10 The Islands of the Hebridean Igneous Province: Skye, Mull, Rùm and Arran

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Abstract

The islands of the Hebridean Igneous Province are largely composed of Palaeogene igneous rocks relating to extensional tectonics and magmatic activity within the interval ~62–55 Ma. Their geology is dominated by plateau lavas, subvolcanic central igneous complexes, and sills and dyke swarms intruded into earlier sedimentary and metasedimentary rocks. Modification of the igneous terrain by successive Pleistocene ice sheets and mountain glaciers has produced radiating troughs and cirques, pinnacled arêtes and glaciated trap topography. During the local Last Glacial Maximum (~30–26 ka), Skye, Mull and Arran sustained independent ice centres that fed ice streams on the adjacent shelves; following decoupling from these ice streams, locally nourished glaciers readvanced on Skye and Arran. During the Loch Lomond Stade (~12.9–11.7 ka) all four islands hosted mountain glaciers that deposited end, lateral and recessional moraines. Postglacial landforms include periglacial and aeolian landforms on high ground, and spectacular landslides (one of which is the largest in Britain) at sites where failure of sedimentary rocks has caused extensive collapse of the overlying lavas. A wide range of coastal features are represented, including shore platforms of various ages, raised deltas, raised shingle ridges and both Lateglacial and Holocene raised beaches. The islands of the Hebridean Igneous Province are internationally renowned not only for their outstanding geodiversity, but also the haunting beauty of their strikingly dramatic landscapes.

Keywords

Subvolcanic plutons • Trap topography • Sills • Radiating glacial troughs • Cirques • Moraines • Solifluction • Patterned ground • Aeolian deposits • Basalt scarp landslides • Coastal rock platforms • Raised beaches

10.1 Introduction

The islands of Skye, Rùm, Mull and Arran on the western seaboard of Scotland (Fig. 10.1) share a common geological heritage: all are largely composed of igneous rocks that were intruded into, or erupted onto, earlier rocks of Neoproterozoic to Jurassic age during a comparatively brief period of intense Palaeogene magmatic activity. All support central igneous complexes that represent the roots of Palaeogene volcanoes; all are seamed with Palaeogene dyke swarms and intruded by sills; and two (Skye and Mull) are largely composed of stacked mafic lava flows that extend far offshore and onlap NW Rùm. All four islands have experienced modification by successive Pleistocene mountain glaciers and ice sheets; all were completely buried under polythermal glacier ice during the local Last Glacial Maximum (LLGM); all supported glaciers during the Loch Lomond Stade of ~12.9–11.7 ka, and all are scarred by postglacial landslides and surrounded by raised shorelines. Yet despite this common heritage, each island contains landscapes and landforms that are distinct from those on the others and often unique in Scotland. Collectively, the islands of the Hebridean Igneous Province capture a range of geodiversity greater than that of any other Scottish region: in the early twentieth century they formed the topic of some of the most seminal Memoirs of the Geological Survey; they contain 45 Sites of Special Scientific Interest (SSSIs), selected for their international geological or geomorphological significance; and they have proved inspiring training grounds for successive generations

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of Earth science students. The most striking geological and geomorphological features have captured the imagination of writers, photographers, poets, artists, composers and other visitors, stimulating an interest in the origin and evolution of some of the most varied and dramatic landscapes in the British Isles.

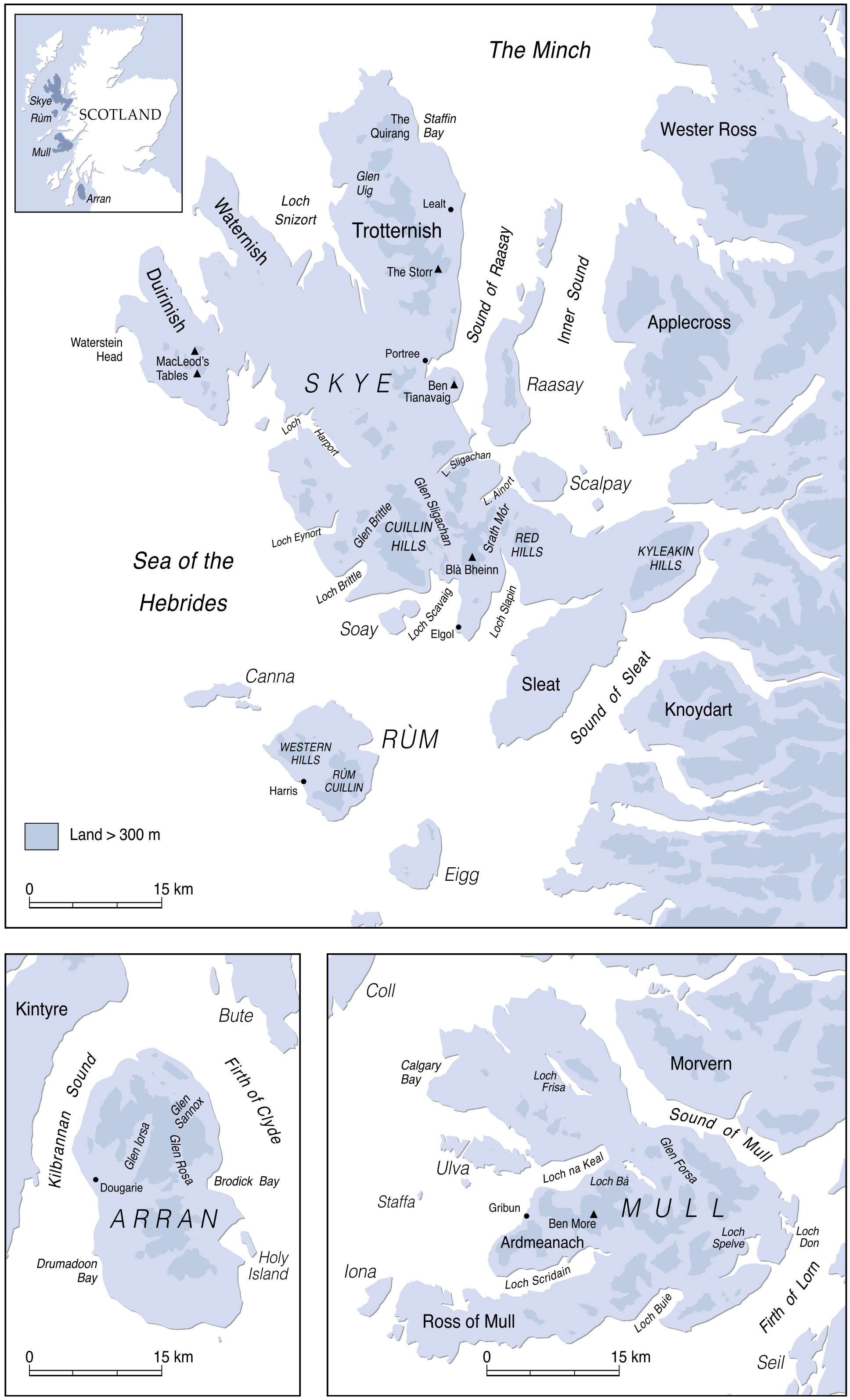


Fig. 10.1 The islands of Skye, Rùm, Mull and Arran: key locations mentioned in the text

10.2 Geology and Geological Evolution

Much of the landscape of the islands of the Hebridean Igneous Province owes its origin to crustal stretching and associated magmatic activity along western Scotland in the interval ~62–55 Ma, immediately prior to the opening of the North Atlantic Ocean. Such magmatic activity was initially associated with fissure eruptions that produced huge volumes of mainly mafic lava, forming the extensive plateaux of stacked, often horizontal lava flows of the Skye and Mull Lava Groups (Fig. 10.2). These underlie most of both islands and extend up to 50 km offshore to form the islands of Canna, Eigg and Muck. Later eruptions were sourced from stratovolcanoes, now eroded to their roots to form central igneous complexes. These had differing individual histories, generally involving intrusion of magma, uplift of surrounding and overlying rocks (possibly to heights of 2000 m or more), eruption of lavas and pyroclastic debris then partial collapse and unroofing by rapid erosion, which exposed their plutonic cores. Thick transgressive sills relating to Palaeogene magmatic activity crop out extensively in northern Skye and southern Arran, and all four islands are seamed by numerous NW–SE aligned dykes of basalt and dolerite, mainly fed from the Skye and Mull central complexes, that indicate intrusion under an early Palaeogene NE–SW extensional stress regime.

The geological complexity of the four islands has engendered a cornucopia of publications. The geological evolution of the entire province is summarized by Bell and Williamson (2002), Emeleus and Bell (2005) and Brown et al. (2009), that of Skye by Bell and Harris (1996), that of Rùm by Emeleus (1997) and Emeleus and Troll (2008, 2011), and that of Arran by MacDonald and Herriot (1983).

