Atlantic Ocean indicates that marine-terminating glaciers were at least intermittently present in Scotland during ~43–35 ka (Hibbert et al. 2010), suggesting that an icefield or ice cap of fluctuating extent occupied the Scottish Highlands during most or all of this period. Subsequent expansion of the SIS is recorded by radiocarbon ages for organic material buried under till. These imply that Highland ice did not expand across adjacent lowlands until ~35 ka and possibly not until ~32 ka (Bos et al. 2004; Brown et al. 2007). Similarly, radiocarbon ages obtained for shells in marine sediments overlain by till in the northern North Sea Basin imply ice-free conditions until ~34 ka or later (Graham et al. 2010).

A generalized pattern of ice-sheet expansion has been proposed by Hughes et al. (2014) through the identification of sequential (cross-cutting) flowsets represented by the alignment of glacial bedforms and meltwater channels. Stage 1 in their reconstruction (Fig. 4.6) approximates conditions around 35–32 ka, when ice enveloped the Midland Valley. Stage 2 depicts build-up of an ice divide over SW Scotland and extension of Scottish ice across Ireland and northern England. By stages 3 and 4, thickening and expansion of ice nourished in the Southern Uplands and Ireland had created an ice divide between SW Scotland and Ireland, diverting Scottish ice westward across the Atlantic shelf. Stage 5 depicts the SIS terminating westward at or near the Atlantic shelf break and eastwards confluence with the Fennoscandian Ice Sheet; it represents the maximum extent of ice sourced in Scotland. Southward ice expansion, however, continued during stage 6, by which time ice margins in the north had begun to retreat.

More detailed local evidence complements this general model. In central and southern Scotland, the evidence provided by sequential flowsets and erratic dispersion indicates that after ~35 ka ice from the SW Highlands moved eastwards across the Midland Valley and southwards down the Firth of Clyde, eventually meeting ice advancing from the Southern Uplands and extending into the Irish Sea Basin and up to 200 km into Ireland (Greenwood and Clark 2009; Finlayson et al. 2010, 2014). Subsequent thickening of the Southern Uplands ice mass led to its confluence with the Irish Ice Sheet and formation of a persistent ice divide between Scotland and Ireland, re-routing ice from the SW Highlands westwards across the Malin Shelf. Only ice from the Galloway Hills in SW Scotland continued to flow south into the Irish Sea Basin, where it joined ice from England, Wales and Ireland to feed the Irish Sea Ice Stream. Development of a north–south ice divide east of the Galloway Hills caused ice from the rest of the Southern Uplands to be evacuated eastwards via the Firth of Forth, Tweed valley and Tyne valley into the North Sea Basin, where it was diverted southwards to impinge on the east coast of England (Livingstone et al. 2012; Busfield et al. 2015).

In the west of Scotland, the evidence provided by striae and erratics indicates that the islands of Skye, Mull and Arran developed ice caps that diverted the flow of ice from the mainland and probably remained centres of ice dispersal throughout the lifetime of the SIS (Chap. 10). Similar evidence indicates that an independent ice cap formed and persisted over the Outer Hebrides, feeding ice southwestwards to the shelf edge via the Hebrides Ice Stream (Barra Fan Ice Stream), westwards across the Hebrides Shelf and northeastwards into the Minch Ice Stream (Bradwell and Stoker 2015a; Dove et al. 2015; Callard et al. 2018; Bradwell et al. 2019; Fig. 4.5). Termination of the Barra Fan Ice Stream at the shelf break is indicated by glacimarine deposits on the Barra-Donegal Fan, a major depocentre abutting the Malin Shelf. Farther north on the Hebrides Shelf, however, the ice sheet failed to reach St Kilda, 40–60 km east of the shelf break (Ballantyne et al. 2017; Chap. 9). The maximum reach of the Minch Ice Stream is uncertain: some accounts place its terminus at the shelf edge, but others propose mid-shelf termination (Bradwell and Stoker 2015a; b; Bradwell et al. 2019).

The evolution of ice movement across Caithness, Orkney and Shetland was complex. In Caithness, initial ice flow was northeastwards and was succeeded by: (i) retreat of the ice margin to the north coast; (ii) northwestwards movement of ice from the Moray Firth; (iii) a second retreat of the ice margin from the north coast; and (iv) persistent northwestwards flow of Moray Firth ice towards the Atlantic shelf edge (Hall et al. 2011; Hall and Riding 2016; Merritt et al. 2019; Chap. 8). Analysis of tills on Orkney suggests that initial northwards ice movement was succeeded by northwesterly ice flow across the islands towards the shelf edge (Hall et al. 2016a). Interpretation of the pattern of ice movement on Shetland has polarised around two views: (i) that the archipelago was initially over-ridden by ice moving northwestwards from the North Sea Basin, but later became an independent centre of ice dispersal; and (ii) that Shetland supported an independent ice cap throughout the lifetime of the SIS. Assessment of the field evidence by Hall (2013) supports the second interpretation, as does reconstruction of the pattern of ice retreat in the northern North Sea Basin and across the Orkney-Shetland Platform (Bradwell et al. 2020; Chap. 7).

The pattern of ice flow across eastern Scotland from the Moray Firth to Angus was also complex. From the evidence provided by striae, erratic transport, lithostratigraphy and sequential flowsets, Merritt et al. (2017, 2019) inferred that an initial southeastwards ice flow from the Moray Firth

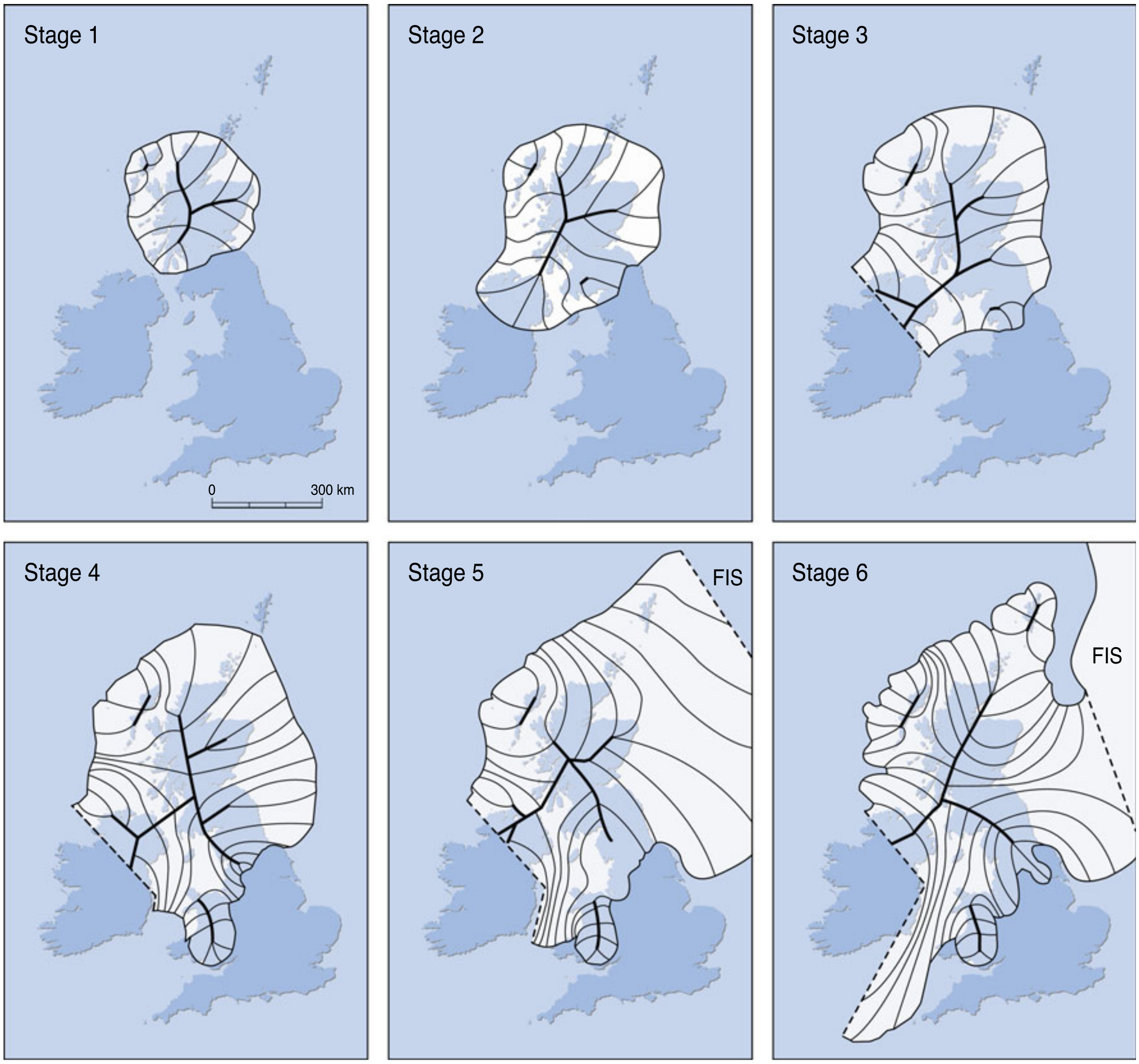

Fig. 4.6 Stages in the growth of the last British-Irish Ice Sheet reconstructed by Hughes et al. (2014). Thick lines represent major ice divides and thin lines represent flowlines interpreted from flowsets and offshore landforms. Smaller centres of ice dispersal are not represented. (Adapted from Hughes et al. (2014) Quat Sci Rev 89:148–169 © 2014 Elsevier Ltd.)

across Buchan was confluent with ice moving eastwards and southeastwards from the Eastern Grampians. At a later stage, ice flowing east from the Moray Firth apparently curved northwestwards across Caithness and Orkney, and ice flow across much of Buchan, Angus and Fife was subsequently dominated by eastwards to southeastwards movement of ice from the Grampians. To explain the switch in the direction of flow of ice from the Moray Firth, Merritt et al. (2017) invoked eastward migration of a major ice divide during ice-sheet build-up, from a westerly axis between Caithness and Shetland, to one in the central part of the northern North Sea Basin, arguing that the latter is necessary to explain northwesterly movement of Moray Firth ice across Caithness and Orkney as the ice sheet expanded.

Radiocarbon ages obtained for marine fauna from sediment cores indicates that all of the central and northern North Sea Basin was over-run by confluence of the SIS with the FIS by ∼27 ka (Hughes et al. 2016). There are, however, conflicting interpretations regarding the position of the suture zone, the location of the major ice divide(s) and the changing directions of ice movement in this region. One interpretation is that a broad ice divide eventually became established between NE Scotland and SW Norway, driving ice movement northwestwards across Caithness and Orkney and southeast towards the southern North Sea Basin (Sejrup et al. 2016; Bradwell et al. 2020; Fig. 4.5). Progressive eastward migration of an ice divide to a similar position (Merritt et al. 2017) represents a refinement of this model with the advantage of explaining the radical shift in the direction of flow of ice emanating from the Moray Firth.

The maximum extent of the BIIS is well-constrained for most sectors (Fig. 4.5), though uncertainties remain regarding the limit of grounded ice west of the Outer Hebrides. The SIS had a complex and shifting surface configuration. The dominant ice centres were those located over the Scottish Highlands, Southern Uplands and over or east of the Orkney-Shetland Platform, but the associated ice divides migrated during ice-sheet expansion, causing shifts in ice-flow directions. Smaller independent centres of ice dispersal (ice domes) persisted over the Outer Hebrides, the Cairngorms, the Galloway Hills and the islands of Skye, Mull and Arran. TCN dating of erratics resting on blockfields on mountains in the NW Highlands, and of tors in the Cairngorms, has demonstrated that the last ice sheet over-topped all of the highest ground in Scotland and that the ice was cold-based and frozen to the underlying substrate over most summits and plateaux (Phillips et al. 2006; Fabel et al. 2012; Hopkinson and Ballantyne 2014). Hughes et al. (2014) calculated that the altitude of the ice divide over northern Scotland must have exceeded ~1400 m and models based on inferred glacio-isostatic depression indicate ice-surface altitudes of up to 2500 m.

The advance of the BIIS to its maximum extent was asynchronous. On the Shetland shelf, the ice sheet probably achieved its maximum extent at ~26–25 ka, and the Minch Ice Stream appears to have reached its limit by ~30.2 ka and was retreating by ~27.5 ka (Bradwell et al. 2019, 2020). The Hebrides Ice Stream reached the Atlantic shelf break at ~26.7 ka and withdrew from the shelf edge by ~25.9 ka (Callard et al. 2018). Advance of the grounded ice margin to its limit west of Ireland occurred after ~24.7 ka. TCN and optically stimulated luminescence (OSL) dating suggest that the southern margin of the Irish Sea Ice Stream impinged on the Scilly Isles at ~26–25 ka (Smedley et al. 2017a), but other evidence suggests that it achieved its maximum southerly reach at the edge of the Celtic Shelf between ~24.3 and ~23.0 ka (Chiverrell et al. 2013). The lobe that extended down the east coast of England may not have achieved its maximum extent until ~21.6 ka (Bateman et al. 2017).

4.4.2 Ice Streams and Ice-Sheet Modelling

Ice streams are corridors of fast-flowing ice that discharge much of the ice from ice sheets. Palaeo-ice streams that drained the SIS have been identified from a range of diagnostic features, notably convergent flow patterns, usually sourced in upland areas, a distinct flow track with well-defined lateral margins and markedly elongate bedforms (Fig. 4.7).

On the basis of such evidence, four east-flowing ice streams that drained the SIS have been identified: the Tyne Ice Stream, which evacuated ice from the Southern Uplands, Cheviots, Lake District and Pennines; the Tweed Ice Stream, which flowed eastwards between the Lammermuir and Cheviot Hills; the Strathmore Ice Stream, which flowed eastwards between the Highland edge and NE Fife; and the Moray Firth Ice Stream, a major artery that drained ice from the Great Glen towards the North Sea Basin (Everest et al. 2005; Golledge and Stoker 2006; Livingstone et al. 2015; Merritt et al. 2017). In the western North Sea Basin, coalescence of ice from the Forth and Tweed valleys (and probably the SE Grampians) fed the North Sea Lobe, a major ice stream that moved southwards along the east coast of England to terminate on the north coast of East Anglia (Busfield et al. 2015; Bateman et al. 2017; Fig. 4.5).

To the west of Scotland, ice from the Galloway Hills fed the Irish Sea Ice Stream, which drained at least 17% of the BIIS and terminated at the edge of the Celtic Shelf (Praeg et al. 2015; Fig. 4.5). Farther north, the Hebrides Ice Stream was fed by ice from the Western Highlands and Hebrides that flowed southwestwards across the Sea of the Hebrides and ice flowing westwards from northern Ireland and SW Scotland (Howe et al. 2012; Finlayson et al. 2014; Dove et al. 2015; Callard et al. 2018). Ice from NW Scotland, Skye and eastern Lewis fed the Minch Ice Stream, which drained an area of 10,000–15,000 km^2 and followed a 40–50 km wide trough that extends northwestwards to terminate at the Sula Sgeir Fan (Bradwell and Stoker 2015a; Bradwell et al. 2019; Fig. 4.8).