10.2.1 Geology

Geologically, Skye consists of three regions (Fig. 10.3). Southeast Skye is underlain by pre-Cenozoic metamorphic and sedimentary rocks. These include thrust sheets of Lewisian gneiss, Moine schists and Torridonian sandstones in Sleat and easternmost Skye, and sedimentary rocks of various ages intruded by Palaeogene sills in the Broadford–Loch Eishort area. The mountains of central Skye are underlain by Palaeogene intrusive rocks emplaced at ~59–56 Ma in the form of four subvolcanic plutons. The earliest, westernmost pluton, the Cuillin complex, comprises concentric masses of layered mafic and ultramafic rocks (mainly gabbros and eucrites) that have been penetrated by thin dolerite cone sheets and numerous discordant basalt dykes. To the northeast, the Cuillin complex is truncated by two further complexes of silicic rocks (mainly epigranites), the Srath na Crèitheach and Western Red Hills complexes. A third epigranite complex (the Eastern Red Hills complex) occupies the ground between Loch Ainort and Loch Slapin. The four complexes represent a gradual eastward shift in the locus of magmatic activity, accompanied by progressively increasing magma acidity, probably due to fractionation and contamination by quartz-rich crustal rocks. Northern Skye is underlain by horizontal or westward-dipping Palaeogene basaltic lava flows, with an aggregate thickness of at least ~1800 m, that were emplaced at ~60 Ma on low-relief terrain underlain by sedimentary rocks. Individual flows are typically 5–15 m thick and frequently separated by tuffs, breccias and laterite horizons (Fig. 10.2a). Mesozoic sediments (primarily shales) and thick transgressive dolerite sills crop out north and east of the lavas on the Trotternish Peninsula.

Rùm comprises the remains of an igneous complex, dated to ~60.5 Ma, that occupies most of the western, central and southern parts of the island, and is intruded into Neoproterozoic sandstones of the Torridon Group, which underlie the north and east. The central complex developed in several phases within a ring fault. The earliest phase involved silicic magmatism, now represented by the felsic rocks of the Western Hills, with uplift of overlying Torridonian rocks and caldera subsidence within the ring fault. The second phase was dominated by intrusion of layered gabbros and ultrabasic rocks of the Rùm Cuillin. Finally, vigorous erosion exposed the plutonic roots of the complex, and basaltic lavas from Skye invaded northern Rùm, and now crop out in parts of the Western Hills.

The geology of Mull is dominated by Palaeogene plateau basalt lavas, which surround the exhumed remains of a central igneous complex that underlies the most mountainous terrain. The main lavas underlie all of northern Mull, most of western Mull and eastern coastal areas, have an aggregate thickness of ~1000 m, and are composed of lava flows typically 10–15 m thick. These are overlain in central Mull by younger lavas that erupted as the central igneous complex collapsed to form a caldera. The central complex itself represents the sequential intrusion of three volcanic centres, and comprises both granitic rocks and layered gabbros, and intrusive rocks in the form of cone sheets and ring dykes. Pre-Cenozoic rocks on Mull include outcrops of Devonian granite and Dalradian metasedimentary rocks on the Ross of Mull, and various Mesozoic sedimentary rocks (sandstones, mudstones and limestones) that underlie the main basalt lavas and crop out in narrow bands along eastern coastal areas and the coast of the Ardmeanach Peninsula.

Arran differs from its Hebridean cousins in lacking extensive Palaeogene lava fields. The pre-Cenozoic geology of

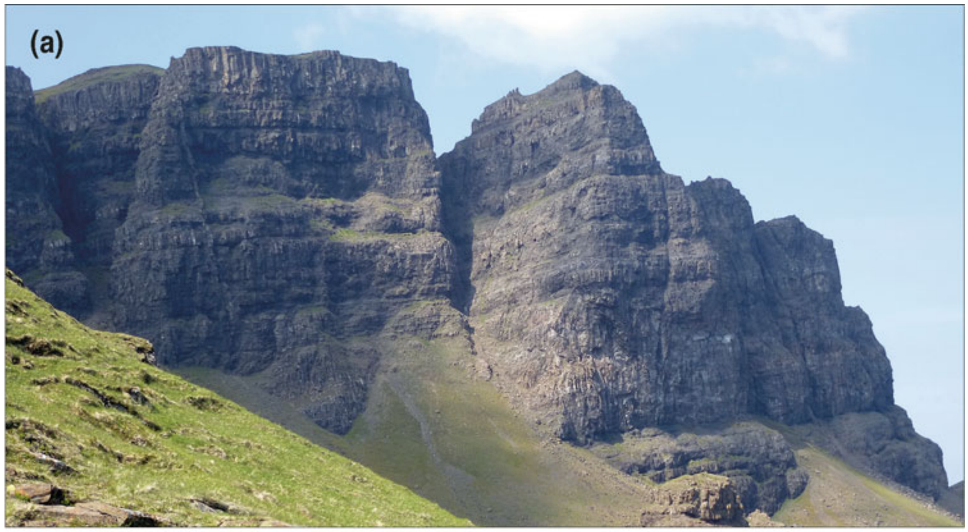


Fig. 10.2 Palaeogene lavas. **a** Stacked basalt lavas of the Trotternish escarpment, northern Skye. **b** Columnar jointing developed in a lava flow on the Isle of Staffa, western Mull. (Images: **a** Colin Ballantyne; **b** John Gordon)

the island is dominated mainly by metasediments of Dalradian age and sedimentary rocks, mainly of Devonian to Triassic age. The Palaeogene igneous components of Arran's geology are fourfold: an unroofed pluton in north Arran; a central igneous complex that represents the remnants of a collapsed volcano; an extensive outcrop of sills in south Arran; and a remarkably dense dyke swarm. The Northern Granite forms a near-circular outcrop, intruded at ~60 Ma, that comprises an outer zone of coarse-grained granite and a slightly younger inner zone of fine-grained granite, both of which have been exhumed from under a thick cover of older rocks. The ring complex to the south is ~5 km in diameter and marks the site of a central volcano that collapsed to form a caldera and contains intrusive rocks of variable composition with localised outcrops of lavas and pyroclastic rocks. The sills that crop out extensively in southern Arran are mainly intruded into Permian sandstones and are of variable composition, though dolerites predominate. The Arran Dyke Swarm is the best example of such a feature in Britain: over 500 individual dykes ranging from 0.3 to 30 m in width have been mapped, most of which are aligned NW–SE or NNW–SSE.

10.2.2 Geology and Landscape

In few parts of Scotland is the relationship between geology and landscape more strikingly illustrated than on the islands of the Hebridean Igneous Province. The plutonic rocks of the subvolcanic central igneous complexes and the Northern Granite of Arran tend to be associated with the highest relief and most prominent mountains, though there are striking contrasts between upland areas. The gabbros and eucrites of the Cuillin Complex on Skye form a serrated ridge of mountains, locally dissected by preferential weathering and erosion of dykes, but the granites of the adjacent Red Hills

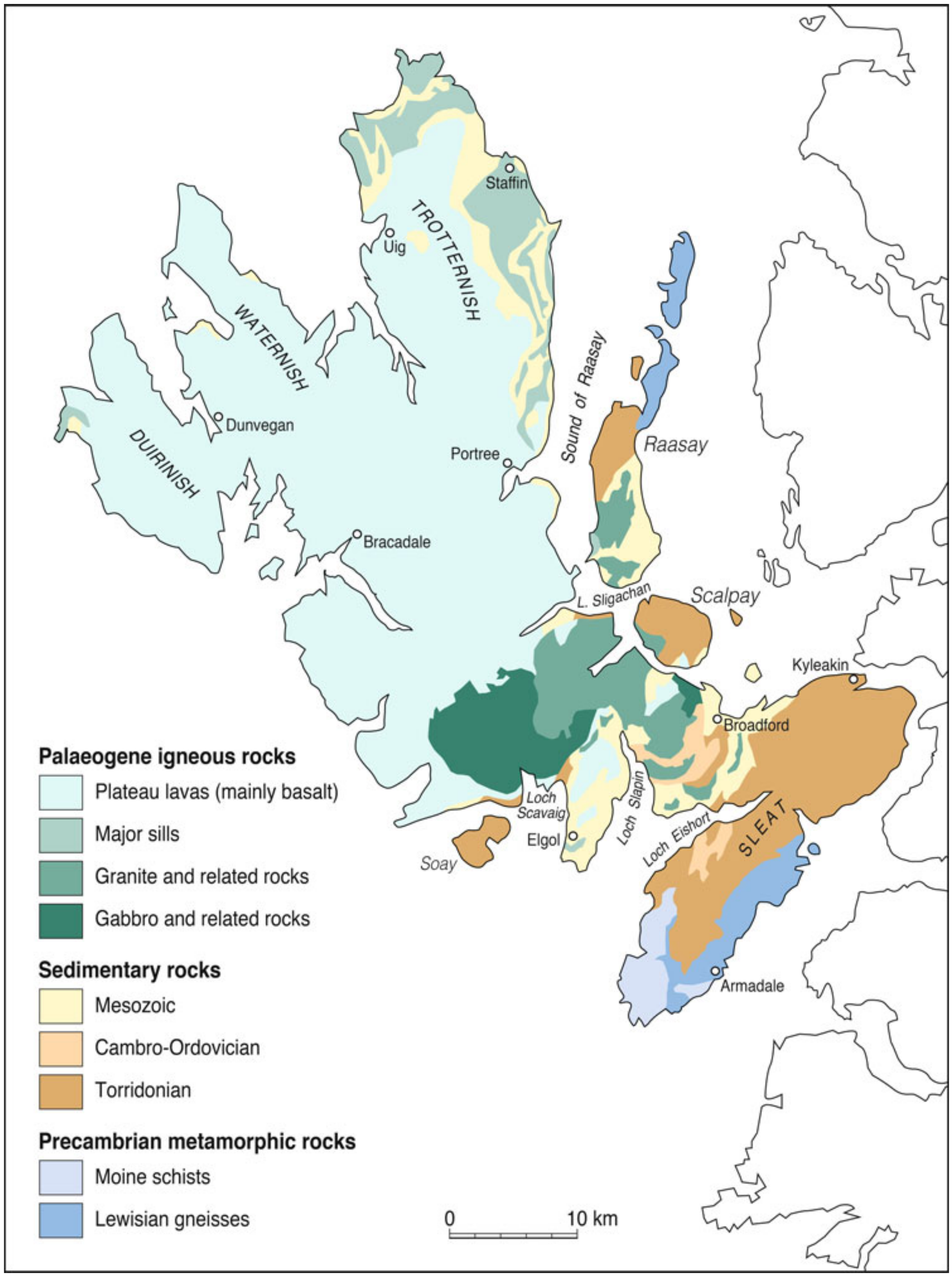


Fig. 10.3 Bedrock geology of Skye

now form domed or conical peaks (Fig. 10.4a, b). The mafic and ultramafic rocks of the Rùm Cuillin form stepped pyramidal peaks, whereas the microgranite that underlies the Western Hills forms a rolling plateau. The fine-grained inner granite of northern Arran forms rolling, domed summits, but the more resistant coarse-grained outer granite forms ridges and peaks that almost rival the Skye Cuillin in topographic ruggedness (Fig. 10.4c). On Mull, the highest ground (Ben More, 966 m) is underlain by the younger lavas that erupted during caldera subsidence.

The extensive basalt lavas of Skye and Mull form the most striking examples of glacially scoured trap topography in Scotland. Over much of the lava terrain, glacial erosion has focused along the tuffs, breccias and laterite horizons that separate near-horizontal lava flows, creating a stepped topography of low hills encircled by lava scarps up to 30 m high, most notably on the Duirinish Peninsula of Skye, where they culminate in the twin ziggurats of MacLeod's Tables (488 m and 468 m). On the Trotternish Peninsula, however, the stacked lavas dip to the west, terminating eastwards in the Trotternish escarpment (Fig. 10.2a), which is crowned by several summits over 500 m and reaches its apogee in The Storr (719 m). The sills and sedimentary rocks that surround the lava fields and central igneous

Fig. 10.4 Mountains of Skye and Arran. **a** The Cuillin Hills on Skye, underlain by gabbro and eucrite. The highest summit shown is Sgùrr na Banachdich, 965 m. **b** The granite Red Hills, Skye. **c** Mountains of the outer (coarse-grained) granite in north Arran. The highest summit is Goat Fell, 874 m. (Images: Colin Ballantyne)

complexes rarely form high ground, except in eastern Skye where sandstones of the Torridon Group rise to the twin summits of the Kyleakin Hills (739 m and 733 m), and southern Arran, where hills up to 500 m are underlain by sills or sandstone.

10.2.3 Columnar Jointing

Few geological formations in the Hebridean Igneous Province have attracted more admiration (and tourists) than the columnar jointing exposed in coastal cliffs, particularly on the tiny island of Staffa. The island is composed of four olivine-tholeiite basalt lava flows overlying a basement of tuff, and superb columnar jointing is present in the lowermost flow, which is overlain by an entablature zone of complex jointing (Fig. 10.2b). The development of columnar jointing on Staffa is attributable to convective cooling of the lava by water (Phillips et al. 2013). Inset into the lava colonnades is the most famous sea cave in Scotland, Fingal's Cave, 20 m high and 75 m deep. The cave and its spectacular columnar jointing have inspired a painting by Turner, an overture (*The Hebrides*) by Mendelssohn, and enthusiastic accounts by several poets (Scott, Keats, Wordsworth and Shelley) and even Queen Victoria (Gordon 2012). Fine columnar jointing also occurs in basalt cliffs elsewhere on the coast of Mull, particularly on Ulva and the Ardmeanach peninsula.

Similar columnar jointing is evident in a sea cliff near Lealt in Skye (Fig. 10.1). Aptly named Kilt Rock on account of its pleated appearance, the vertical columnar jointing in the upper part of the cliff is developed in a dolerite sill that rests on Jurassic sandstones. Here the columnar jointing is thought to have developed through slow cooling of the sill from its contacts with the rocks into which it was intruded. The overlying sandstones have been removed by erosion, but the sill forms a caprock that has protected the underlying sandstones from a similar fate. Columnar jointing in sill rocks is also conspicuous on Arran, most notably at the margins of the quartz-felspar-porphyry sill that underlies The Doon, a prehistoric fort near Drumadoon Bay.

10.3 Glacial History

Although there is evidence for pre-Late Devensian sediments on the Hebrides Shelf (Fyfe et al. 1993; Dove et al. 2015), no terrestrial Pleistocene deposits predating the local Last Glacial Maximum (LLGM) have been found on any of the four islands. During the advance, culmination, retreat and demise of the last Scottish Ice Sheet (~35–14 ka), the islands experienced a similar glacial history. As they all nourished glaciers during the Loch Lomond Stade (~12.9–11.7 ka; Sect. 10.4), it seems inevitable that independent icefields or ice caps formed on each island during the initial phase of ice-sheet expansion (~35–32 ka). On Skye, Mull and Arran, the absence of mainland erratics from the main mountain areas indicates that local ice caps persisted throughout the lifetime of the last ice sheet, forming centres of ice dispersal that were confluent with ice flowing from the Scottish mainland; Rùm, however, was over-run by ice from the western Highlands. During the LLGM, ice from central Skye, Mull and north Arran fed ice into the Hebrides Ice Stream, which terminated at the shelf break northwest of Ireland at ~26.7–25.9 ka (Dove et al. 2015; Callard et al. 2018; Fig. 10.5). The Skye Ice Cap also fed the Minch Ice Stream, which terminated at or near at the shelf edge at

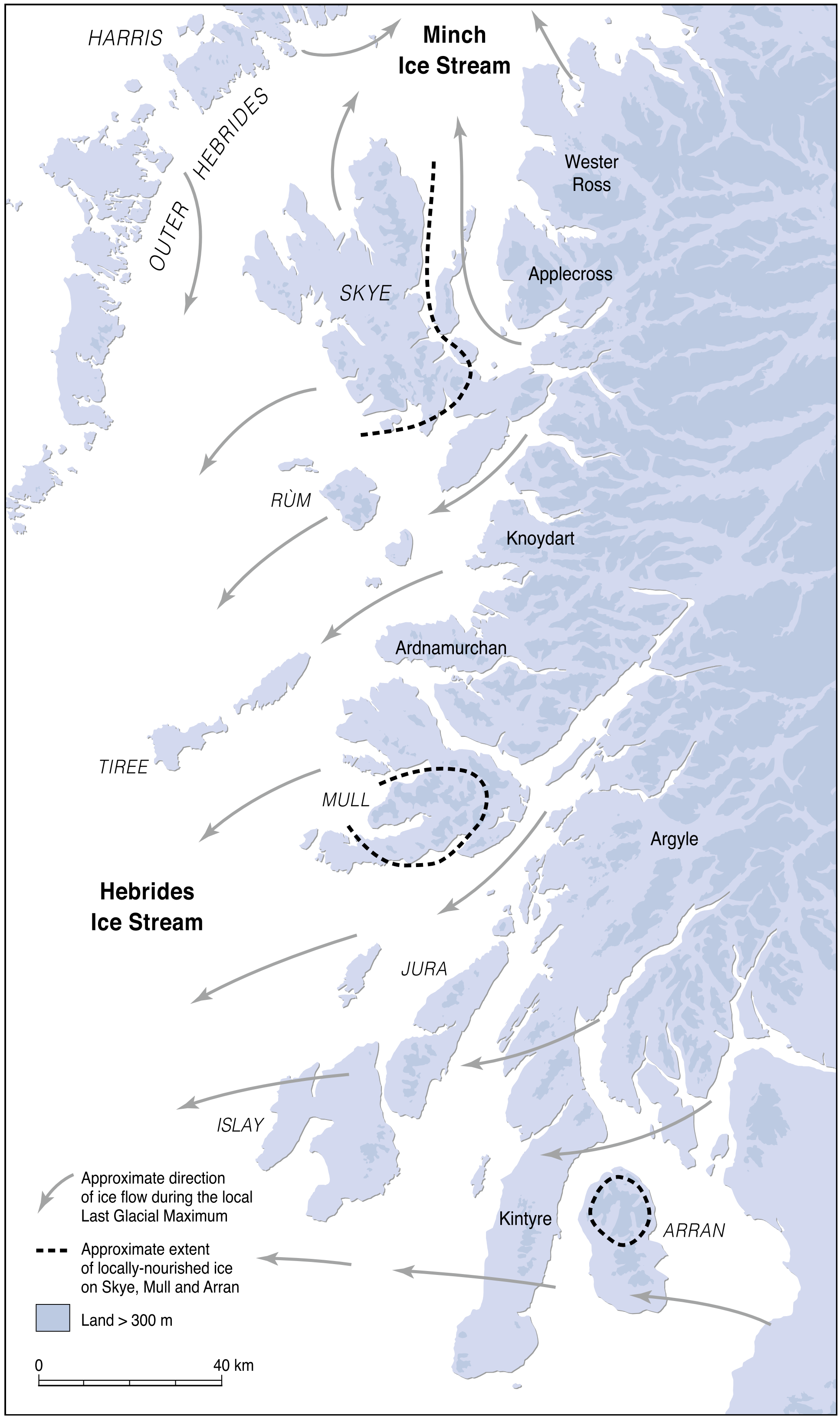


Fig. 10.5 Approximate directions of ice movement in western Scotland and the adjacent shelves during the local Last Glacial Maximum (~30–26 ka)

~30.2–27.5 ka (Bradwell et al. 2019). Retreat of these ice streams resulted in decoupling of local icefields or valley glaciers from mainland ice within the period ~17.0–15.5 ka.