It is not known whether the ice streams draining the SIS operated throughout much of its existence or only at particular times. Numerical models of the expansion and contraction of the BIIS driven by a scaled NGRIP oxygen-isotope record indicate that the ice sheet experienced 'binge and purge' cycles, with prolonged phases of thickening of predominantly cold-based ice alternating with 'purge' episodes triggered by rapid warming (Hubbard et al. 2009). These models suggest that purge phases were accompanied by the development of ice streams that drew down the ice-sheet surface over its source areas. The best-fit model of Hubbard et al. (2009) generated transient but recurrent ice streaming at all the Scottish ice-stream locations described above. Ice-stream activation probably played a major role in ice-divide migration on land: rapid evacuation of ice by the Minch Ice Stream, for example, may have driven eastward relocation of the ice divide across much of the Northern Highlands.

4.4.3 Deglaciation of the Offshore Shelves

The pattern of deglaciation on the shelves adjacent to Scotland has been reconstructed from bathymetric data depicting seafloor moraines and grounding-zone wedges, complemented by acoustic profiles of sediment facies and depths (Bradwell et al. 2008a, 2020; Clark et al. 2012;

Fig. 4.7 Megagrooves in the onset zone of the Tweed Ice Stream. Ice flow was from bottom left (west) to top right. (Image: Google Earth™)

Bradwell and Stoker 2015b; Callard et al. 2018; Fig. 4.9; Chap. 6). The offshore moraines delimit readvances that interrupted ice-margin retreat and the grounding-zone wedges represent locations where retreat of grounded ice margins slowed, paused or oscillated, depositing thick ridges of sediment, often tens of kilometres long and sometimes several kilometres wide.

For the three major ice streams that drained ice from the southwest and west of Scotland, the timing of ice-margin retreat is constrained by radiocarbon ages of shell fragments and foraminifera in sediment cores, complemented by TCN and OSL ages from terrestrial sites. Rapid retreat of the Irish Sea Ice Stream after ~24 ka (Smedley et al. 2017b) slowed as the ice margin became pinned against the Isle of Man in the northern Irish Sea Basin at ~20.8–20.2 ka (Chiverrell et al. 2018). Within the interval 19.3–18.3 ka, retreat was interrupted by a readvance of ice from the Solway Firth (the Scottish Readvance), after which the ice margin underwent oscillatory retreat towards its sources in the Galloway Hills of SW Scotland, where TCN ages record deglaciation at ~15.2 ka (Ballantyne et al. 2013). Retreat of the Hebrides Ice Stream was underway by ~25.9 ka, the outer Hebrides Shelf was ice-free by ~23.2 ka and glacimarine conditions were present in the Sea of the Hebrides by ~20.2 ka (Callard et al. 2018). Thereafter, retreat slowed as streaming behaviour ceased and the ice margin oscillated over a ~3 ka period: Barra was deglaciated at ~17.1 ka, south Harris by ~17.3 ka, southern Skye at ~17.6 ka, SW Mull at ~17.5 ka and western Jura at ~16.6 ka (Small et al. 2017; Fig. 4.10). The chronology of retreat of the Minch Ice Stream is based mainly on TCN exposure ages and inferred connections with a sequence of 17 grounding-zone wedges that straddle The Minch and the trough followed by the ice stream towards the shelf edge (Bradwell et al. 2019). TCN ages from North Rona suggest that retreat of the ice margin was underway before ~27.5 ka and by ~23.3 ka the ice margin lay at the northern exit of The Minch. After ~18.5 ka, retreat was apparently

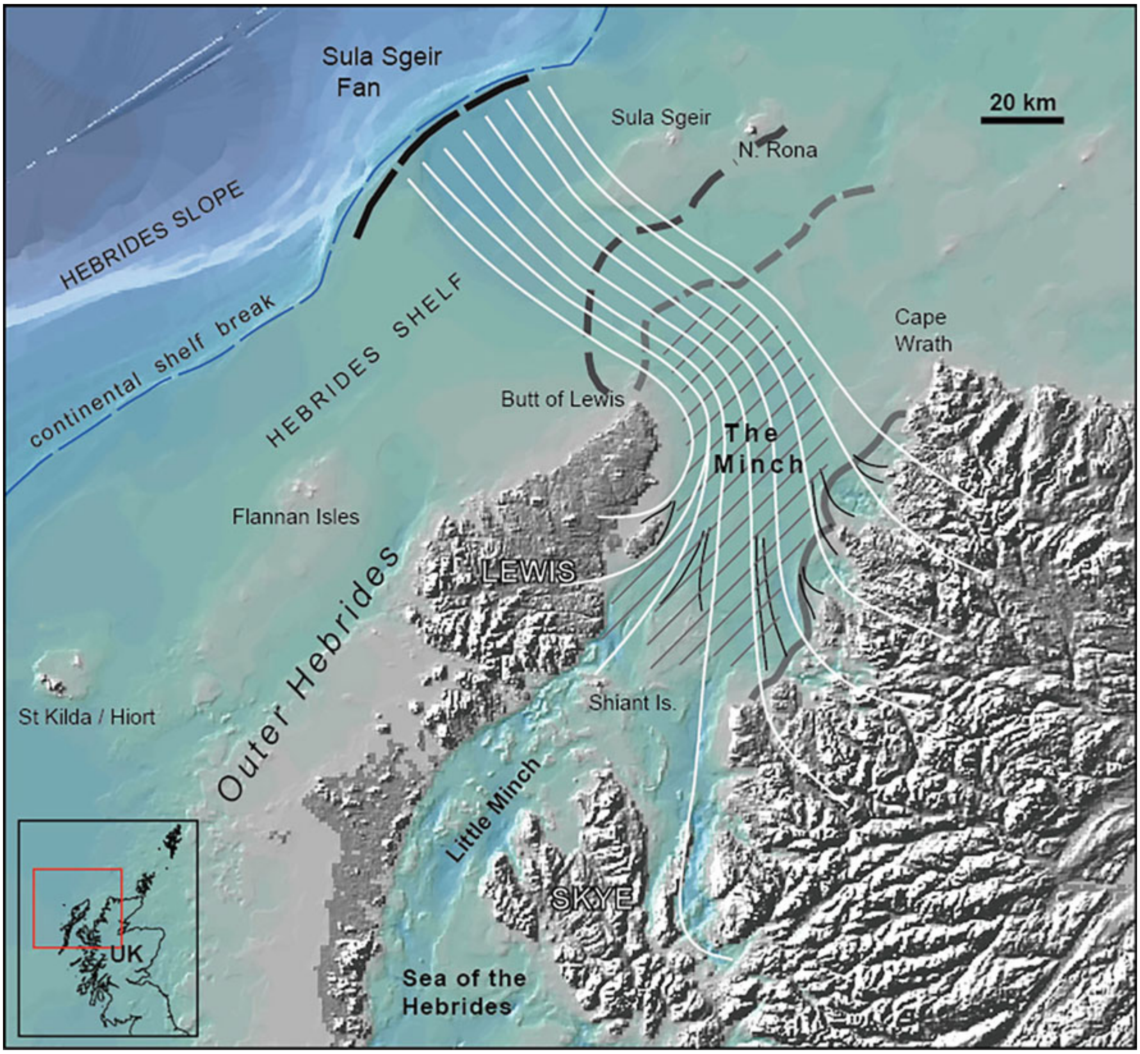

Fig. 4.8 The track of the Minch Ice Stream. White lines are ice-stream flowlines, the thick lines are terminus positions and the hatching indicates an area of streamlined subglacial bedforms and iceberg scours. (From Ballantyne and Small (2019) Earth Env Sci Trans R Soc Edinb 110:93–131 © 2018 The Royal Society of Edinburgh)

accelerated by opening of a calving bay east of the Outer Hebrides, before the ice margin became grounded on Skye and much of the northwest mainland by 16.2–15.4 ka.

The retreat of all three western ice streams therefore occurred under stadial conditions prior to the onset of the Lateglacial Interstade (~14.7 ka) and may have been initiated by enhanced calving losses at marine-terminating ice margins due to rising relative sea levels caused by glacio-isostatic depression of the shelf. Rates of ice-stream retreat were also affected by subglacial topography, accelerating over reverse bed slopes and in deep troughs or basins, and slowing at topographic constrictions. Bradwell et al. (2019) also associated accelerated retreat of the Minch Ice Stream after ~18.5 ka with a change from a 'soft' sediment-covered bed to a 'hard' bed underlain mainly by bedrock.

North of the Scottish Mainland, the pattern of seafloor moraines implies progressive decoupling of mainland ice from a major ice cap centred on the Orkney-Shetland Platform (Bradwell and Stoker 2015b; Bradwell et al. 2020; Fig. 4.9). TCN exposure ages averaging ~23.8 ka for Cape Wrath date the onset of decoupling, and others averaging ~17.5 ka for Dunnet Head on the north coast of Caithness suggest prior severance of the Orkney-Shetland ice centre from the mainland (Fig. 4.10). TCN ages suggest deglaciation of Orkney by ~16.5 ka, isolation of the remnant Shetland ice cap by ~17.0–16.5 ka and complete deglaciation of Shetland within the period 16.5–15.0 ka (Phillips et al. 2008; Bradwell et al. 2020).

Two scenarios have been proposed for severance of the SIS from the FIS in the North Sea Basin. Several accounts suggest that this occurred through southwards extension of a

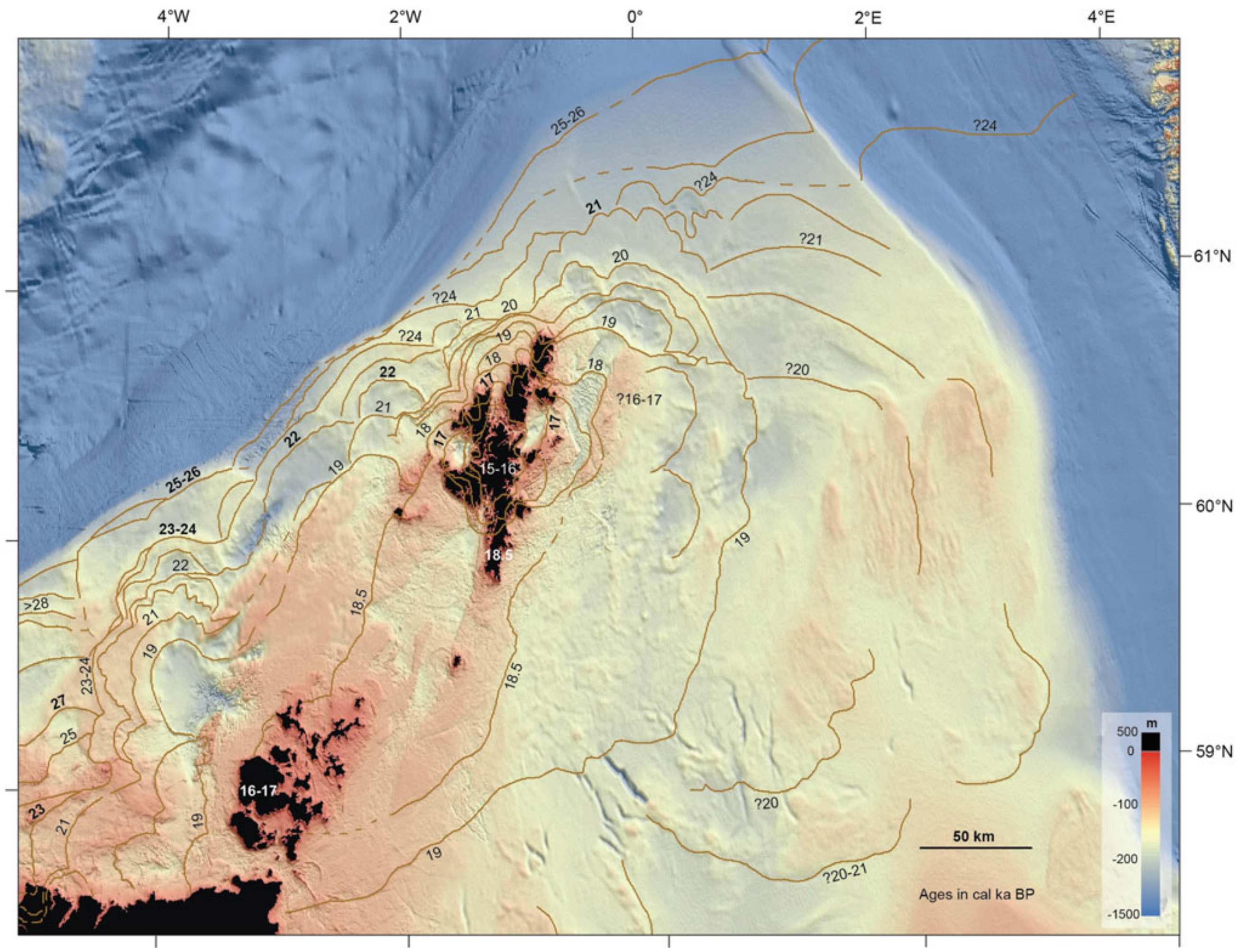

Fig. 4.9 Reconstruction of the pattern and timing of deglaciation in the northernmost sector of the last Scottish Ice Sheet. Ice margin positions (brown lines) are based on the available geomorphological and geological evidence and the numbers are ages (ka). The bold numbers represent the most securely dated ice-margin positions. (From Bradwell et al. (2020) J Quat Sci doi:10.1002/jqs.3163 © The authors)

marine embayment from the shelf edge north of Shetland (Bradwell et al. 2008a; Clark et al. 2012; Merritt et al. 2017). Sejrup et al. (2016) have argued that rapid retreat of the Norwegian Channel Ice Stream (the dominant routeway discharging ice northwards off the west coast of Norway) resulted in decoupling of the two ice sheets at ~18.5 ka and was followed by an eastward readvance of Orkney-Shetland ice. Bradwell et al. (2020) inferred earlier (~23–21 ka) severance of the SIS from the FIS in this sector and subsequent major expansion of the ice cap centred on the Orkney-Shetland Platform. Farther south in the North Sea Basin, there is evidence for at least two later readvances of Orkney-Shetland or Moray Firth ice, at ~17.5 ka and ~16.2 ka (Sejrup et al. 2015). Moraine ridges and grounding-zone wedges indicate oscillation of the margin of Moray Firth ice during its subsequent retreat (Graham et al. 2009).

4.4.4 Deglaciation of Western Scotland

Multiple TCN and radiocarbon ages permit the pattern and timing of deglaciation to be established for western Scotland. The timing of deglaciation at key sites on the Scottish Mainland and the Hebrides is summarized in Figs. 4.10 and 4.11.

In NW Scotland, TCN exposure ages indicate that the ice margin had retreated to the fjords and peninsulas of the west coast by ~16.5–16.0 ka and that mountain summits had emerged from the downwasting ice sheet by ~16.0 ka (Fabel et al. 2012); recessional moraines on the floors of fjords indicate oscillatory retreat of the ice margin in this area (Stoker et al. 2006). Retreat of the ice margin across land was interrupted by the Wester Ross Readvance, which is represented by moraines that can be traced across the peninsulas of Wester Ross from Applecross to Achiltibuie.