10.3.1 The Last Ice Sheet on Skye and Rùm

On Skye, an independent ice cap covered much the island before being partly encircled by ice advancing from the east (Ballantyne et al. 2016a). Erratics of mainland rocks are restricted to eastern Skye, the Sleat Peninsula and islands of Scalpay and Raasay, but are absent from the mountains of central Skye and the northern peninsulas, suggesting that these areas remained within the domain of the Skye Ice Cap. The distribution of mainland erratics implies that the ice cap diverted mainland ice both northwards into The Minch to feed the Minch Ice Stream and southwestwards to feed the Hebrides Ice Stream (Fig. 10.5).

Terrestrial cosmogenic nuclide (TCN) exposure ages from various sites allow the chronology of the ensuing deglaciation of Skye to be reconstructed. These indicate that the Trotternish hills in northern Skye were deglaciated by ~16.5 ka, Raasay by ~16.2 ka and a site near Strollamus in central Skye at ~16.0 ka (Stone et al. 1998; Small et al. 2012; Bradwell et al. 2019), suggesting that the mainland ice sheet decoupled from the northern margin of the Skye Ice Cap at ~16.0 ka. At several locations there is stratigraphic evidence for expansion of mountain glaciers on Skye following retreat of the mainland ice (Benn 1997). Samples from boulders on readvance moraines in lower Glen Brittle have yielded a mean ^{36}Cl exposure age of ~17.6 ka (Small et al. 2016), but it is likely that the youngest age of 15.5 ± 1.4 ka more accurately reflects of the timing of the readvance. A readvance of Skye ice is also represented by a submarine end moraine that loops around the mouth of Loch Scavaig and onlaps the island of Soay. TCN dating of boulders on the Soay moraine places the culmination of the Loch Scavaig Readvance at 15.2 ± 0.9 ka, approximately coeval with the Wester Ross Readvance on the adjacent mainland (Small et al. 2016; Ballantyne and Small 2019; Chap. 13). The apparent contemporaneity of the Wester Ross Readvance, Loch Scavaig Readvance and (possibly) the readvance represented by the Glen Brittle moraines suggests that late-stage expansion of the residual Skye Ice Cap and mainland ice margin were driven by a pronounced cooling at this time that has been detected in North Atlantic deep-ocean cores (Scourse et al. 2009).

On Rùm, westward-aligned striae and roches moutonnées indicate that the island was over-run by the mainland ice sheet during the LLGM, though basal ice movement was deflected around the mountains of the Rùm Cuillin. Erratics from the mainland are scattered over the north and centre of the island and occur near the summit of Barkeval (591 m) in central Rùm. Ice-moulded bedrock occurs up to 695 m, but the highest summits support shattered rock and periglacial blockfields (Ballantyne and McCarroll 1997), suggesting that they were occupied by a persistent cover of cold-based ice. The timing and pattern of deglaciation on Rùm has not been established, though it is likely that local glaciers persisted on Rùm for some time after retreat of the offshore ice margin.

10.3.2 The Last Ice Sheet on Mull

On Mull, the evidence provided by striae and the distribution of mainland erratics indicates that during the LLGM a persistent ice divide over the central mountains diverted ice from the mainland westward along the Sound of Mull, and southwestward down the Firth of Lorn (Figs. 10.1 and 10.5). Ice from the mainland eventually over-ran all of northern and eastern Mull, as well as the Ross of Mull and Iona in the extreme southwest. Ice-moulded bedrock occurs up to 760 m in the area occupied by the Mull Ice Cap, but the summit of the highest mountain (Ben More, 966 m) hosts a periglacial blockfield of basalt boulders (Ballantyne 1999). The alignment of streamlined submarine bedforms on the shelf adjacent to Mull demonstrates that it occupied the onset zone of the Hebrides Ice Stream, feeding ice to the shelf edge (Dove et al. 2015). The Sea of the Hebrides southwest of Mull was extensively deglaciated by ~20.2 ka (Callard et al. 2018), but for the following ~3 ka the ice margin oscillated in a narrow corridor between Tiree and Mull, backstepping to the Ross of Mull at ~17.5 ka (Small et al. 2016). Over the following millennium the margin of mainland ice gradually retreated, probably leaving residual glaciers occupying the mountains of Mull until the climate warmed at the onset of the Lateglacial Interstade (~14.7 ka).

10.3.3 The Last Ice Sheet on Arran

The history of ice-sheet build-up and changing flow directions on Arran has been reconstructed by Finlayson et al. (2014) from the evidence provided by sequential flowsets derived from streamlined bedforms on Arran and the neighbouring Kintyre Peninsula. During the early stages of ice advance (~35–32 ka), glaciers nourished in the mountains of north Arran merged with southward flow of ice from the SW Highlands down the Firth of Clyde. Subsequent development of an ice divide to the east resulted in westward flow of ice across Arran and Kintyre to feed the Hebrides Ice Stream (Fig. 10.5). Finlayson et al. (2014) suggested that westward ice flow across Arran persisted to ~18.0–17.0 ka, after which southwards flow was re-established and the ice margin advanced into NE Ireland, possibly at ~16.5 ka. The final stage of ice-sheet deglaciation on Arran involved progressive decoupling of glaciers radiating from the mountains of north Arran from southward-flowing ice in the Firth of Clyde. End moraines near valley mouths suggest that glaciers occupying the glens of north Arran readvanced after the retreat of the Clyde ice (Ballantyne 2007). TCN exposure ages obtained for two granite erratics on lateral moraines at Dougarie in west Arran suggest that the readvance of local ice occurred at ~16.2 ka or earlier (Finlayson et al. 2014), but the representativeness of these ages is uncertain (Ballantyne and Small 2019).

Allochthonous erratics occur only along the coastal margins of north Arran, suggesting that during and after the LLGM an ice dome centred over the mountains of northern Arran diverted and fed into the mainland ice sheet. Glacially emplaced perched boulders on several summits suggest that ice over-ran all of the highest ground, but the presence of unmodified tors along ridge crests suggests that the overlying ice was cold-based throughout much or all of the duration of the last ice-sheet glaciation (Finlayson et al. 2014).

10.3.4 The Loch Lomond Readvance

The term 'Loch Lomond Readvance' (LLR) describes the final glaciation in Scotland, which culminated during the Loch Lomond (≈Younger Dryas) Stade of ~12.9–11.7 ka, following the disappearance or near-disappearance of glacier ice under the comparatively temperate conditions of the Lateglacial Interstade (~14.7–12.9 ka). Though it is possible that glaciers persisted on high plateaux and cirques on mainland Scotland during the interstade, it is likely that glaciers disappeared completely from the Hebrides and Arran at this time, as cirque floors are at lower altitudes than those on the mainland, and extensive high plateaux are absent.

The earliest account of a readvance of mountain glaciers in the Hebrides is that of the pioneering Scottish glaciologist James Forbes (1846), who recorded striated and ice-moulded bedrock in the Cuillin Hills of Skye and published a map of an end moraine fronting Coir' a' Ghrunnda in the southern Cuillin. Forbes' account was the forerunner of numerous observations of glacial landforms produced by the readvance of mountain glaciers on Skye, Rùm, Mull and Arran, but until the 1970s no systematic attempt was made to map the landforms associated with these glaciers or reconstruct their former dimensions. The landforms relating to the readvance were later mapped or re-mapped on all four islands (Ballantyne and Wain-Hobson 1980; Ballantyne 1989, 2002, 2007) and employed to delimit its former extent and to reconstruct the three-dimensional form of the readvance glaciers.

The evidence provided by end and lateral moraines, recessional moraines, drift limits and trimlines indicates that during the Loch Lomond Stade substantial icefields developed on the mountainous areas of Skye and Mull and fed outlet glaciers that terminated on land or a short distance offshore (Fig. 10.6). The Cuillin Icefield on Skye occupied an area of ~156 km^2 and the Mull Icefield extended across ~143 km^2. On both islands the central icefield was flanked by cirque glaciers that ranged in size from ~0.4 to ~6.0 km^2. Outlying glaciers also formed on Skye in the form of a small icefield in the Kyleakin Hills, one or two cirque glaciers at the foot of the Trotternish escarpment in northern Skye (Ballantyne 1990) and a small glacier in Duirinish (Ballantyne and Benn 1994). A Loch Lomond Stadial age for the readvance glaciers on Skye and Mull is indicated by stratigraphic evidence: Lateglacial sediments occur in kettle holes and other enclosed basins outside the readvance limits but are absent from similar sites within these limits (Walker and Lowe 1982, 1985; Walker et al. 1988; Benn et al. 1992). Cosmogenic ^{10}Be exposure dating of boulders on readvance moraines at two sites on Skye yielded mean ages of 12.5 ± 0.7 ka and 12.4 ± 0.6 ka (Small et al. 2012; recalibrated in Ballantyne et al. 2016b), suggesting that some readvance glaciers reached their maximum extent in mid-stade. On Mull, a Loch Lomond Stadial age for the readvance is confirmed by calibrated radiocarbon ages of ~13.9–12.6 ka obtained for marine shell and barnacle fragments recovered from till at the western limits of the readvance near Loch Spelve (Bromley et al. 2018).