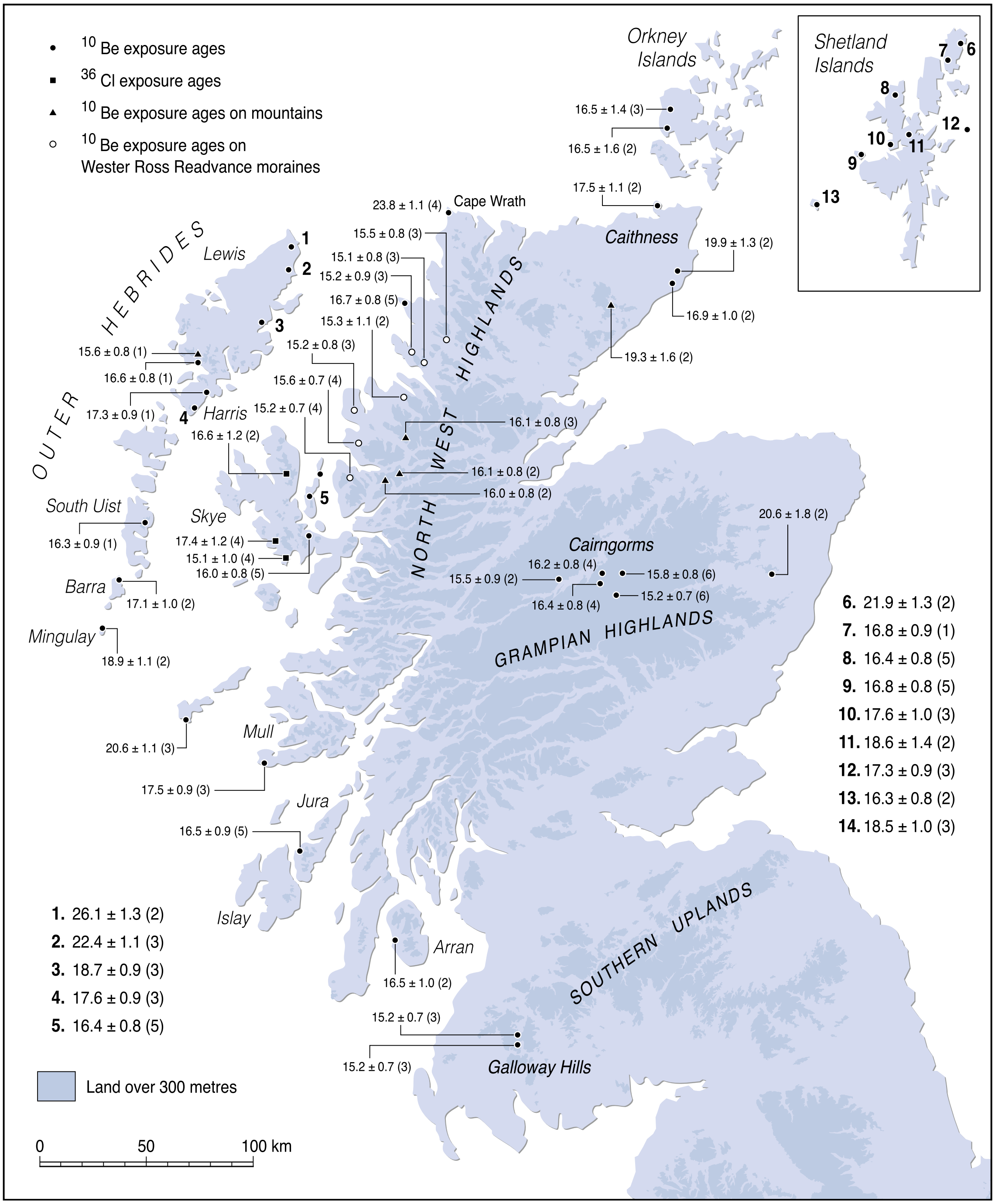

Fig. 4.10 Terrestrial cosmogenic nuclide exposure ages indicating the timing of deglaciation. The dates shown represent uncertainty-weighted means. Statistical outliers are excluded. Each age is followed by the full ($\pm$ 1σ) uncertainty and the number of individual ages in the sample is shown in brackets. (Based on Ballantyne and Small (2019) Earth Env Sci Trans R Soc Edinb 110:93–131 © 2018 The Royal Society of Edinburgh, updated from Bradwell et al. 2019, 2020)

TCN ages for these moraines indicate that the readvance occurred at 15.3±0.7 ka (Ballantyne and Stone 2012; Ballantyne and Small 2019), possibly in response to cooling evident in the Greenland ice-core oxygen isotope record that culminated at ~15.7–15.3 ka (Fig. 4.11; Chap. 13). Similarly, moraines on the island of Soay that delimit a readvance of the Skye ice cap have yielded a mean TCN age of ~15.2 ka, suggesting that the associated readvance (the Loch Scavaig Readvance) also represents a response to cooling at this time (Small et al. 2016; Chap. 10). South of Skye, the margin of mainland ice had backstepped from most of the Inner Hebrides by ~16.0 ka, by which time the westernmost mainland peninsulas and mountain summits were emerging from the retreating ice sheet (Small et al. 2017). By ~15.0 ka, mainland ice had probably retreated from the coastline of western Scotland, but the subsequent deglacial history of this zone cannot be traced, as the fjords and valleys of western Scotland were reoccupied by glaciers during the Loch Lomond Stade.

The pattern of deglaciation in the Firth of Clyde and adjacent areas has been reconstructed by Finlayson et al. (2010, 2014), who inferred that at ~16.5 ka all of this region was still covered by ice flowing down the Firth of Clyde to impinge on NE Ireland, where there is evidence of a readvance of Scottish ice (the East Antrim Coastal Readvance) sometime after ~17.3–16.6 ka (Ballantyne and Ó Cofaigh 2017). Subsequent retreat resulted in decoupling of Highland and Southern Uplands ice and deglaciation of much of Ayrshire, though a glacier fed by ice from the SW Highlands continued to occupy the Firth of Clyde. The timing of retreat of the Clyde glacier is uncertain, but the inner Clyde estuary and the Glasgow area were almost certainly deglaciated by ~14.7 ka, at the onset of the Lateglacial Interstade (Peacock et al. 2012).

4.4.5 Deglaciation of Eastern and Southern Scotland

During ice-sheet retreat, northwestwards flow of ice from the Moray Firth across Caithness was succeeded by northeastwards ice movement from the mountains of Sutherland (Hall and Riding 2016). TCN ages obtained for sites in Caithness are inconsistent (Fig. 4.10), but the balance of evidence suggests that retreat of Moray Firth ice occurred within the period 17.5–17.0 ka and was succeeded by eastwards expansion of ice from high ground across western Caithness.

In NE Scotland there was major reorganization of ice flow during the period 22–19 ka: ice flowing eastwards from the Grampians and Cairngorms appears to have met ice flowing southeast from the Moray Firth and ice flowing northeastwards from Strathmore. Merritt et al. (2017) concluded that initial deglaciation on land occurred close to the confluence of these three ice masses near Peterhead, where radiocarbon dating of a shell in raised marine silts indicates deglaciation prior to ~17.7 ka. There is evidence for readvances of Moray Firth ice near Elgin and Inverness before the ice front retreated into Loch Ness, then open to the sea (Chap. 15). Recessional moraines in northern Loch Ness indicate punctuated retreat of a grounded ice margin, followed by deposition of a large moraine midway down the loch (Turner et al. 2012).

The timing of deglaciation of the eastern coast of Scotland is controversial. Radiocarbon ages for foraminifera in raised marine muds near Montrose imply very early deglaciation (21–20 ka; McCabe et al. 2007) but are at variance with other evidence indicating much later deglaciation (Ballantyne and Small 2019). Radiocarbon dating of marine shells in ice-proximal estuarine sediments implies deglaciation of the Firth of Tay shortly before ~16.3 ka (Peacock 2003). There is stratigraphic evidence that retreat of the Tay glacier was interrupted by a readvance (the Perth Readvance), though the timing and extent of this event are uncertain. In the eastern Highlands, TCN exposure ages for boulders on moraines indicate retreat of Strathspey ice along the northern flank of the Cairngorms within the period ~16.5–15.5 ka (Hall et al. 2016b; Chap. 18) and are consistent with TCN and radiocarbon ages indicating retreat of ice to the upper Spey valley by ~15.5 ka (Ballantyne and Small 2019; Fig. 4.10).

The timing of ice retreat in southern and SE Scotland has not been established, though a TCN deglaciation age of ~15.2 ka obtained for the Galloway Hills (Ballantyne et al. 2013) suggests that much of the Southern Uplands was deglaciated by that time. Radiocarbon ages from sites near Callander on the Highland boundary imply that all of the central and eastern Midland Valley was deglaciated before ~15.2 ka (Fig. 4.11).

4.4.6 Ice-Sheet Demise

The Greenland ice-core oxygen isotope record provides evidence for rapid warming at ~14.7 ka, the start of the Lateglacial Interstade in Scotland. This warming is captured by subfossil chironomid assemblages at various sites; these indicate a rapid rise in mean July temperatures to 11–13 °C early in the interstade (Brooks and Birks 2000; Brooks et al. 2012, 2016; Fig. 4.11). Rapid warming at this time is generally attributed to northward migration of the North Atlantic Polar Front, resumption of thermohaline circulation in the NE Atlantic and increased penetration of warm airmasses across Scotland.

The chronological evidence outlined above and in Figs. 4.10 and 4.11 suggests that by 15.0–14.7 ka, remnants of the SIS were confined to the Western Grampians and NW Highlands, and thus lay within the limits of the glaciers that formed in Scotland during the Loch Lomond Stade. There has been recurrent debate as to whether glacier ice persisted in the Scottish Highlands during the Lateglacial Interstade (~14.7–12.9 ka). Definitive evidence is elusive. The modelling experiments of Hubbard et al. (2009) suggest that limited ice cover may have survived interstadial warming in the western Highlands and Finlayson et al. (2011) have argued that a thin ice cap survived the interstade on the Beinn Dearg massif in the NW Highlands. Conversely, the TCN ages of erratics on summits in Wester Ross demonstrate that these mountains became ice-free at ~16.0 ka and remained so until the present (Fabel et al. 2012). Ice-rafted debris in a

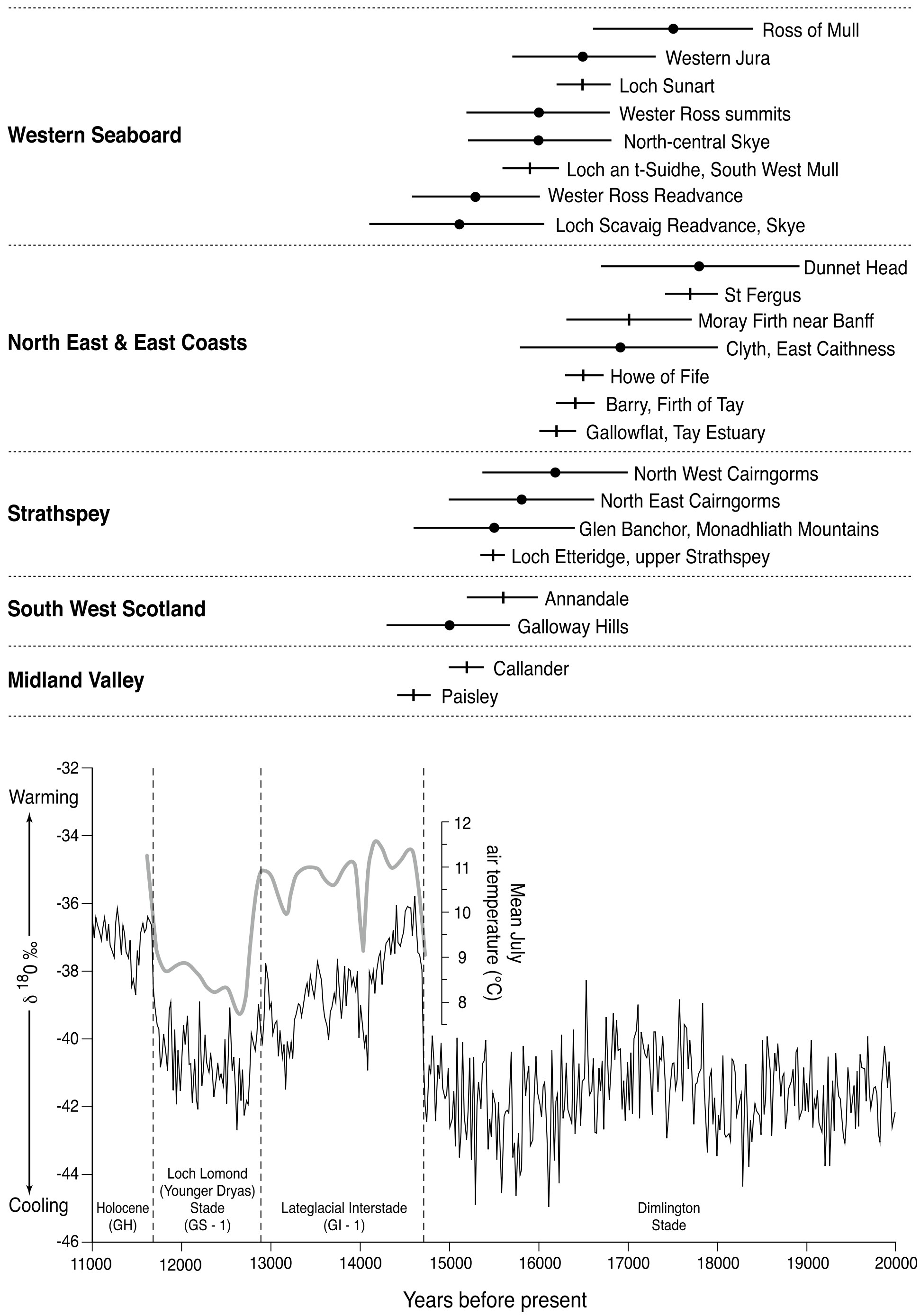

Fig. 4.11 Key TCN and calibrated radiocarbon ages constraining the deglaciation of mainland Scotland and the Inner Hebrides, plotted above the NGRIP ice-core δ^{18}O record for 20–11 ka (Rasmussen et al. 2014) and mean July temperatures inferred from chironomid assemblages in SE Scotland (Brooks and Birks 2000). Dots are TCN ages and vertical dashes are radiocarbon ages; horizontal lines are $\pm 1\sigma$ uncertainties. TCN ages represent the approximate timing of deglaciation; radiocarbon ages are minimal for the timing of deglaciation. (From Ballantyne and Small (2019) Earth Env Sci Trans R Soc Edinb 110:93–131 © 2018 The Royal Society of Edinburgh)

core from the Hebrides shelf has been dated to ~14.1–13.9 ka, but it is uncertain whether this is of distal (Laurentian) provenance or whether it indicates marine-terminating glaciers in the western Highlands at this time (Small et al. 2013a; b). Given the rapid warming at the onset of the Lateglacial Interstade, it is likely that glaciers occupying the glens and fjords of the Highlands experienced rapid retreat after ~14.7 ka. Survival of high plateau ice caps and cirque glaciers throughout the interstade is possible but remains to be conclusively demonstrated.