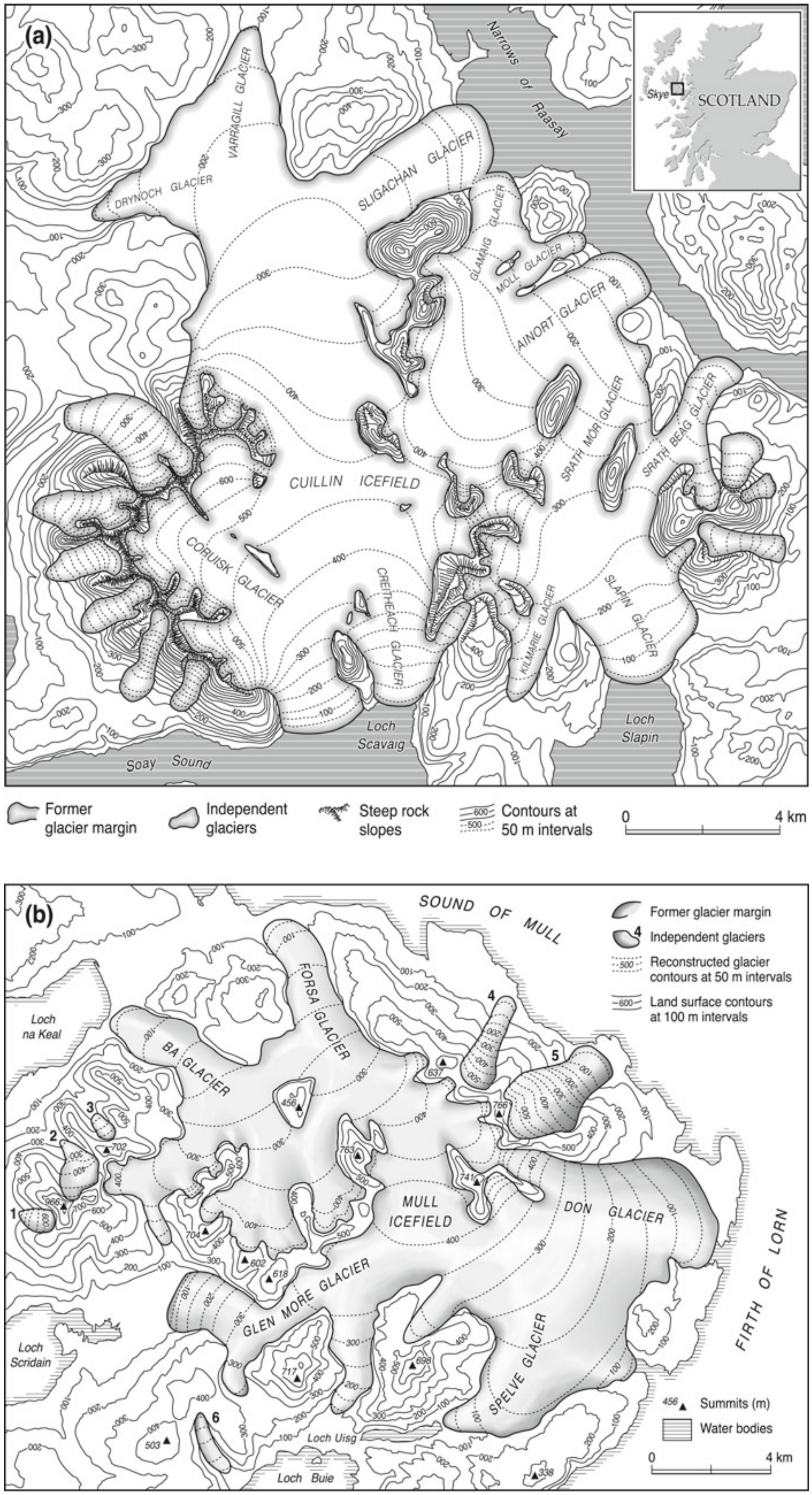
On Rùm and Arran there is evidence for the formation of only small cirque or valley glaciers during the Loch Lomond Stade and none of these apparently exceeded 2.5 km^2 in extent. There is evidence for eight or nine former small glaciers in the Rùm Cuillin, two below the north-facing cirques of the Western Hills on Rùm, and ten in the mountains of north Arran. The readvance moraines on Rùm and Arran have not been dated, and a Loch Lomond Stadial age for the glaciers that formed them has been inferred mainly from absence of Lateglacial periglacial landforms inside the mapped readvance limits.

10.4 Glacial Landforms

10.4.1 Large-Scale Erosional Landforms

Although the islands contain a wealth of depositional landforms and small-scale erosional features that developed during the last (Late Devensian) glacial stage, large-scale landforms such as glacial troughs and breaches, cirques (corries), rock basins, fjords and ice-scoured terrain have a much longer history of development, potentially extending back to the beginning of the Pleistocene at ~2.6 Ma. During

Fig. 10.6 Contoured reconstructions of the maximum extent of Loch Lomond Readvance glaciers in **a** south-central Skye and **b** Mull. (**a** is adapted from Ballantyne (1989) © Longman Group UK Ltd 1989; **b** is reproduced from Ballantyne (2002) © 2002 John Wiley & Sons Ltd)



successive glacial episodes, erosion by mountain glaciers and ice sheets has progressively widened and deepened the pre-glacial valley system, a process aided by rockfall and landslides from the rockwalls of glacial troughs and cirques during intervening interglacials. One consequence of such long-term glacial erosion has been the development of glacial breaches that severed Mull and Skye from the mainland (Sissons 1983).

Glacial troughs on the four islands tend to radiate away from the main mountain masses (Fig. 10.1). This is particularly evident in central Skye, where troughs terminate in fjords that radiate away from the highest ground. A similar radial pattern of troughs is evident in the mountains of Mull and north Arran. Although this pattern is almost certainly inherited from a pre-glacial valley system formed by rivers draining away from the uplifted central igneous complexes, it also suggests that during successive glacial stages radial ice movement predominated. It is notable that glacial breaches on the islands, such as the Srath Mòr and Glen Sligachan–Srath na Creicheach valleys on Skye, are aligned athwart the westward direction of ice flow from the mainland. The most elegant troughs are those developed in granite, such as Srath Mòr on Skye and Glens Sannox and Rosa on Arran (Fig. 10.7a), which in cross-section describe almost perfect parabolas, reflecting the isotropic nature of the rock. Inland rock basins are few and relatively shallow: Loch Coruisk in the Skye Cuillin is no more than 38 m deep (Fig. 10.7b) and Loch Bà on Mull has a maximum depth of 44 m; the largest rock basin is that occupied by Loch Frisa on Mull, 7.2 km long and up to 62 m deep, which is aligned SE–NW along the axis of a dyke swarm and formed a major artery of ice flow across northern Mull.

The numerous cirques within and at the margins of the central igneous complexes and the Northern Granite of Arran also reflect radial outflow of former glaciers, being oriented at all aspects. This radial tendency is strikingly illustrated by the great arc of cirques of the Cuillin Hills on Skye but can also be detected on Mull and Arran (Fig. 10.6). Most cirque floors on Skye, Mull and Rùm are below 400 m, reflecting a westward decline in cirque altitude across Scotland, and are flanked by steep, cliffed headwalls and sidewalls that are skirted by talus accumulations that represent rockwall retreat since the disappearance of the last glaciers (Fig. 10.7c). Three cirques deserve particular mention. Coire Làgan is the archetype of the Cuillin cirques, being surrounded by precipitous rockwalls, flanked by bouldery talus cones, and containing a rock basin; the lip of the cirque supports the finest examples of ice-moulded and striated whalebacks in Scotland (Fig. 10.7d). Coire Cuithir is a broad, low-lying (<200 m elevation) embayment at the foot of the Trotternish escarpment, containing a shallow loch that is dammed by a moraine deposited by a LLR glacier (Fig. 10.8). The floor of the cirque below Sròn an t-Saighdeir in NW Rùm is almost entirely covered by large microgranite boulders that extend in a series of transverse ridges to the terminal LLR moraine, suggesting that the last glacier to occupy the cirque was fed by an extraordinary volume of rockfall debris from the headwall.

The extensive lowland areas of northern Skye and much of Mull that are underlain by stacked lava flows form a distinctive glaciated trap topography of low, stepped, flat-topped hills flanked by lava scarps up to 30 m high. The most impressive landscape of such ice-scoured trap topography is that of the Duirinish peninsula in NW Skye, which is dominated by the flat-topped hills known as MacLeod's Tables, Healabhal Mhòr (468 m) and Healabhal Beag (488 m). By contrast, the low-lying Devonian granite intrusion that forms the westernmost part of the Ross of Mull forms an area of knock-and-lochan topography, where low, ice-scoured hills, whalebacks and roches moutonnées alternate with water- and peat-filled hollows excavated by ice along fracture zones within the granite.

10.4.2 Landforms of Glacial and Glacifluvial Deposition

The most impressive end moraines on the islands are those that formed at the limits of small LLR cirque glaciers. Examples include that below Coir' a' Ghrunnda in the Skye Cuillin, the two end moraines marking the limits of cirque glaciers in the Western Hills of Rùm and the bouldery moraines that record the extent of two small glaciers at the head of North Glen Sannox on Arran (Fig. 10.7e). Elsewhere, limits of cirque glaciers are often marked by arcs of scattered boulders, as at the head of Glen Rosa on Arran (Fig. 10.7f). The development of pronounced end moraines appears to have been conditioned by the amount of sediment carried by the parent glaciers, which in turn appears to reflect the volume of debris deposited on glacier surfaces by rockfalls and avalanches or reworked from talus that accumulated prior to the readvance (Benn 1989). This relationship is strikingly illustrated by the end moraine that forms the limit of a small glacier that occupied Coire Fearchair in the Red Hills of Skye during the Loch Lomond Stade: a massive drift ramp up to 20 m high is located downslope from a rock-slope failure scarp, suggesting that one or more rockslides or major rockfalls supplied the debris that was transported by the glacier to build the ramp (Ballantyne et al. 2016b).

Recessional moraines occur only within 200–300 m of the former termini of most LLR cirque glaciers, suggesting that the termini of these glaciers oscillated close to their limits for a prolonged period before experiencing uninterrupted retreat. Conversely, multiple recessional moraines occur within the limits of the outlet glaciers of the Skye and

Fig. 10.7 Glacial landforms of Skye and Arran. **a** Glacial trough in granite, Glen Sannox, Arran. **b** Lock Coruisk, which occupies a shallow (<40 m deep) rock basin excavated in gabbro, Skye. **c** Coir' a'Ghrunnda, Cuillin Hills, Skye. **d** Striated ice-moulded bedrock whaleback, Coire Làgan, Skye. **e** End moraine of granite boulders at the head of North Glen Sannox, Arran. **f** Arcuate spreads of boulders define the limit of a small glacier that occupied the head of Glen Rosa, Arran, during the Loch Lomond Stade. (Images: Colin Ballantyne)

Mull Icefields (Benn 1992; Ballantyne 2002). In some areas such moraines extend back to glacier source areas, notably on Mull and in the Kyleakin Hills on Skye, indicating that ice-margin retreat was interrupted by minor readvances until the glaciers had shrunk to their sources. In central Skye, however, multiple hummocky recessional moraines occur within a broad zone inside the limits of some of the larger outlet glaciers but are rare or absent farther upvalley. Benn et al. (1992) interpreted this pattern as representing an initial period of slow oscillatory retreat caused by reduction in snowfall, followed by uninterrupted ice recession and localised ice stagnation initiated by rapid warming after ~11.7 ka. However, July temperature reconstructions based on Lateglacial chironomid assemblages at various sites in

Fig. 10.8 Coire Cuithir, a deep embayment in the Trotternish escarpment of northern Skye. The floor of the cirque is only 180 m above sea level. The cirque was occupied by a small (~1.7 km^2) LLR cirque glacier that deposited the end moraine on the left. (Image: Colin Ballantyne)

Scotland indicate gradual summer warming during the later part of the stade (Brooks et al. 2016), suggesting that initial pulsed retreat may also represent a response to gradual increases in ablation-season temperatures.

Outwash deposits associated with the Loch Lomond Readvance are fragmentary on Skye, Rùm and Arran but well represented on Mull by broad terraces of kettled outwash 10–20 m above present sea level at the outlet of Loch Bà and in lower Glen Forsa. These features indicate that relative sea level was below ~10 m when the glaciers occupying these locations achieved their maximum extent (Gray and Brooks 1972).

10.5 Periglacial and Aeolian Landforms

10.5.1 Relict Periglacial Features

Relict periglacial phenomena include both features of pre-Late Devensian age that escaped glacial erosion during the LLGM because they were covered by cold-based ice (Fabel et al. 2012; Fame et al. 2018) and Lateglacial landforms that developed after ice downwastage exposed mountains to frost action on ground underlain by permafrost. Of the former, the most widely represented are summit blockfields. Some are expanses of openwork, frost-heaved boulders, as on the basalt summit of Ben More on Mull and the microgranite summits of the Western Hills on Rùm. Others are composed of clasts embedded in fine sediment, particularly on the granite summits of northern Arran and Skye. On Arran, granite tors are studded along ridge crests (Fig. 10.4c), notably those at the summit of Caisteal Abhail (859 m), and low tors rise above basalt blockfields along the Trotternish hills on Skye. In some areas a trimline representing the upper limit of glacial erosion marks the lower limit of blockfield debris, notably on the Trotternish hills (Ballantyne 1990). Although such trimlines were originally interpreted as indicating the maximum altitude of the last ice sheet, they are now considered to represent an englacial boundary between warm-based sliding ice on lower ground and cold-based ice on summits, implying that the last ice sheet was polythermal (Fame et al. 2018). Above-trimline bedrock surfaces on the Trotternish hills have yielded apparent ^{36}Cl exposure ages >50 ka, indicating limited erosion by the last ice sheet, whereas bedrock outcrops on cols below the trimline have produced (recalibrated) exposure ages of ~16.5 ka, consistent with the timing of ice-sheet deglaciation (Stone et al. 1998).

During the Lateglacial period, frost debris moved downslope to form bouldery stone-banked lobes. These are most abundant on moderate upper slopes underlain by granite in Skye and Arran, but also occur on high ground underlain by sandstone on the Kyleakin Hills of Skye and on both felsic and mafic igneous rocks on Rùm. On Arran, they terminate at or close to the limits of LLR glaciers (Ballantyne 2007), indicating that movement ceased at the Lateglacial–Holocene transition (~11.7 ka) as the climate warmed and permafrost degraded.

10.5.2 Active (Holocene) Periglacial Landforms

Active periglacial landforms on the four islands are best represented on high ground underlain by lavas that have weathered to produce silt-rich, frost-susceptible soil. Shallow active solifluction lobes, ploughing boulders and frost-sorted circles and stripes up to 0.6 m wide occur above ~580 m on the basalt lavas of The Storr and Hartaval in northern Skye and Ben More on Mull (Godard 1965). Miniature frost-sorted nets and stripes produced by growth and collapse of needle ice occur on bare ground underlain by various igneous rocks on Skye, mostly above 600 m. Earth hummocks (thúfur) up to 0.3 m high are developed on aeolian deposits near the summit of The Storr in Trotternish, and locally grade into nonsorted relief stripes that run obliquely across gentle slopes. As the parent aeolian deposits are of Holocene age (Sect. 10.5.5), such features may still be actively developing, though whether they represent the products of frost heave or selective erosion by surface wash (or both) is unknown.

10.5.3 Periglacial Landscapes of the Western Hills of Rùm

The rolling plateau and surrounding slopes of the Western Hills of Rùm (Sròn an t-Saighdeir, 522 m and Orval, 571 m) occupy an area of only ~5 km^2 yet contain a greater range of periglacial features than any comparable mountain area in Scotland (Godard 1965; Ryder and McCann 1971; Ballantyne 1993; Fig. 10.9). To a large extent this reflects geological contrasts: Sròn an t-Saighdeir and the surrounding slopes are underlain by densely-jointed microgranite, which has weathered to produce an openwork blockfield of boulders up to ~1.2 m long, whereas much of Orval is underlain by hawaiite lavas that support a regolith of smaller clasts embedded in frost-susceptible soil.

On Sròn an t-Saighdeir the summit blockfield is flanked by cirques to the north and debris-mantled slopes (blockslopes) on other aspects. West of the summit, the latter extend down to 270 m, where they terminate at the crest of sea cliffs. Former downslope movement of debris by