4.5 The Loch Lomond Stade (~12.9–11.7 ka) and Loch Lomond Readvance

The Loch Lomond Stade (LLS) is the Scottish equivalent of the Younger Dryas chronozone or Greenland Stadial 1; the term Loch Lomond Readvance (LLR) refers to the growth and culmination of glaciers in Scotland during this period. The stratotype for the LLR is near the southern end of Loch Lomond, where organic detritus radiocarbon-dated to 12.1–11.9 ka is overlain in succession by glacilacustrine deposits, till deposited by a glacier that advanced over the site, then glacifluvial or deltaic sediments deposited during subsequent glacier retreat (MacLeod et al. 2011).

The return of stadial conditions was rapid. Evidence provided by Lateglacial chironomid assemblages implies that mean July sea-level temperatures at the beginning of the Lateglacial Interstade reached ~11–13 °C, then experienced a slight overall decline, punctuated by centennial-scale cold excursions (Brooks et al. 2012, 2016; Fig. 4.11). The onset of the LLS was marked by a fall in mean July temperatures on low ground to ~6.0–8.5 °C. This rapid cooling was caused by disruption of Atlantic meridional overturning circulation (AMOC) and consequent southwards migration of the oceanic polar front, so that polar waters returned to the shores of the British Isles and warm airmasses followed a more southerly trajectory. Disruption of AMOC probably resulted from an influx of freshwater into the North Atlantic Ocean though its source remains contentious (Carlson 2010; Carlson and Clark 2012).

Permafrost features of LLS age in England and Ireland imply that mean annual air temperatures (MAATs) during the coldest part of the stade fell to, or slightly below, −4 to −6 °C (Ballantyne 2018), implying that sea-level MAATs in Scotland during the thermal nadir of the LLS were no higher than about −6 °C to −8°C and mean January temperatures lay within the range –18 to –14 °C, a regime similar to that of present-day Svalbard. The chironomid record for three sites in Scotland suggests that the coldest summer temperatures occurred near the beginning of the stade and were succeeded by gradual, oscillatory warming of 1–2 °C, then rapid warming at the Lateglacial–Holocene transition; the record for a fourth site (on Skye), however, suggests a cooling trend during the LLS that may reflect the proximity of glacier ice.

The extent of the LLR has been determined through mapping of moraines, drift limits, trimlines and meltwater channels, and directions of ice flow have been reconstructed from striae, roches moutonnées, streamlined bedrock outcrops, erratic transport and fluted moraines. Moreover, occupancy of upland terrain by LLS glaciers is often represented by glacial landsystems that differ radically from those outside the LLR limits, which are often dominated by soliflucted till deposits, outwash terraces and relict periglacial landforms (Lukas 2006; Sects. 4.6 and 4.7).

The evidence for the extent of the LLR has been comprehensively summarised by Bickerdike et al. (2016, 2018a). The largest ice mass, the West Highland Icefield (or West Highland glacier complex) straddled the main Highland drainage divide, had a maximum altitude of ~900 m and fed large outlet glaciers westwards into the fjords of western Scotland, southwards to occupy Loch Lomond and the upper Forth valley and eastwards across Rannoch Moor and the eastern glens of the Northern Highlands (Fig. 4.12). Flanking the West Highland Icefield were satellite icefields on Mull and Skye, the mountains of Sutherland, west Drumochter Hills and Eastern Grampians, as well as ice caps on the Beinn Dearg massif and the Monadhliath and Gaick plateaux (Chaps. 10, 12, 13 and 20) and the Tweedsmuir Hills in the Southern Uplands (Chap. 27). Many mountain areas from Orkney in the north to the Galloway Hills in the south and Cairngorms in the east also supported small cirque or valley glaciers; more than 100 small independent glaciers formed in Scotland during the LLS.

Few LLR limits have been dated directly, but the contrasting stratigraphy of sites inside and outside the mapped limits of the readvance has provided evidence for assigning a LLS age (Walker and Lowe 2019) and the radiocarbon ages of basal organic sediments inside mapped readvance limits constrain the timing of subsequent deglaciation (e.g. MacLeod et al. 2011). Such stratigraphic evidence has been supported by the identification of distinctive microscopic shards of volcanic ash in Lateglacial and Early Holocene deposits, notably the Borrobol (~14.1 ka) and Penifiler (~13.9 ka) tephras of Lateglacial Interstadial age, the Vedde Ash (~12.0 ka) of LLS age and the Early Holocene Abernethy tephra (~11.5 ka) and Askja-S tephra (~10.8 ka). Collectively, these represent robust stratigraphic markers for dating deposits relating to the Last Glacial-Interglacial Transition (Timms et al. 2019). At a few sites, the LLS age of readvance moraines has been confirmed by radiocarbon dating of marine shell fragments within morainic deposits (Bromley et al. 2018).

TCN dating of boulders or bedrock surfaces has also been used to confirm a LLS age for mapped readvance limits (e.g. Finlayson et al. 2011; Small et al. 2012). The imprecision inherent in TCN dating, however, has made it difficult to pinpoint the timing of the culmination of the readvance or that of subsequent deglaciation, though TCN ages obtained for boulders on moraines suggest that some glaciers reached their maximum extent before 12.4–12.1 ka (Ballantyne 2012; Ballantyne et al. 2016). Numerical modelling of the expansion and contraction of LLS glaciers based on Greenland ice-core data suggests that icefields in northern Scotland, Mull and Skye reached their terminal limits early

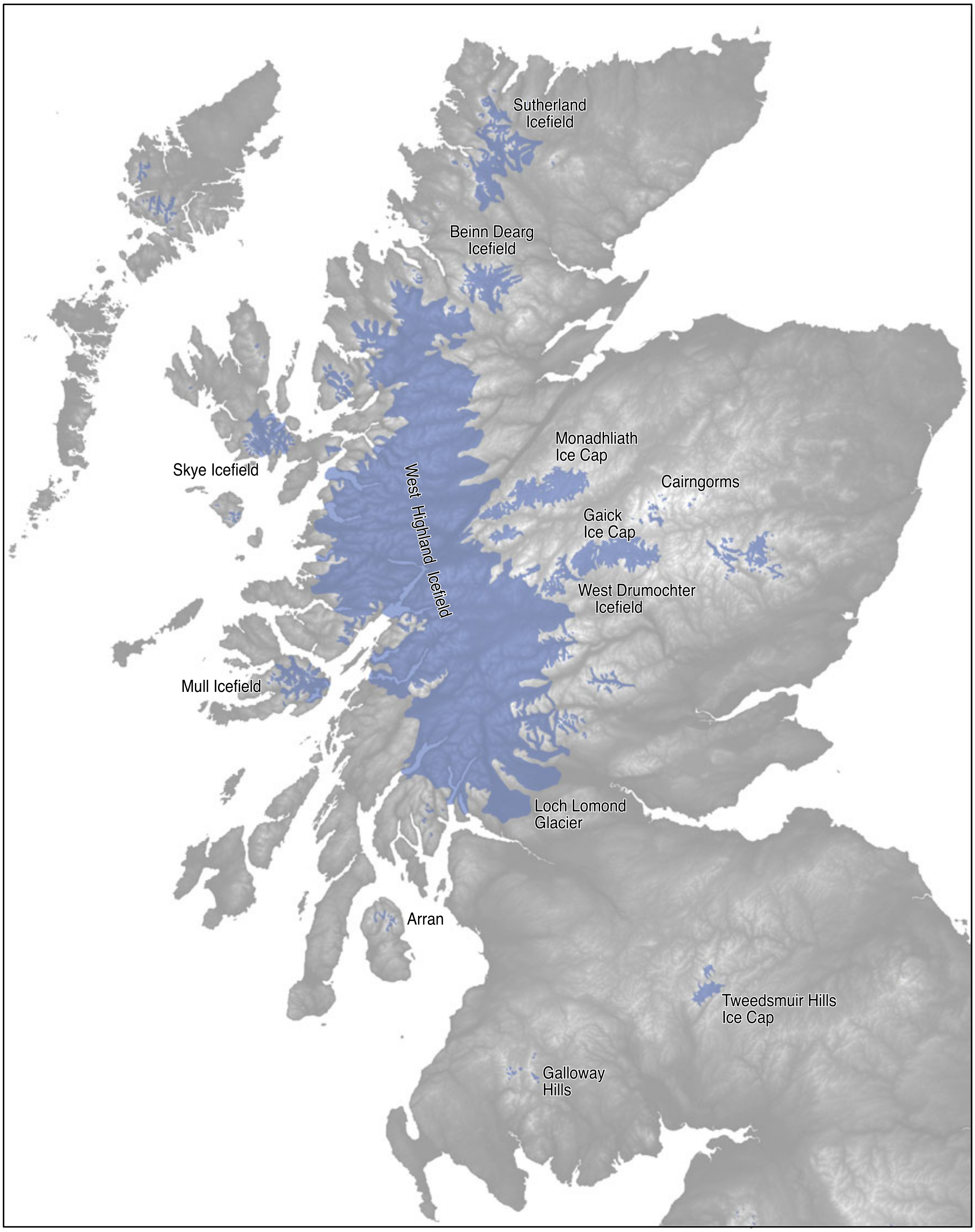

Fig. 4.12 The mapped extent of the Loch Lomond Readvance in Scotland. Numerous summits protruded through the West Highland Icefield as nunataks but are not shown. Recent research has shown that the Gaick Ice Cap was smaller than depicted here (Chandler et al. 2019) and that some glaciers in parts of the southern and SE Grampians were more extensive (Ballantyne unpublished). (From Ballantyne (2019a) Scotland's mountain landscapes: a geomorphological perspective. © 2019 Dunedin Academic Press)

in the LLS ($\sim$12.7–12.6 ka) and that most outlet glaciers of the West Highland Icefield achieved their maximum extent by $\sim$12.5 ka (Golledge et al. 2008). This suggestion must be treated with caution, however, because of disparities between the ice-core record and the summer temperature record inferred from chironomid assemblages, particularly for the final centuries of the Lateglacial Interstade (Fig. 4.11). Early culmination of the LLR has also been advocated by Bromley et al. (2014, 2018) on the basis of radiocarbon dates obtained for marine shells incorporated within coastal moraines and minimum (deglacial) ages obtained for basal organic deposits near the centre of the West Highland Icefield. From these ages they concluded that the West Highland Icefield reached its maximum extent between ~12.8 ka and ~12.6 ka and that subsequent glacier retreat was driven by warming summers, but the validity of their radiocarbon ages has been contested (Lowe et al. 2019). Moreover, their conclusions conflict with: (i) TCN ages indicating deglaciation of Rannoch Moor at ~11.5 ka (Small and Fabel 2016); (ii) a tightly-constrained radiocarbon- and varve-based chronology established for advance and retreat of the southernmost outlet glacier of the West Highland Icefield (MacLeod et al. 2011); and (iii) a varve-based chronology proposed for the glacial lakes dammed by the ice margin in Glen Roy and vicinity (Palmer et al. 2010, 2020). These studies indicate that glacier advance continued until near the end of the LLS and that extensive ice masses persisted (at least locally) until the LLS-Holocene transition (~11.7–11.6 ka). It seems likely that though some small glaciers and icefields culminated in mid-stade at ~12.5–12.4 ka, some of the outlet glaciers of the West Highland Icefield continued to expand until near the end of the LLS.

The abundant geomorphological evidence for the lateral and vertical extent of some LLS glaciers and icefields has permitted contoured reconstructions of their dimensions (e.g. Benn and Ballantyne 2005; Ballantyne 2007a, b; Finlayson et al. 2011; Boston et al. 2015; Chandler and Lukas 2017; Chandler et al. 2019; Fig. 4.13). Equilibrium line altitudes (ELAs) calculated from these reconstructions show two trends: a northwards decrease in ELAs along the west coast from SW Scotland to Lewis (Ballantyne 2007a) that probably represents a northward decline in ablation-season temperatures; and a pronounced eastward rise in ELAs across the Highlands (from 250 m on Mull and 277 m on Skye to 714 m in the Monadhliath Mountains, 751 m on the Gaick plateau and 918 m in the Cairngorms). The latter trend represents an eastwards reduction in LLS snowfall due to the snow-scavenging effects of the West Highland Icefield on westerly airmasses, so that mountains east of the icefield experienced relative aridity (Sissons 1979). Estimating the associated trends in mean annual precipitation (MAP) is difficult, as estimates are strongly influenced by seasonality (Golledge et al. 2010), but by assuming a 'neutral' estimate and mean July sea-level temperature of 8.5±0.3 °C, Chandler et al. (2019) calculated that sea-level MAP exceeded 2000 mm a^{-1} across much of the Hebrides, declining eastwards to <600 mm a^{-1} near the Cairngorms.

4.6 Late Devensian Glacial Landsystems

4.6.1 Glacial Landsystems Associated with Ice-Sheet Retreat

In upland areas of Scotland, major glacial erosional landforms (cirques, glacial troughs, glacial breaches, rock basins, fjords and landscapes of glacial scouring) are the products of multiple episodes of Pleistocene glaciation and it is likely that the last ice sheet accomplished only slight modification of pre-existing erosional features (Sect. 4.2.3). Similarly, the erosional features of the lowlands, such as glacially-steepened scarps and crag-and-tail features, are pre-existing landforms only slightly modified by the last ice sheet. Late Devensian glacial landsystems are therefore represented mainly by glacigenic deposits, depositional landforms and minor erosional landforms superimposed on glaciated landscapes of essentially pre-Late Devensian age.

In most areas, the glacial landsystems (landform-sediment assemblages) that formed during the advance and retreat of the last ice sheet differ strikingly from those associated with the LLR. In lowland areas outside the limits of the LLR, such as much of the Midland Valley, the Solway lowlands and the lower Tweed valley, the landscape is dominated by till sheets locally overlain by outwash deposits, the latter now extensively terraced and quarried for sand and gravel extraction. In many parts of the Midland Valley the till sheets form gently undulating expanses of sediment that blanket the underlying bedrock, burying the rockhead topography except where igneous outcrops protrude through the sediment cover (Fig. 4.3d). Though the lowland till sheets are barely a metre thick in places, glacigenic sediments infilling palaeovalleys in parts of the Forth and Clyde basins reach depths of over 50 m (Kearsey et al. 2019). The deepest deposits in lowland areas of Scotland are locally pre-Late Devensian in age, but the uppermost tills and overlying glacifluvial sediments were deposited by the last ice sheet, although probably containing sediment reworked from earlier glacial deposits (Merritt et al. 2019). High-resolution digital elevation imagery reveals that in many areas the till sheets form broad swells and depressions aligned in the direction of former ice movement. In some areas these grade into drumlin fields or ribbed moraine, notably those of the Glasgow region in west-central Scotland, which record southeastward then eastward movement of the last ice sheet from the SW Highlands towards the Forth valley (Rose and Smith 2008; Finlayson et al. 2010; Chap. 26) and those in the Solway and Galloway lowlands (Chap. 28). In the Tweed valley, eastward-aligned drumlins, megadrumlins and megaflutes represent bedforms in the

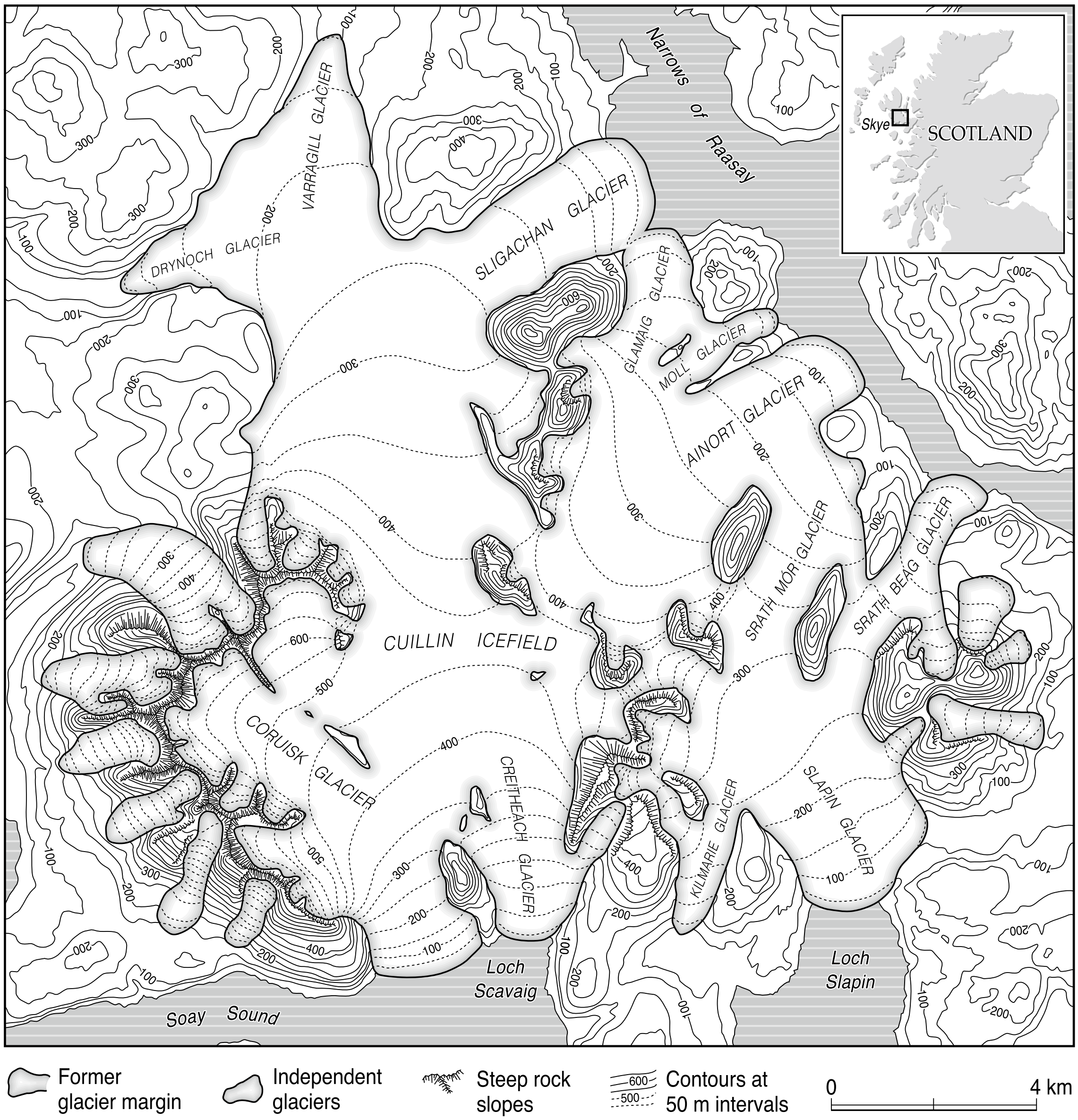

Fig. 4.13 Contoured reconstruction of the Loch Lomond Readvance glaciers that occupied the mountains of south-central Skye. (Adapted from Ballantyne (1989) J Quat Sci 4:95–108 © 1989 Longman Group UK Ltd.)

onset zone of the Tweed Ice Stream (Everest et al. 2005) and in Strathmore, streamlined bedforms and bedrock outcrops define the track of the ice stream that flowed eastwards between the Highland boundary and Fife (Golledge and Stoker 2006).

Throughout lowland Scotland, there is abundant evidence that vigorous meltwater activity accompanied ice-sheet retreat. Networks of meltwater channels mark the routeways of former subglacial and proglacial meltwater channels, some of which are now occupied by underfit streams, whilst others form dry valleys. Numerous meltwater channels aligned obliquely across hillslopes record the locations of ice-marginal and submarginal meltwater flow as the last ice sheet retreated (Evans et al. 2017) and some connect with subglacial esker systems (Chaps. 15 and 25). Deposition of sediment by proglacial meltwater rivers is represented by outwash plains of stratified sands and gravels, particularly in the Moray Firth coastlands, Strathmore, Fife, the Lothians, upper Clyde valley and lower Nith valley; many form flat sandur plains, others form mounds and depressions due to melt-out of buried ice and some have been terraced by later fluvial incision. Where tributary meltwater streams discharged into main valleys, large outwash fans were deposited that merge with sandur plains (Marren 2001) and large palaeosandar composed of coarse, bouldery outwash sediments indicative of high palaeo-discharges accumulated along the Highland boundary in eastern Scotland (Russell 2019). Readvance and recessional moraines are rarely represented in the lowland glacial landsystem, though discontinuous moraine systems are present in the western Midland Valley and Moray Firth coastlands (Finlayson et al. 2010; Merritt et al. 2017, 2019).

The characteristic glacial landsystems of upland areas outside the limits of the LLR, notably the Eastern Grampians and Southern Uplands, are dominated by two elements: thin deposits of till, smoothed by Lateglacial solifluction, that mantle lower slopes; and valley-fill deposits of till, often overlain by thick outwash deposits, as in major upland valleys such as those of the Spey, Dee and Tweed and the glens of the Eastern Grampians. The evidence of powerful meltwater activity as the last ice sheet downwasted is also evident in the form of high-level meltwater channels cut across cols and along hillslopes, and kame terraces stranded high above valley floors (Brazier et al. 1998; Hall et al. 2016b). Most river terraces in this zone are outwash terraces that represent abandoned proglacial sandur surfaces. Such terraces typically occur up to 30 m above present floodplains, are underlain by stratified sands and gravels and support a microtopography of braided palaeochannels; the highest terraces are often pitted with kettle holes, confirming a glacifluvial origin (Robertson-Rintoul 1986; Aitken 1998; Chap. 20). During ice-sheet retreat, large outwash fans developed at the confluence of major upland rivers and at the mouths of tributary valleys, where they grade into the highest outwash terraces (Werritty and McEwen 1997). Such fans often exceed 500 m in width but have been incised and terraced by postglacial rivers. As in lowland areas, there is limited morphological evidence for ice-margin oscillations or readvances. The main exceptions are the moraines delimiting the Wester Ross Readvance ($\sim$15.3 ka) in NW Scotland and the Loch Scavaig Readvance ($\sim$15.2 ka) on Skye (Sect. 4.4.4), together with evidence for readvance of the ice margin in Strathspey and along the northern flanks of the Cairngorms at $\sim$15.8 ka (Hall et al. 2016b).

4.6.2 Glacial Landsystems of the Loch Lomond Readvance

The landsystems associated with the LLR are typically dominated by glacial rather than glacifluvial landforms. The lateral extent of LLS glaciation is often represented by end and lateral moraines, or by the downvalley extent of glacially-deposited boulders, recessional moraines or thick till deposits (Fig. 4.14). On high ground, the extent of readvance glaciers is locally defined by the upper limit of gullied till or by trimlines. Many upland valleys within the LLR limits are occupied by hummocky moraines in the form of mounds and ridges up to $\sim$30 m high (Fig. 4.14d). Although some of these represent drumlinoid bedforms or ice-stagnation landforms (Benn 1992), most are recessional moraines, many of which originated as ice-contact fans that were modified by ice push and subglacial deformation as ice margins experienced multiple short-lived advances during overall active retreat (Benn and Lukas 2006; Chandler et al. 2020).

Bickerdike et al. (2018b) identified five LLR landsystems. The most widespread of these is the alpine icefield landsystem, which is typical of most of the West Highland Icefield as well as the smaller icefields of Mull, Skye and Sutherland (Fig. 4.15). During the LLS, these areas supported transection glacier complexes, overlooked by nunataks and fed by ice nourished in cirques; directions of ice flow were constrained by topography, along troughs and across cols. The former altitudinal limits of these icefields are marked by trimlines or drift limits that are locally continued downvalley by lateral moraines deposited at the margins of outlet glaciers. End moraines sometimes mark the former termini of icefield outlet glaciers, but in many locations their lateral extent is represented by the outer limit of hummocky recessional moraines.

In the Western Grampian Highlands, however, the ice cover thickened to an altitude of about 900 m, forming a broad dome that covered all but the highest summits. This area contains an ice-cap landsystem characterized by topographically-discordant glacier flow away from the ice centre across cols and locally transverse to the underlying valleys (Golledge 2007). The geomorphological signature of this landsystem includes ice-smoothed bedrock, roches moutonnées, striae and fluted moraines indicating radial ice flow, thick accumulations of till where ice movement was up reverse slopes and recessional moraines aligned obliquely across valleys. Around the margins of this domed ice cap is a transitional zone where the former glaciers became increasingly constrained within major troughs. The limits of these outlet glaciers are sometimes marked by end moraines (such as that which marks the eastern terminus of the Rannoch Moor glacier), or by the lateral extent of hummocky drift.

Distinct from both of the above is the plateau icefield (or plateau ice cap) landsystem that developed where thin, cold-ice-based ice caps on high ground fed outlet glaciers that occupied adjacent valley heads. The main examples are those associated with the high plateaux of the Monadhliath and Gaick in the Grampians (Boston et al. 2015; Chandler et al. 2019), the Beinn Dearg massif in the Northern Highlands (Finlayson et al. 2011; Fig. 4.15) and the Tweedsmuir Hills in the Southern Uplands (Pearce 2014). In these areas, glacial landforms on the plateaux are mainly limited to meltwater channels, and periglacial regolith has been preserved under the ice cover. The limits of some outlet glaciers are marked by moraines, but some outlet valleys contain

Fig. 4.14 Glacial landforms of the Loch Lomond Readvance. **a** End moraine crossing a valley below Beinn Dearg (1084 m) in the NW Highlands. **b** End and lateral moraines and a boulder spread define the limits of a cirque glacier on Beinn na Caillich (732 m), Skye. **c** Boulder limit defining the extent of an outlet glacier of the Beinn Dearg ice cap, NW Highlands. **d** Hummocky moraines in Drumochter Pass, central Grampian Highlands. (Images: **a**, **c**, **d** Colin Ballantyne; **b** Google Earth™ image)

little or no evidence of LLS glaciation, suggesting that the glaciers flowing into these valleys were cold-ice-based or starved of sediment.

The cirque/niche glacier landsystem of Bickerdike et al. (2018b) occurs at the sites of small LLR glaciers peripheral to the main ice masses (Fig. 4.15), such as those of An Teallach and Ben Mòr Coigach in NW Scotland, the Cuillin Hills on Skye, the Isle of Arran, the NW Cairngorms and the Galloway Hills (e.g. Ballantyne 2007b; Chandler and Lukas 2017; Chap. 10; Fig. 4.14b). Landforms characteristic of this landsystem include glacially-abraded bedrock, roches moutonnées and whalebacks in cirque source areas, and glacial limits defined by massive end moraines (where glaciers were fed by rockfall or rockslide debris), arcuate spreads of boulders or broad outer belts of closely-spaced end and recessional moraines.

Examples of the lowland piedmont-lobe landsystem are limited to the distal zones of the glaciers that advanced down Loch Lomond and the upper Forth valley to terminate on low ground in the Midland Valley. The limits of these piedmont lobes are characterized by glacitectonic landforms (thrust-block moraines) and lateral moraines, inside which are chaotic hummocky moraines, eskers, kames and kame terraces (Chap. 24).

Additionally, ice-dammed lake landsystems characterized by varved glacilacustrine deposits, deltas and shorelines occur at locations where LLR glaciers impounded substantial water bodies. The most famous of these is at Glen Roy in Lochaber, where three pronounced shorelines skirt the lower slopes of the glen (Palmer and Lowe 2017; Chap. 16), but shorelines, deltas and glacilacustrine deposits also indicate the former existence of ice-dammed lakes at various other locations, notably east of Loch Tulla in the central Grampians, at Loch Garry in the Drumochter area and at Achnasheen and in Glen Doe in the northern Highlands. Advance of the Loch Lomond glacier also dammed a lake near its terminus (Glacial Lake Blane), depositing a proglacial delta that was glacitectonised as the glacier advanced over it, depositing subglacial till (Macleod et al. 2011; Chap. 24).