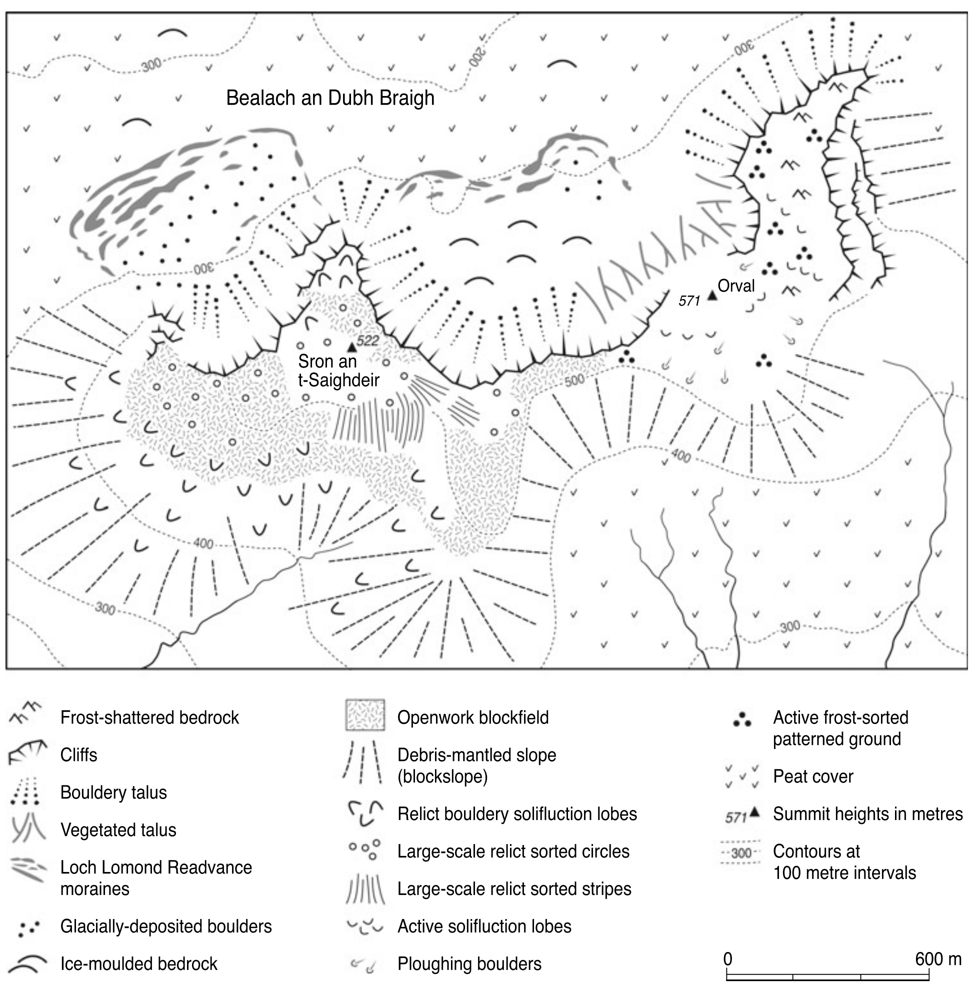


Fig. 10.9 Glacial and periglacial landforms on the Western Hills of Rùm (Adapted from Ballantyne 1984)

solifluction operating over permafrost is evident in the form of relict boulder terraces and lobes that extend down to ~380 m. The plateau and adjacent gentle slopes also support relict frost-sorted circles and nets 2.0–3.0 m in diameter, and sorted stripes of similar width, now represented by vegetation-covered cells or stripes of clasts embedded in fine sediment alternating with borders or stripes of openwork boulders. Such large-scale relict sorted patterns are thought to develop through differential frost heave in the active layer above permafrost (Ballantyne and Harris 1994; Ballantyne 2018) and thus provide evidence for permafrost during the Lateglacial period.

By contrast, the frost-susceptible regolith on the lavas adjacent to Orval supports a range of active periglacial features, including vegetated solifluction lobes with low, steep risers, ploughing boulders and small-scale frost-sorted patterned ground. The sorted patterns mainly occur on deflation scars above 500 m, and include sorted circles, polygons and nets up to 0.5 m in diameter and miniature sorted stripes, 0.2–0.3 m in width, formed by differential growth of needle-ice during periods of superficial ground freezing and enhanced by frost heave of the finer sediment during periods of deeper freezing (Ballantyne 2018).

10.5.4 Aeolian Landforms

The effects of wind erosion are evident on high ground on all four islands. Deflation surfaces (expanses of boulders and lag gravels from which fine soil and vegetation cover have been stripped by wind) occur on the Red Hills and Trotternish hills on Skye, and smaller deflation scars carpeted by lag gravels are present on plateaux, ridge crests and cols above 450–500 m, notably on Ben More on Mull and the Trotternish hills. On some upper slopes, regularly-spaced wind stripes (alternating bands of vegetated and unvegetated ground) have been transformed into flights of turf-banked terraces, where bands of vegetation aligned across-slope have arrested downslope creep of debris to form horizontal step-like terraces with vegetated risers up to a metre high. On Skye, turf-banked terraces are widespread above 550 m on the Red Hills, and north of the summit of Hartaval (668 m) in Trotternish. An uncannily regular suite of turf-banked terraces comprising vegetated risers 0.3–0.6 m high and perfectly horizontal treads covered in small clasts occurs at ~600 m on the Ruinsival ridge in SW Rùm, probably the most perfect example of this type of landform on any Scottish mountain.

Aeolian deposits in the form of vegetation-covered sand sheets up to a metre thick occur on several mountains in the Inner Hebrides, notably on the lavas of Ben More on Mull, the mafic and ultramafic rocks on Rùm, and the granitic rocks that underlie the Red Hills on Skye. Some of those on the Red Hills consist of a lower unit of weathered, windblown sand overlain by a unit of fresh sand. The latter represents recent widespread erosion of soils and sand deposits from upwind deflation surfaces; luminescence dating of these deposits has shown that the onset of upper-unit sand deposition coincided with the exceptionally stormy conditions of the Little Ice Age of the sixteenth to nineteenth centuries (Morrocco et al. 2007).

10.5.5 Aeolian Deposits on the Storr

The most remarkable high-level aeolian deposits in the Hebrides are those that blanket the summit of The Storr (719 m) in northern Skye. Here the highest ground is covered by a cap of vegetation-covered windblown sediment up to 2.9 m thick that covers an area of 33,000 m^2 (Fig. 10.10). Both the thickness and particle size of the deposits decline away from the edge of the adjacent cliff. These trends suggest that grains released from the cliff by weathering have been entrained by strong winds that accelerated upwards on meeting the cliff face, and that deceleration of airflow above the cliff caused the suspended particles to rain down on the summit plateau, where they were trapped by vegetation cover, slowly accumulating to form the summit sand sheet (Ballantyne 1998). The cliff that formed the source of the windblown sediment was exposed by the Storr landslide at 6.1 ± 0.5 ka (Sect. 10.6.2), and radiocarbon dating of organic material from the base of the sand sheet has shown that it began to accumulate sometime between 7.1 ka and 5.7 ka, suggesting that exposure of the cliff initiated sediment accumulation on the summit. Radiocarbon dating of organic material within the windblown sediments has allowed calculation of average rates of sand accumulation, which ranged from about 14 mm per century near the downwind edge of the sand sheet to roughly 60 mm per century in the thickest deposits near the cliff crest.

10.6 Postglacial Landslides, Talus Accumulations and Debris Flows

Large inland postglacial rock-slope failures are rare on most lithologies on the four islands. Two rockslides have been identified on the Torridonian sandstone of the Kyleakin Hills in eastern Skye, and another occupies the northeast face of Glas Bheinn Mhòr, a granite mountain in the Red Hills. Foundering of basalt lavas that overlie weak sedimentary rocks, however, has produced the largest and most dramatic landslides in the British Isles.

Fig. 10.10 Aeolian sand deposits on the summit of The Storr (719 m), northern Skye. The inset shows a pit, 2.9 m deep, excavated in the deposit. At the base of the pit an organic soil dated to ~7.1 ka overlies frost-weathered regolith. (Images: Colin Ballantyne)

10.6.1 The Trotternish Landslides

The Trotternish Peninsula is dominated by the Trotternish escarpment, which extends north–south along much of the peninsula and comprises stacked lava flows overlying Jurassic sedimentary rocks that crop out to the north and east (Fig. 10.2a). Transgressive dolerite sills occur deep within the Jurassic strata and the entire sequence dips gently westwards. Displaced rock masses extend continuously along the foot of the escarpment. The area of landsliding comprises an inner zone of detached blocks, representing slope failure since retreat of the last ice sheet at ~16.5 ka, and an outer region of undulating terrain consisting of older landslide blocks that have been over-ridden by successive ice sheets (Fig. 10.11). Postglacial rock-slope failure along the escarpment takes several forms. Resting against or detached from the scarp are large, intact lava blocks have experienced lateral movement with limited vertical displacement. Elsewhere, detached lava blocks are back-tilted or tilted away from the scarp face. Not all failures have involved block displacement: others take the form of large-scale rockfalls, sometimes with debris runout, as on the northern spur of The Storr, where a tongue of coarse debris 260 m wide and 500 m long descends from the foot of the scarp (Ballantyne 2016).

Interpretation of the structure of the Trotternish landslides has focused on the Storr and Quiraing landslides. Few landforms in Scotland are more impressive than the Storr landslide—'cette topographie anarchique' as Godard (1965) described it. The landslide receives over 200,000 visitors each year and is probably the most photographed landform in Scotland. The entire south face of The Storr (719 m) has collapsed to create a large hollow, Coire Faoin, bounded by lava cliffs 200 m high. The undercliff zone is a labyrinth of lava blocks, narrow clefts and pinnacles of shattered rock, of which the 49 m high Old Man of Storr is the most impressive (Fig. 10.12a). The dip of the lavas in the zone of postglacial landsliding is eastwards, indicating that failure was dominantly translational, along a failure plane within the underlying Jurassic shales. ^{36}Cl exposure dating of rock samples chiseled from the tops of basalt pinnacles indicates that the landslide occurred at 6.1 ± 0.5 ka (Ballantyne et al. 1998, 2014), about 10,000 years after deglaciation of the site.