The evidence provided by recessional moraines suggest that the LLR glaciers experienced three styles of retreat

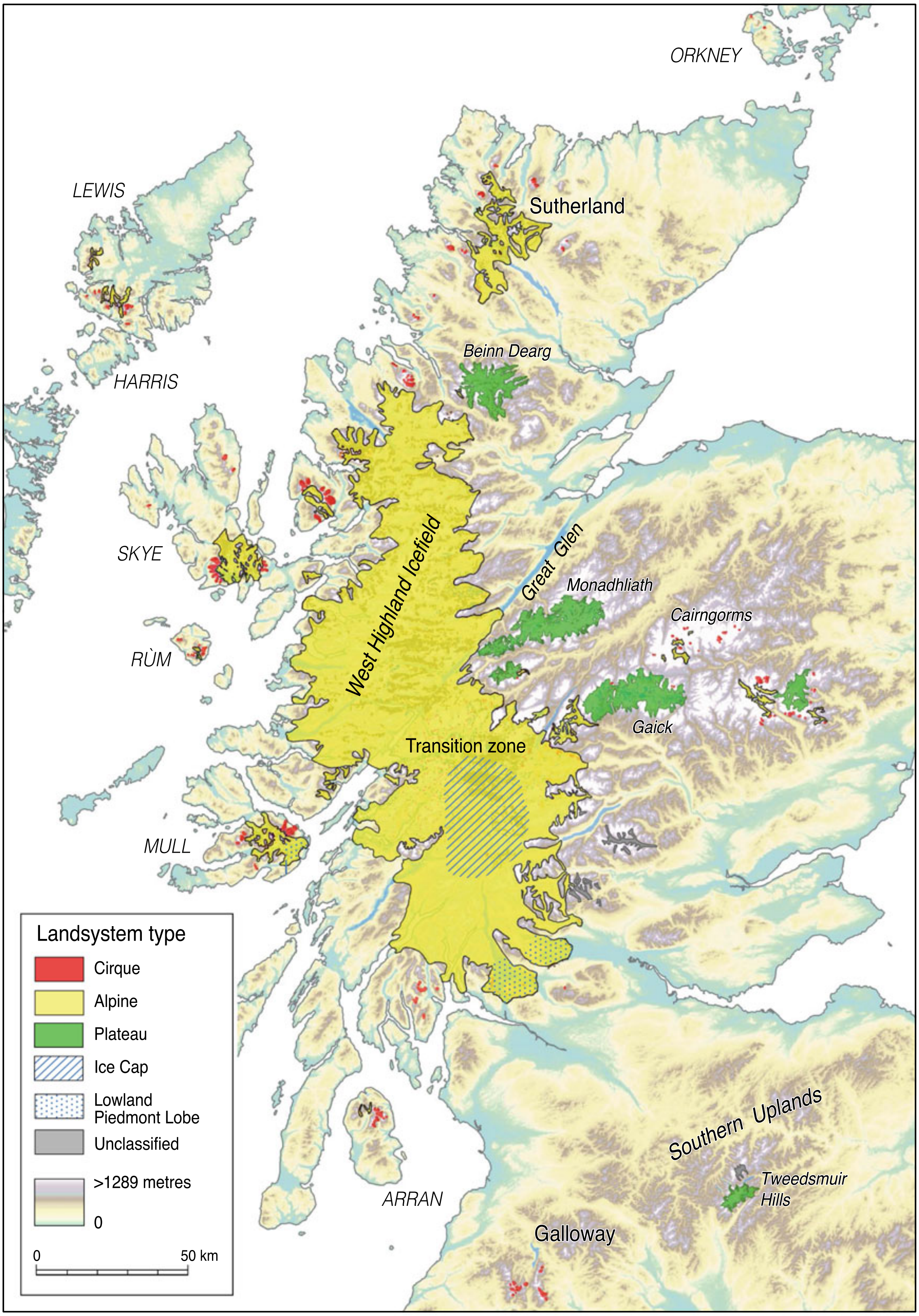

Fig. 4.15 Landsystems of the Loch Lomond Readvance. The main ice mass, the West Highland Icefield or West Highland glacier complex, comprises an ice-cap landsystem that transitions radially into an alpine icefield landsystem and terminates to the south in the piedmont-lobe landsystems south of Loch Lomond and in the upper Forth valley. (Adapted from Bickerdike et al. (2018b) Boreas 47:202–224 © 2017 The authors)

(Bickerdike et al. 2018b). In many locations, recessional moraines extend from former glacier termini to (or almost to) source areas, implying climatically active retreat of oscillating ice margins and suggesting that retreat occurred mainly under stadial conditions. In a few locations, particularly on Skye, initial oscillatory retreat appears to have been succeeded by uninterrupted retreat of the ice margin, or in situ ice stagnation (Benn et al. 1992). At some other locations, particularly at the margins of small cirque glaciers, the glacier terminus appears to have oscillated within a narrow zone, building massive end moraines or multiple moraine ridges, then experienced uninterrupted retreat (Fig. 4.14b). Whether these contrasts indicate different responses to climatic forcing or reflect progressive exhaustion of sediment transported by some glaciers as they retreated has not been established.

4.7 Lateglacial Periglacial and Paraglacial Landforms

The term 'Lateglacial' as employed here refers to the period between the retreat of the last ice sheet (which varied spatially) and the beginning of the Holocene at ~11.7 ka.

Evidence for the development of continuous permafrost down to sea level takes the form of ice-wedge pseudomorphs and polygonal crop marks representing former frost polygons (Murton and Ballantyne 2017). All recorded examples fall outside the limits of the LLR (Fig. 4.16) and though they are undated, evidence from elsewhere in the British Isles indicates that permafrost developed in Scotland both on terrain exposed by the retreating ice sheet and again during the LLS (Ballantyne 2018, 2019b).

In lowland Scotland, sediment-mantled slopes were affected by widespread Lateglacial solifluction. Soliflucted tills occur both below and above organic layers of Lateglacial Interstadial age, implying that solifluction operated both prior to warming at ~14.7 ka and again during the LLS (Ballantyne 2019b). In some parts of the Southern Uplands and Cheviot Hills, Lateglacial valley-fill deposits of reworked till or weathered rock accumulated on valley floors. These deposits have been incised by rivers to form steep-fronted terraces 20–300 m wide, and OSL dating suggests that they mainly accumulated during the LLS (Harrison et al. 2010). Although initially attributed to Lateglacial solifluction over permafrost, their thickness at some sites suggests that they could have been emplaced by debris flows or active-layer failures (Harrison 2002; Chap. 27).

As noted earlier, many Scottish mountain summits and plateaux are mantled by periglacial blockfields, typically up to a metre deep, and in a few areas (mainly the Cairngorms) tors protrude through the blockfield debris (Sect. 4.2.4). Although studies of Scottish blockfields have shown that they developed primarily through frost weathering of bedrock (Ballantyne 1998a, 2010; Hopkinson and Ballantyne 2014), TCN dating of erratics resting on blockfield debris has shown that mature blockfields are of pre-Late Devensian age, and survived beneath the last ice sheet because the ice was cold-based and frozen to the underlying substrate (Fabel et al. 2012); only thin covers of frost-weathered regolith formed on glacially-scoured summits during the Lateglacial period. Some blockfields support large relict sorted circles, nets and stripes, typically 2–4 m in width, that represent frost sorting of the active layer above former permafrost (Fig. 4.17a). Nonsorted patterned ground features on some mountains (earth hummocks and relief stripes) have also been interpreted as representing differential frost heave of frost-susceptible soils during the Lateglacial (Ballantyne and Harris 1994). The most common Lateglacial periglacial landforms on the upper slopes of Scottish mountains, however, are large 'stone-banked' terraces and lobes of bouldery debris that has been rafted downslope through solifluction of underlying fine sediment or (less plausibly) permafrost creep (Fig. 4.17b).

Most talus accumulations in Scotland are relict, vegetation-covered landforms and many are scarred by gullies eroded by debris flows (Fig. 4.17c). Those outside the limits of the LLR accumulated mainly during the Lateglacial period; enhanced rockfall activity at this time has been attributed to a combination of paraglacial stress release and frost wedging of rockwalls (Hinchliffe and Ballantyne 1999, 2009). Lateglacial snow avalanche activity is represented by relict avalanche boulder tongues at a few locations; it is likely that snow avalanches were common under stadial conditions during the Lateglacial, but their geomorphological effects have often been obliterated by Holocene debris flows (Luckman 1992).

Paraglacial rock-slope failures (large-scale rockslides, large rockfalls, rock avalanches and rock-slope deformations) are common features of the Scottish landscape. Over 900 probable sites (mainly on schist mountains) have been identified in the Highlands alone, including over 170 with areas exceeding 0.25 km^2 (Jarman and Harrison 2019; Chap. 14). Many others occurred along scarps in the Midland Valley and Inner Hebrides, and on steep slopes in the Southern Uplands (Chaps. 10, 24 and 27; Fig. 4.17d). TCN dating of the runout debris from 20 rock avalanches or fragmented rockslides outside the limits of LLR glaciers in the Highlands and NW Ireland has shown that all but one occurred during the Lateglacial period, with peak activity 1.6–1.7 ka after ice-sheet deglaciation. Ballantyne et al. (2014) inferred that this time lag represented time-dependent reduction of rock-mass integrity (progressive failure) following deglaciation, but also noted that the peak in landslide activity coincided with maximum rates of glacio-isostatic uplift, suggesting that failure in some cases was triggered by

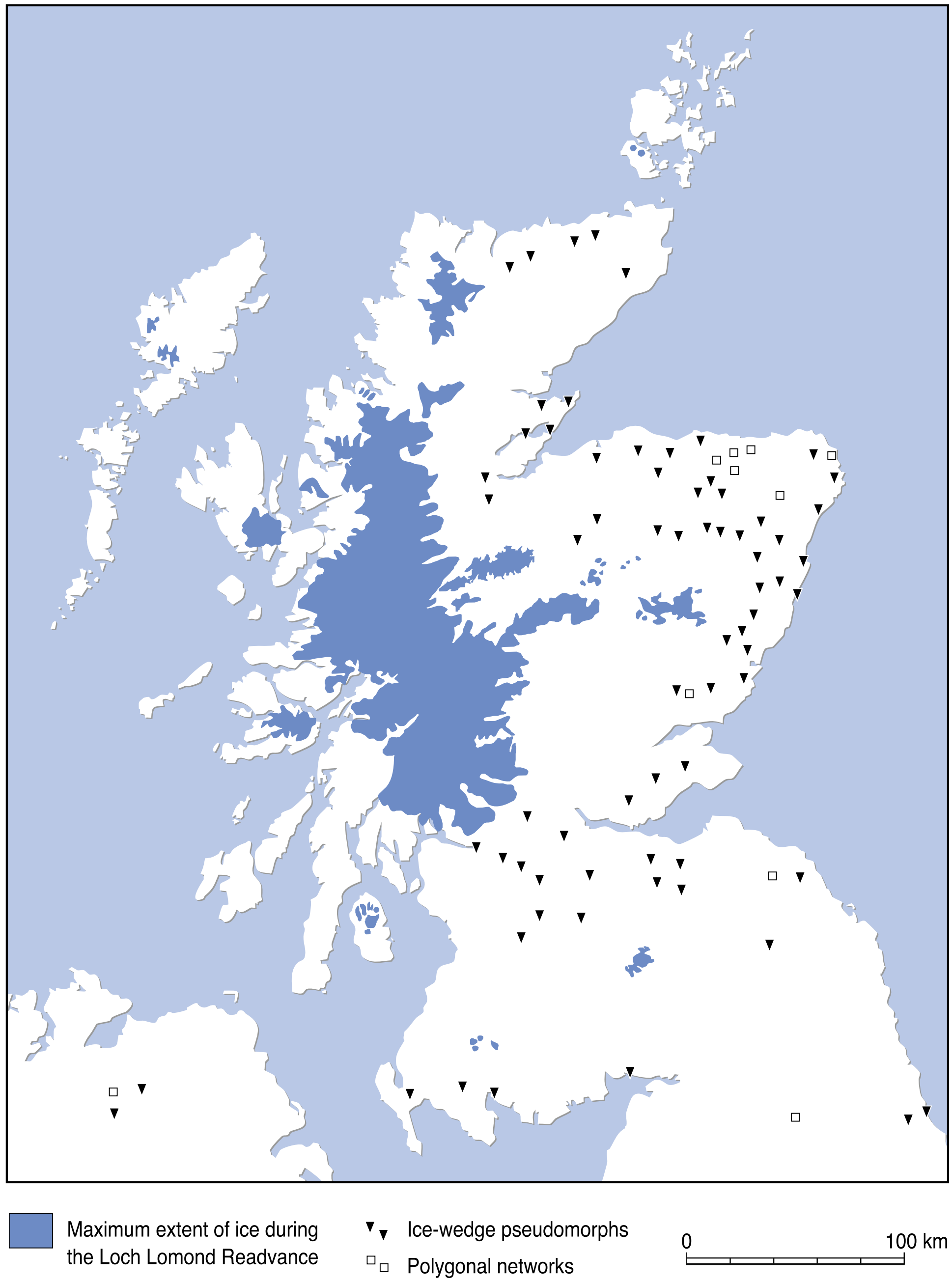

Fig. 4.16 Distribution of documented ice-wedge pseudomorphs and polygonal networks in Scotland. These features indicate that permafrost formed down to sea level following retreat of the last ice sheet. (From Ballantyne (2019a) Scotland's mountain landscapes: a geomorphological perspective. © 2019 Dunedin Academic Press)

uplift-driven seismic activity. Inside the limits of the LLR, numerous rockslide scars represent the sites of Lateglacial landslides where the runout debris was subsequently removed by glacier ice (Ballantyne 2013a; Cave and Ballantyne 2016).

In many major valleys in Scotland, river terraces flank active floodplains. All but the lowest of these are probably outwash terraces that represent abandoned proglacial sandur surfaces (Fig. 4.17e). The limited dating evidence suggests that fluvial incision of palaeosandar began soon after deglaciation as upvalley sources of sediment diminished, and continued throughout most or all of the Lateglacial period (Robertson-Rintoul 1986), and it is notable that the highest terraces inside the limits of the LLR rarely occur more than a few metres above active floodplains. The only evidence for floodplain aggradation during the LLS is from the Kelvin valley in central Scotland (Tipping et al. 2008). In upland areas, however, net incision of outwash sediments appears to have predominated throughout the Lateglacial period (Ballantyne 2019b).

Lateglacial alluvial fans are common throughout Scotland. Large, low-gradient fans, now incised by their parent rivers, occur at the confluences of major upland rivers, such as the Feshie and Spey (Werritty and McEwen 1997;

Fig. 4.17 Lateglacial landforms. **a** Large, relict sorted circles on a summit blockfield, SE Grampians. **b** A stone-banked solifluction lobe, Cairngorm Mountains. **c** Relict, vegetated talus slopes, Wester Ross. **d** Lateglacial rock-slope failure, Lomond Hills, Fife. **e** River terraces, Glen Garry, central Grampians; the higher terraces are outwash terraces formed during retreat of the last ice sheet. **f** Lateglacial fan in upper Glen Roy, Lochaber. (Images: Colin Ballantyne)

Chap. 19). Large Lateglacial alluvial fans also occur in lowland areas, though some, such as the Lindores fan in Fife (Marren 2001) were fed by glacial meltwater streams and should strictly be regarded as outwash fans. Most large upland fans at the mouths of steep tributary valleys are probably paraglacial landforms that accumulated through fluvial reworking of glacigenic deposits; these commonly terminate on high-level outwash terraces, indicating a Lateglacial origin, and have subsequently been incised by their parent streams. Much of the research on Lateglacial fans in Scotland has focused on those associated with the ice-dammed lakes in Glen Roy (Chap. 16; Fig. 4.17f). These were initially interpreted as paraglacial landforms, but stratigraphic investigations by Cornish (2017) suggest that they represent sublacustrine outwash fans deposited as lake levels rose, capped with a layer of gravel deposited when the higher lakes drained. The Glen Roy fans are now deeply incised, with nested lower-level fans inset within their Lateglacial predecessors.

4.8 The Holocene

The onset of the Holocene Epoch at ~11.7 ka was marked in Scotland by rapid warming, degradation of permafrost and the disappearance of glacier ice; temperate conditions similar to those of the present were established by ~11.0 ka (Brooks et al. 2012; Fig. 4.11). Much of the earlier Holocene was characterized by relatively warm summers (the Holocene thermal maximum), followed by a very gradual cooling trend over the past five millennia, during which average temperatures oscillated by up to 2 °C over decades or longer. Apart possibly from a brief cooling event at ~8.2 ka, the most severe period of Holocene cooling in Scotland was the Little Ice Age of the sixteenth to nineteenth centuries, a period characterized by decades of cool, wet summers, exceptional storms and perennial snowcover on some mountains. Tree-ring evidence suggests that within the period AD 1580–1810 summer temperatures in the Cairngorms averaged about 1 °C lower than the 1961–1990 mean (Ryvdal et al. 2017). Some authors have argued that niche glaciers briefly formed in the Cairngorms at this time (Kirkbride et al. 2014), though the dating evidence on which this proposition is based is equivocal.

During the Holocene, many Lateglacial paraglacial landforms (talus accumulations, debris cones, alluvial fans and floodplains) experienced net erosion or incision as a result of reduction or exhaustion of sediment supply (Ballantyne 2008), even though glacigenic sediment continued to dominate paraglacial sediment budgets in headwater catchments (Fame et al. 2018). Superimposed on this trend were: (i) the influence of extreme climatic events (possibly related to periods of wetter, cooler or stormier climate); (ii) the effects of woodland clearance, burning and grazing pressure in altering runoff regimes and lowering the thresholds for erosion of sediment-mantled hillslopes; and (iii) autogenic changes related to pedogenesis, peat formation or (in fluvial systems) local changes in base level. Because of the site-specific nature of most research on Holocene landforms, the relative importance of these effects in dictating Holocene landscape change is difficult to assess (Ballantyne 2019b).

4.8.1 Holocene Periglacial and Aeolian Landforms on Scottish Mountains

It is likely that the present maritime periglacial environment on high plateaux and summits in Scotland is reasonably representative of conditions throughout the Holocene. Above 700–800 m altitude the climate is characterized by mean annual temperatures (1981–2010) of 0.5–5.0 °C and winter air temperatures below −10 °C are fairly uncommon. Permafrost is absent, though seasonal ground freezing may reach depths of 0.4–0.5 m. Gale-force winds (>80 km h^{-1}) are frequent, with occasional gusts exceeding 150 km h^{-1} , and all but the most easterly summits receive >2000 mm of annual precipitation. During much of the last century, average snow-lie (>50% cover) exceeded 100 days per year at 600 m altitude, though in recent winters snowcover has been less persistent.

On Scottish mountain summits, Holocene frost weathering has been limited to granular disaggregation and flaking of exposed bedrock and boulder surfaces, resulting in rounding of outcrops and exposed boulder surfaces. Active frost-patterned ground takes the form of small-scale sorted circles, nets and stripes, formed by differential growth of needle ice (Ballantyne 2001a), though such patterns are limited to unvegetated, frost-susceptible soils containing small clasts. The most widespread active periglacial landforms above 700 m on Scottish mountains are vegetation-covered solifluction terraces and lobes (Fig. 4.18a) with steep risers up to a metre high. Radiocarbon dating of organic matter buried by downslope movement of solifluction lobes has shown that these have been at least intermittently active over the past 5500 years, and recent surface movement averaging ~8–10 mm a^{-1} has been measured over a 35-year period (Ballantyne 2013b). Commonly associated with active solifluction lobes are ploughing boulders that have migrated downslope faster than the surrounding soil, leaving a vegetated furrow upslope. Boulder movement has been attributed to the development of high pore-water pressures during thaw of sub-boulder ice lenses, causing boulders to slide downslope on liquified or softened soil at rates of up to 30 mm a^{-1} (Ballantyne 2001b).

The combined effects of frost and wind erosion have created various landforms on exposed plateaux and cols, notably deflation scars, wind stripes and turf-banked terraces (Ballantyne and Harris 1994) . The most impressive manifestation of upland wind erosion, however, takes the form of

Fig. 4.18 Holocene landforms. **a** Active solifluction terraces at 750 m above Glen Strathfarrar. **b** Deflation surface and remnant 'island' of windblown sand on Ward Hill, Orkney. **c** The Hell's Glen rock-slope failure, Argyll. **d** A Holocene debris cone in Glenuaig, NW Highlands; fresh debris cover indicates recent deposition. **e** The River Coe in Glen Coe, a typical wandering gravel-bed river. **f** Holocene alluvial fan, NW Highlands; most of the fan is now inactive due to fan-head trenching by the parent river. (Images: Colin Ballantyne)

deflation surfaces, expanses of bare ground where wind scour has winnowed away soil particles, leaving sterile surfaces covered by boulders and lag gravels (Chap. 13). Some deflation surfaces support remnant islands of vegetation-covered sand or aeolisols, demonstrating that soil cover was formerly more extensive (Fig. 4.18b). A few plateaux, however, support an intact cover of aeolian deposits preserved under a cover of grasses and sedges. The summit of The Storr (719 m) in northern Skye, for example, is mantled by a vegetation-covered sand sheet up to 2.9 m thick. This deposit consists of particles released from an adjacent cliff by weathering and blown upwards to rain down on the summit, where they have been anchored by vegetation (Ballantyne 1998b; Chap. 10). Other windblown sand accumulations on summits and plateaux may have a similar origin.

Most high-level aeolian deposits, however, form vegetation-covered sand sheets up to 4.0 m thick on lee slopes downwind from deflation surfaces. Many contain a lower unit of weathered sand that slowly accumulated throughout much of the Holocene and an upper unit of unweathered sand. OSL dating of the contact between the two units on several mountains has shown that the upper unit began to accumulate between AD 1550 and 1750 as a result of catastrophic erosion of soils and aeolian deposits on plateau areas upwind (Ballantyne and Morrocco 2006; Morrocco et al. 2007). The timing of such erosion coincides with the Little Ice Age, suggesting that it was triggered by vegetation degradation under persistent snowcover and consequent erosion of exposed soil and sand deposits by strong winds (Chap. 13).

4.8.2 Holocene Slope Failures

A few hundred postglacial rock-slope failures (RSFs) occur within the limits of the LLR in the Scottish Highlands. Of these, only eleven rock avalanches or fragmented rockslides have been securely dated: two apparently deposited debris on LLR glacier ice, two failed shortly after deglaciation and the remainder occurred at intervals throughout the Holocene (Ballantyne and Stone 2013; Ballantyne et al. 2014). There is, however, no information regarding the timing of the numerous arrested rockslides or rock-slope deformations that occur within LLR limits, though failure/displacement of most within a few millennia following final deglaciation is likely. Notable Holocene RSFs include the Beinn an Lochain rock avalanche (~11.7 ka) and Hell's Glen RSF (~3.8 ka; Fig. 4.18c) in Argyll, the Storr landslide (~6.1 ka; Chap. 10) on Skye, the Beinn Alligin rock avalanche (~4.4 ka; Chap. 14) in Torridon, the Coire Gabhail rockslide near Glen Coe (~1.7 ka; Chap. 17) and the huge rock-slope deformation on Beinn Fhada in Kintail (Chap. 14). There are very few reports of recent RSFs, apart from those involving collapse of coastal cliffs (Ballantyne et al. 2018).

Many talus accumulations and other steep sediment-mantled slopes have been eroded by Holocene debris flows, and debris flow is probably the dominant agent of hillslope sediment transport on such slopes at present. Some debris flows follow gullies, often depositing sediment on slope-foot debris cones (Fig. 4.18d); others begin as translational slides on open hillslopes (Chap. 5). Radiocarbon dating of organic soils and peat horizons buried by successive debris flows extends back to ~7.0 ka, but the thickness of some debris cones implies that they began to accumulate much earlier (Ballantyne 2019b). There is evidence, however, that Late Holocene woodland clearance and other land-use changes have made some sediment-mantled slopes more vulnerable to slope failure and recurrent debris-flow activity (Foster et al. 2008). All documented recent debris flows have been triggered by rainstorms of exceptional intensity (Milne et al. 2009). Upland hillslopes have also been modified by gully erosion by flood torrents, small-scale translational landslides that have left cuspate scars, and peat slides (e.g. Dykes and Warburton 2008). Recent snow-avalanche activity is usually limited to uprooting of turf and deposition of debris downslope, though active avalanche boulder tongues occur in the Cairngorms (Luckman 1992).

4.8.3 Holocene Fluvial Landforms

The limited dating evidence available suggests little consistency in the timing of Holocene floodplain aggradation or incision in different parts of Scotland. Low-level river terraces in Highland glens may represent a widespread pattern of Late Holocene floodplain aggradation then incision, but this scenario is supported by radiocarbon ages from only three sites (Ballantyne 2008). In the Southern Uplands, radiocarbon dating of Holocene terrace sequences suggests that floodplain stability or aggradation was typical of much of the Early and Middle Holocene, but that subsequent alluvial history was catchment-specific, with sediment accumulation on some floodplains coinciding with fluvial downcutting in others. In this region, Late Holocene episodes of floodplain aggradation have been attributed to release of sediment into river systems due to Neolithic woodland clearance, Iron Age settlement expansion or other anthropogenic impacts (Tipping 1995; Tipping et al. 1999; Chap. 27), but the evidence relating alluviation to prehistoric land-use changes (particularly woodland clearance) is inconclusive. Recent fluvial incision and abandonment of some low-level terraces may reflect increased flood discharges during the Little Ice Age (Tipping 1994). Research on the fluvial history of rivers in the Midland Valley is limited to a study by Tipping et al. (2008) of the alluvial deposits of central reaches of the River Kelvin, where net floodplain aggradation appears to have predominated throughout much of the Early and Middle Holocene but ceased at least 2000 years ago.

Recent floodplain changes in the Highlands have been investigated through comparison of historical records with modern maps and aerial photographs. These studies have focused on rivers in 'piedmont zones': high-energy, low-threshold fluvial environments where steep mountain streams join major rivers. Over the past two centuries, the floodplains of such rivers have experienced neither net aggradation nor net incision (Werritty and Leys 2001). Many, however, exhibit cyclic changes in channel planform in response to major flood events and gradual inter-flood adjustment, manifest in lateral channel shifts and changes in active channel area and sinuosity. Studies of channel change on the floodplain of the River Feshie, for example, have shown that alluvial reaches are intrinsically unstable, with evidence of avulsion, channel switching, erosion of sediment from bars and channels and flow reorganization operating over annual to decadal timescales (Chap. 19); it appears that the Feshie and kindred gravel-bed rivers in the Highlands are subject to divergent braiding and meandering tendencies. Other Highland rivers have experienced recent channel switching: the River Coe in the Western Grampians shifted laterally by over 200 m between 1968 and 1988 (McEwen 1994; Fig. 4.18e); the main channel of the lower River Spey migrated laterally by up to 400 m between 1968 and 1992 (Riddell and Fuller 1995); and reaches of the River Tay have experienced lateral channel migration of up to a kilometre since 1783 (Gilvear and Winterbottom 1992). Regulation of major rivers over the past 160 years, however, has tended to reduce channel migration (Winterbottom 2000).

Holocene alluvial fans in the Highlands and Southern Uplands include low-gradient fans inset within Lateglacial fans at the confluence of major rivers (Werritty and McEwen 1997) and numerous small fans at the mouths of steep tributary valleys (Fig. 4.18f). The latter represent episodic erosion of hillslopes or moraines by flood torrents, though in some cases debris flows have also contributed to fan accumulation. A small fan in the Edendon valley (central Grampians), for example, accumulated during just three flood events after ~2.2 ka, implying that the fan was built within a few hours over a timescale of more than two millennia (Ballantyne and Whittington 1999). Similarly, a larger fan in Gleann Lichd (Kintail) apparently accumulated in the course of 12–15 flood episodes after ~3.8 ka (Reid et al. 2003). Intriguingly, all small fans dated through radiocarbon assay of buried soils or peat appear to have accumulated within the past four millennia. Foster et al. (2008) have provided compelling evidence that gully erosion and associated fan accumulation in the Southern Uplands followed cycles of settlement expansion, arguing that anthropogenic effects (particularly woodland clearance) made hillslopes more susceptible to gully formation and erosion during rainstorms. They suggested that the earliest gullying events occurred during the Late Bronze to Early Iron Age (~4.0–2.0 ka), with further periods of intensive gully development at ~1.3–1.1 ka, 0.9–0.7 ka and 0.55–0.45 ka. Analyses of buried peat or soil horizons under or within other fans in the Southern Uplands and Highlands, however, provide no evidence for vegetation change prior to fan accumulation, so it is unlikely that all Late Holocene fans represent a response to human activity in destabilizing slopes.

Several recent studies have focused on the Holocene evolution of bedrock channels in the Highlands. Jansen et al. (2011) employed TCN dating of strath terraces (bedrock channel remnants) to show that knickpoint retreat was most rapid in the Early to Middle Holocene and has since slowed by about two orders of magnitude. They attributed this trend to reduction in the availability of fluvially-transported clasts that constitute the ‘tools’ responsible for bedrock detachment and incision during floods. For rivers draining the Western Grampians, Jansen et al. (2010) found that bedrock channel widths increase nonlinearly with catchment area and that bedrock channel morphology is conditioned by lithology; quartzite outcrops have formed resistant pinning points that slowed knickpoint retreat. Other studies in Highland catchments have shown that the dimensions of river channels in both alluvial and bedrock reaches are related to catchment area (and thus flood discharges), valley-floor gradient and the calibre of bed material (Addy et al. 2011, 2014). From a strong relationship observed between bedrock channel widths and upstream catchment area, Whitbread et al. (2015) concluded that fluvial erosion has reconfigured bedrock channel morphology since deglaciation, resulting in the adaptation of channels to Holocene runoff regimes and sediment supply.

4.9 Relative Sea-Level Changes and Associated Landforms

4.9.1 Introduction

The patterns of relative sea-level change across Scotland during the Quaternary were influenced by the dimensions of former ice sheets and the spatial and temporal patterns of regional deglaciation. The numerous raised, intertidal and submerged shore platforms, raised beaches and raised deltas along the Scottish coastline represent the interaction between vertical glacio-isostatic movements (centred on the axis of uplift in the Western Grampians) and eustatic changes in global ocean volume caused by expansion and shrinkage of the Pleistocene global ice sheets, modulated by changes in the geoidal sea surface, particularly those caused by changes in the gravitational attraction between ocean water and ice sheets (Dawson 2019).

Although very few older raised shoreline deposits have survived the last ice-sheet glaciation, various raised shore platforms of pre-Late Devensian age locally form prominent features of the coastal landscape. The dimensions of the last ice sheet (Fig. 4.5) and its duration (~35–14 ka) defined the amount of glacio-isostatic downwarping of the lithosphere and the development of a crustal forebulge near and beyond the former ice-sheet margins. Deglaciation was accompanied

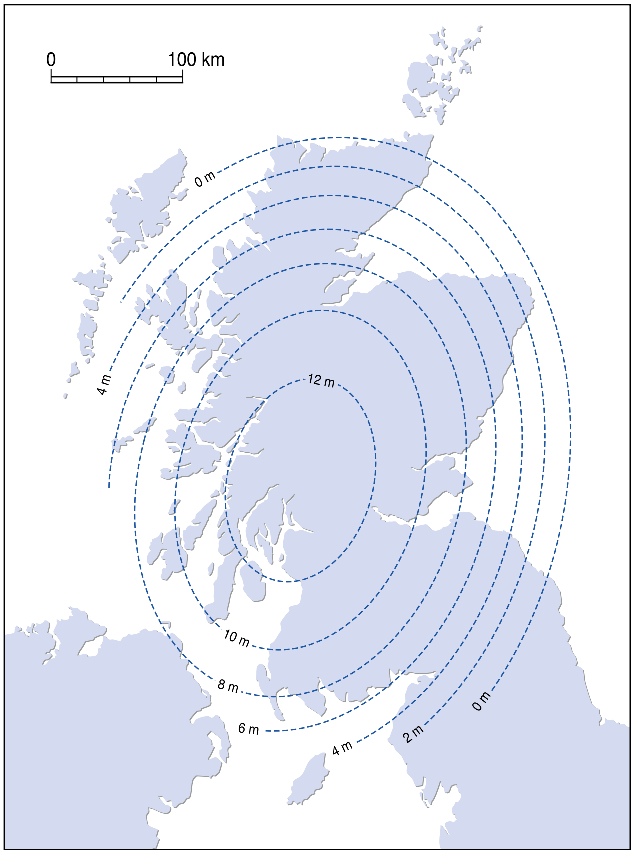

Fig. 4.19 Isobase contours (metres) of the Main Postglacial Shoreline, which formed around Scotland's coasts within the period ~7.8–6.2 ka. Subsequent differential glacio-isostatic uplift has tilted this shoreline, so that it declines in altitude radially away from the uplift centre in the Western Grampians

and followed by glacio-isostatic rebound of areas covered by the ice sheet and forebulge collapse across peripheral areas (Shennan et al. 2018; Smith et al. 2019). Isostatic rebound accounts for the occurrence of Lateglacial and Holocene raised shoreline features at altitudes of up to ~40 m OD (Ordnance Datum). Because the amount of rebound has been greatest near the axis of isostatic uplift, diminishing towards peripheral areas, postglacial raised shorelines decline in elevation away from the uplift centre, passing below present sea level in outlying areas (Fig. 4.19). Moreover, the degree of shoreline tilting has diminished through time, so that the oldest postglacial (Lateglacial and Holocene) raised shorelines exhibit the steepest regional gradients and the youngest have the gentlest gradients. Crustal forebulge collapse partly accounts for the absence of postglacial raised beaches in peripheral areas such as the Outer Hebrides, Orkney and Shetland, where many Quaternary shoreline features are now submerged.

4.9.2 Pre-Late Devensian Coastal Landscapes

Shore platforms (cut in bedrock) that formed prior to the advance of the last ice sheet fall into three categories: strandflat; low-level platforms close to the present tidal range; and high rock platforms. Extensive areas of strandflat occur on several Hebridean islands, notably Benbecula and the Uists in the Outer Hebrides and the outlying islands of Tiree and Coll in the Inner Hebrides (Chaps. 9 and 11) The strandflat consists of subhorizontal, glacially-moulded rock platforms ~3–15 km wide and no higher than ~30 m OD, mainly cut across Lewisian gneiss (Fig. 4.20a). The exceptional width of the Scottish strandflat has prompted suggestions that it may represent a modified subaerial planation surface (Smith et al. 2019) or was formed by coastal erosion during prolonged periods of relative sea-level stability in the Pliocene (Dawson et al. 2013).

Near-horizontal shore platforms at elevations within or close to the present tidal range occur around both the west and east coasts of Scotland (Fig. 4.20b). Some exhibit evidence of glacial abrasion in the form of ice-smoothed rock and others pass below till bluffs, indicating formation prior to the last (and possibly earlier) ice-sheet glaciation(s). Such low-level platforms have been interpreted as inherited landforms that developed through marine erosion during successive interglacials when sea levels were similar to that of the present (Dawson 1980a), locally modified by glacial erosion and postglacial coastal processes.

High rock platform fragments occur along west-facing coastal areas of the Inner Hebrides and the adjacent mainland (Chaps. 10 and 11). The most extensive examples are typically 200–600 m wide and backed by cliffs up to 90 m high. The inner edges of most high platform fragments occur at ~18–35 m OD. On some coasts, platform altitudes vary by several metres over distances of less than 2 km, suggesting that the platform fragments represent more than one former shoreline or tectonic dislocation of a former shoreline. Early accounts attributed an interglacial age to the high platforms of western Scotland, but Sissons (1982) argued that they developed due to periglacial coastal erosion when the margin of the last ice sheet was located along the western seaboard between Wester Ross and Islay. More recently it has been suggested that the origins of these platforms pre-date the Quaternary since their considerable widths imply a prolonged period (or periods) of relative sea-level stability (Dawson et al. 2013). Similar features also occur along parts of the east coast, notably the spectacular high rock platforms at Dunbar, Berwick and Eyemouth. Raised rock platforms partly buried beneath till are also present in some peripheral locations, such as Orkney and the Outer Hebrides (Smith et al. 2019).

Fig. 4.20 Coastlines of Scotland. **a** Strandflat, North Uist, Outer Hebrides. **b** Intertidal rock platform on the Fife coast; the abandoned stack is a volcanic neck. **c** Lateglacial raised delta and modern bay-head beach, Camas Mòr, Coigach. **d** The Main Rock Platform on the islands of Seil and Luing, Firth of Lorn. **e** Sea cliffs and sea caves, Villians of Hamnavoe, Shetland. **f** Sandy beach and eroding dune cordon near the mouth of the Ythan estuary, NE Scotland. (Images: **a**, **e** John Gordon; **b**, **c** Colin Ballantyne; **d** Murray Gray; **f** Google Earth™)

4.9.3 Relative Sea-Level Changes Associated with Ice-Sheet Deglaciation

Retreat of the last ice sheet was accompanied by marine incursion into most coastal areas. In western Scotland, the Lateglacial marine limit reached ~40 m OD across parts of the Inner Hebrides but is lower on the coast of eastern Scotland. At Camas Mòr in Coigach, for example, it is represented by a raised delta at ~15 m OD that merges inland with outwash terraces deposited by the retreating ice sheet (Fig. 4.20c). Relative sea levels subsequently fell as glacio-isostatic rebound outpaced eustatic sea-level rise. The most complete sequence of emerged Lateglacial shorelines representing this lowering of relative sea level is in western

Jura, where extensive spreads of unvegetated Lateglacial gravel beach ridges decline in altitude seaward from the marine limit (Chap. 11). This fall in relative sea level started across the Inner Hebrides at ~16 ka and continued until the onset of the LLS at ~12.9 ka (Shennan et al. 2018).

4.9.4 Shoreline Formation During the Loch Lomond Stade

There is abundant evidence for rapid coastal erosion of bedrock under the severe cold conditions of the LLS, particularly in western Scotland where a conspicuous raised rock platform (the Main Rock Platform or Main Lateglacial Shoreline) and associated backing cliff extend along long stretches of coastline from Ayrshire and Kintyre northwards to Mull and Ardnamurchan (Fig. 4.20d; Chaps. 10 and 11). This shore platform cuts across a range of lithologies and is typically 50–150 m wide with a ~15–20 m high backing cliff indented by numerous relict sea caves. The platform has an altitude of 10–11 m OD in the Oban area and declines in elevation away from the centre of glacio-isostatic uplift along a regional gradient averaging ~0.16 m km^{-1}, passing below present sea level in Ayrshire, southern Arran, Islay and western Mull. Because this platform occurs only outside the limits of the Loch Lomond Readvance, exhibits no evidence of glacial modification and is well developed in areas of limited fetch, it is believed to have formed rapidly under periglacial conditions during the LLS through a combination of frost-wedging of bedrock and removal of debris by wave erosion and sea ice (Dawson 1980b; Sissons 1983; Stone et al. 1996). In eastern Scotland, the Main Lateglacial Shoreline forms a buried gravel layer that occurs under Holocene estuarine deposits in the upper Forth valley. This feature declines eastwards along the uplift gradient; submerged rock platforms at −4 m near Rosyth and −9 m near Cockenzie probably represent the eastward continuation of the same shoreline.

4.9.5 Holocene Relative Sea-Level Changes and Associated Landforms

Along coastlines near the axis of glacio-isostatic uplift, crustal rebound at the start of the Holocene continued to outpace eustatic sea-level riseand relative sea level continued to fall, but coastlines distal to the uplift axis experienced a sustained rise in relative sea level at this time. Numerical modelling of relative sea level at the start of the Holocene suggests that it may have been as low as −20 m to −30 m OD around the Orkney Islands, −15 m OD at Aberdeen and between 0 m and +5 m OD in the Firth of Clyde (Shennan et al. 2018).

During the period ~9.5–7.0 ka, however, rapid glacio-eustatic sea-level rise exceeded rates of glacio-isostatic uplift throughout Scotland, resulting in a relative marine transgression that culminated at ~7.8–6.2 ka. This transgression is represented by the Main Postglacial Shoreline, which constitutes the Holocene marine limit in coastal areas near the axis of uplift. In major estuaries this transgression resulted in the extensive deposition of estuarine sediments (carse clays); subsequent relative marine regression due to continuing (though slowing) isostatic uplift formed the distinctive, low-gradient, emerged carseland surfaces of the lower Forth, Tay and Clyde valleys. Along coastlines exposed to open-fetch conditions, this transgression was associated with the deposition of beach gravels, such as those that mantle the Main Rock Platform along the coasts of Kintyre and the outer Clyde estuary. Continuing glacio-isostatic uplift has elevated such Holocene beach deposits well above present sea level. Near the centre of uplift the Holocene marine limit occurs at ~12–14 m OD, declining radially outwards to intersect present sea level near the north coast of mainland Scotland (Fig. 4.19). However, because of oscillations in eustatic sea level at a time of continuing (though gradual) isostatic uplift, the Holocene marine limit is diachronous: it is represented by the Main Postglacial Shoreline near the uplift axis, but farther from the axis the highest Holocene raised shoreline becomes progressively younger in age (Smith et al. 2012, 2019).

4.9.6 Recent Coastline Changes

Over the past 4000 years, relative sea level around Scotland's coasts has remained fairly stable, with some areas near the centre of isostatic uplift experiencing slow falls in sea level and others distal to the uplift axis experiencing gradual sea-level rise. The present coastline is one of great diversity (May and Hansom 2003). Steep plunging cliffs indented with caves and geos and flanked by stacks and arches occur along several parts of the mainland but are particularly well represented on the coasts of Orkney, Shetland and Caithness, where relative sea level has risen throughout the Holocene. Other rock coasts take the form of bedrock ramps or boulder-strewn intertidal rock platforms (Fig. 4.20b). Such coastlines are relatively stable, though continuing sea-level rise has been implicated in the ongoing collapse of coastal cliffs around Shetland (Ballantyne et al. 2018; Fig. 4.20e) and storm waves on Atlantic coastlines have been shown to overtop coastal cliffs up to 40 m high, quarrying angular boulders from cliff crests and depositing these inland from the cliff top (Hall et al. 2007; Chaps. 7 and 8).

Many low-lying coastlines support a range of depositional coastal landsystems (Chaps. 22 and 23), including beaches of sand or gravel, spits, bars, offshore sandbanks, salt marshes, dune systems and, on some Hebridean islands, coastal plains comprising aeolian deposits of calcareous shell sand, known as machair (Hansom and Angus 2006; Chaps. 9 and 11). Glacigenic deposits constitute the main source of most coastal sediment, though trajectories of sediment transport have been complex: glacigenic sediments may have been directly eroded from the shoreface, transported to estuaries by rivers, derived from the adjacent shelf or eroded from raised beaches, deltas or spits that were originally sourced from glacigenic deposits (Firth et al. 1995). Most present-day coastal deposits therefore represent secondary paraglacial sediment stores; sediment input from eroding rock cliffs is comparatively unimportant.

Hansom (2001) has identified a general decline in sediment supply to depositional coastal systems after the mid-Holocene and a consequent reorganization of sediment transfer into progressively smaller cells and sub-cells separated by headlands. The recent history of such coastal units has been dictated by local circumstances. In the past few decades, net sediment loss has predominated, leading to decreases in beach width, increases in beach slope and erosion of landward dune cordons (Fig. 4.20f; Chap. 5). A survey of the beaches of the Highlands and Hebrides in 1977, for example, found that only 7% were progradational, with widespread erosion of dunes on the Atlantic coastline (Mather and Ritchie 1977). This generalization, however, obscures considerable local diversity. At Tentsmuir in Fife, for example, there has been over 3.5 km of coastal advance in the last 5000 years as relative sea level fell (Ferentinos and McManus 1981; Chap. 23) and historical records show that although the southern part of the Tentsmuir coast has receded over the past two centuries, such erosion has been counterbalanced by shoreline progradation of over 870 m farther north. Nevertheless, projections of future sea-level rise suggest that many Scottish shorelines are vulnerable to increased erosion during this century, with modification or disappearance of sediment-starved beaches and spits, erosion and breaching of dune cordons and reduction in the areas of salt marsh and machair, all which provide important zones of habitat diversity (Chap. 5).

4.10 Conclusion

The Quaternary was a period of recurrent climatic changes, manifest in Scotland by the alternation of cold (glacial) stages and temperate (interglacial) stages, punctuated by stadial and interstadial climatic shifts. Prior to ~0.78 Ma, ice cover in Scotland was mainly limited to mountain areas during successive glacial stages, but up to ten extensive ice sheets subsequently covered most or all of the present land area and extended far out across the adjacent shelves. The cumulative effects of Pleistocene glacial erosion varied spatially. Mountain glacial landscapes developed in the western Highlands; landscapes of areal scouring formed along parts of the western seaboard and Hebrides; upland landscapes of selective linear erosion evolved in the eastern Highlands and Southern Uplands; lowland landscapes of differential glacial erosion and streamlined bedforms developed in the Midland Valley; and landscapes of limited glacial modification were preserved in NE Scotland. Because the last (Late Devensian) ice sheet covered all of the land area, the terrestrial stratigraphic record of earlier events is fragmentary, but the last ice sheet provides a template for understanding the behaviour of its predecessors.

The last Scottish ice sheet expanded after ~35 ka, reached its maximum extent at ~30–27 ka and had retreated to its mountain sources by ~14 ka. To the south it was confluent with ice nourished in Ireland and England, to the east with the Fennoscandian ice sheet and westwards it extended locally to the Atlantic shelf edge. It was polythermal, experienced major changes in configuration and flow patterns and was drained by major ice streams. During the Lateglacial Interstade (~14.7–12.9 ka) ice disappeared or was confined to high plateaux. The Loch Lomond Stade (~12.9–11.7 ka) witnessed a final readvance of mountain glaciers in the form of ice caps, icefields and cirque glaciers. Glacial landsystems associated with the last ice sheet are dominated by till sheets, drumlin fields, ribbed moraine, megaflutes, meltwater channels and outwash deposits. Those produced during the Loch Lomond Stade are dominated by end, lateral and recessional moraines.

Retreat of the last ice sheet was accompanied and followed by the development of permafrost, widespread solifluction and paraglacial landscape modification by rock-slope failure, rockfall activity and reworking of glacigenic sediments by debris flows and rivers. Such processes continued into the Holocene, when periglacial activity became confined to high ground, the incidence of rock-slope failures declined and there was net erosion or incision of talus accumulations, debris cones, alluvial fans and floodplains. Changes in relative sea level during the Quaternary resulted in the formation of shore platforms of varying age and elevation and the formation of Lateglacial and Holocene raised beaches. Many present-day coastal deposits exhibit net sediment loss, which is likely to be exacerbated by future sea-level rise.

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