The Quiraing landslide complex is the largest in Scotland, covering ~8.5 km^2 and extending ~2.2 km from the scarp crest to the coast. It comprises an inner zone of tabular blocks (Fig. 10.12b), narrow corridors and rock pinnacles formed by failure since deglaciation, and an outer zone of more subdued landslide blocks that represent ancient landslides that occurred before the last (and probably earlier) ice sheet(s) crossed the area. The backscarp and some of the slide blocks have rectilinear geometries controlled by pre-existing discontinuities (Fenton et al. 2015). The deep structure of the Quiraing landslide is complex. Anderson and Dunham (1966) inferred that a thickness of ~200 m of sedimentary rocks and tuff had failed under the weight of ~300 m of stacked lava flows as successive rotational slides seated on a westward-dipping dolerite sill. However, several large landslide blocks have moved laterally from the

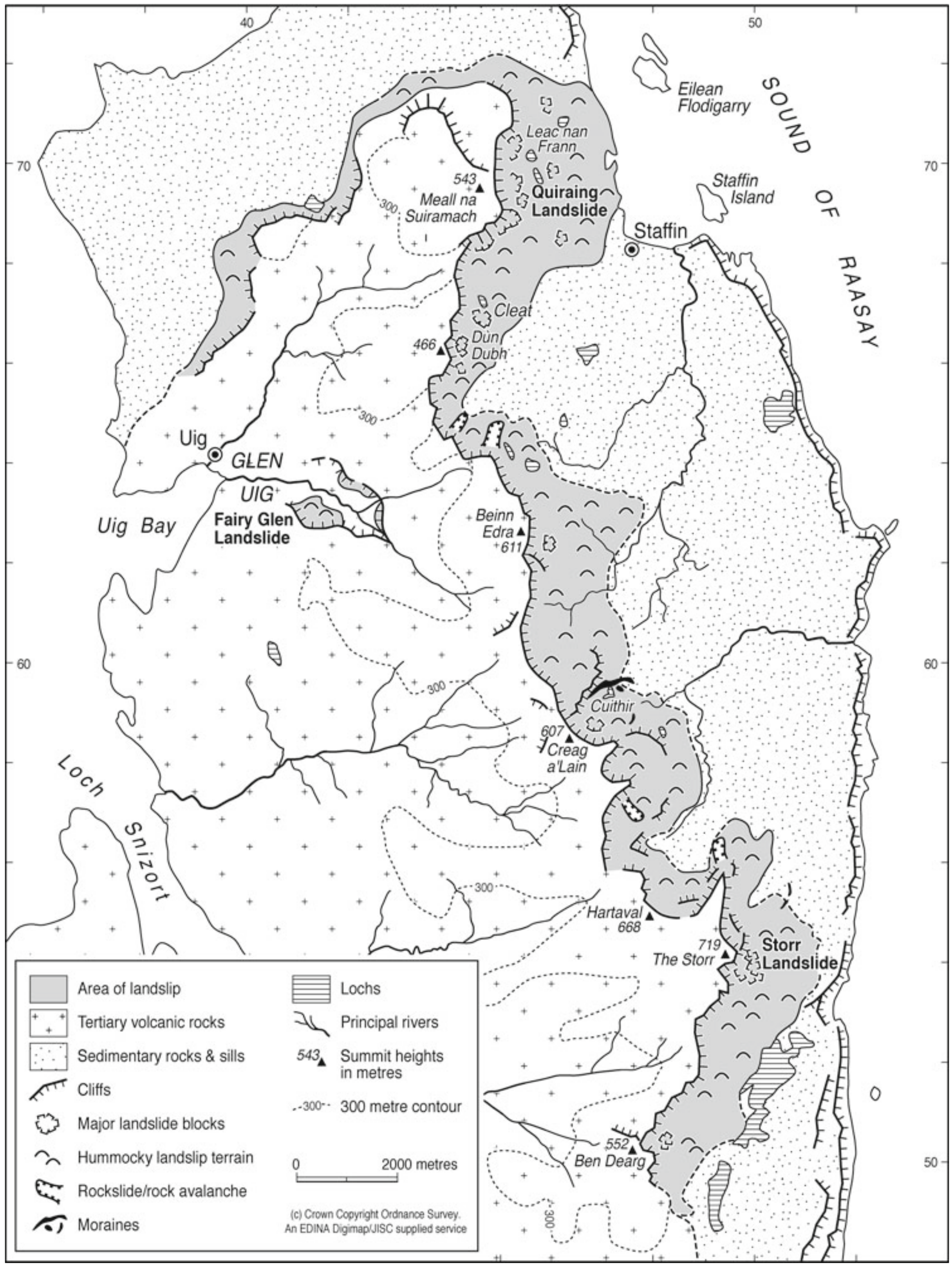


Fig. 10.11 The Trotternish Peninsula, northern Skye, showing the approximate extent of landslide terrain and the location of the Storr, Quiraing and Fairy Glen landslides. (From Ballantyne 2016)

headscarp without back-tilting, leading Martin (2011) and Fenton et al. (2015) to conclude that postglacial landsliding has been dominated by translational sliding of detached blocks over a failure plane within the underlying shales, with toppling of intact rock masses in the gaps created by extensional block detachment and minor rotation of blocks at the margins of the zone of postglacial failure. More speculatively, they suggested that the outer zone of the landslide involved block rotation as a result of reactivation of listric faults in the underlying Jurassic sediments.

The causes of the Storr and Quiraing landslides are incompletely understood. Both may represent a response to paraglacial stress release, but it is possible that the thick sills that are intruded into the underlying shales have acted as aquicludes, allowing high water pressures to build up in the shales, thereby destabilizing the overlying lava pile. At the Quiraing there is evidence that although most of the landslide complex is now stable, occasionally this sleeping giant stirs: there are reports of earth tremors at Flodigarry, on the seaward margin of the complex. Anderson and Dunham (1966, p. 192) considered that 'continuous though not extensive movement' had caused frequent dislocation of the road crossing the distal margin of the complex, and Fenton et al. (2015, p. 182) noted 'areas of ongoing movement,

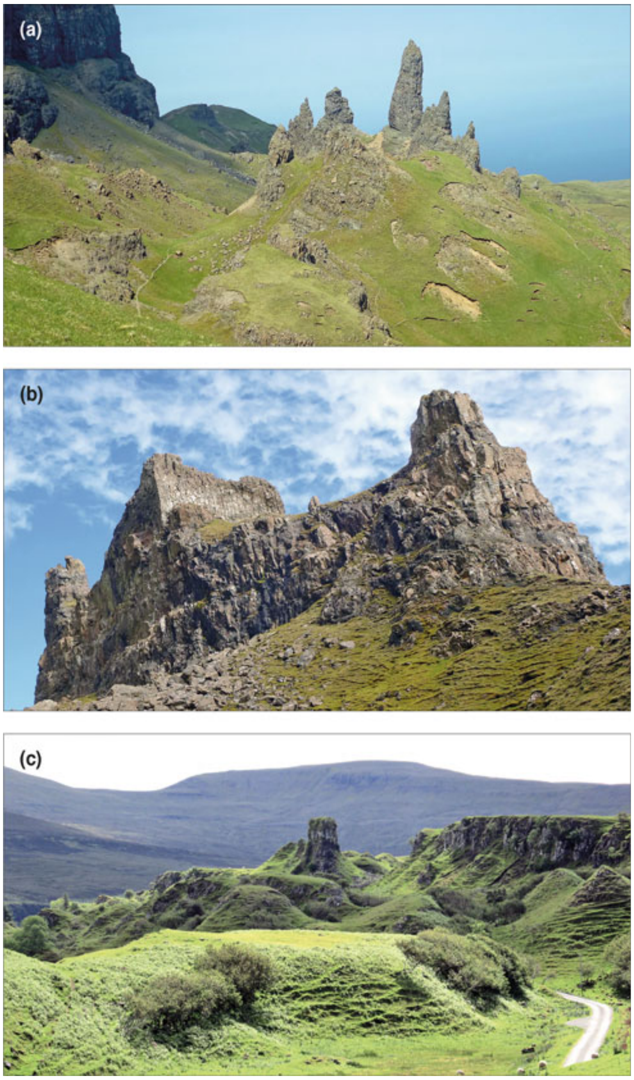


Fig. 10.12 The Trotternish landslides. **a** The Storr landslide. The pinnacled area represents a shattered lava block that slid and tilted eastwards from the cliffs in the background. The highest pinnacle is the 49 m high Old Man of Storr. **b** The Prison, a lava block that forms part of the postglacial failure zone of the Quiraing landslide. **c** Displaced lava blocks of the Fairy Glen landslide. The conspicuous tower is Castle Ewen, which apparently moved laterally from the basalt headscarp on the right with limited vertical displacement. (Images: Colin Ballantyne)

especially where the toe of the slide is expressed in weak, thinly laminated shales'.

The dramatic geomorphology of the Storr and Quiraing landslides has overshadowed that of landslides in Glen Uig, a valley underlain by Jurassic shales in western Trotternish. Here the landslides are located on the dip slope, and the lava headscarps are much lower. The largest (0.5 km^2) of the Glen Uig rock-slope failures is the Fairy Glen landslide on the south side of the glen, which extends up to 370 m northwards from its headscarp. The outer landslide blocks form degraded hummocks that may have been modified by glacial erosion (Fenton et al. 2015) but the inner zone consists of tabular blocks, of which Castle Ewen (Fig. 10.12c) is the most impressive. Murphy (2011) observed that the dip of the lavas in the inner zone is identical to that of the headscarp and concluded that failure had occurred through lateral translational sliding of stacked lavas over the underlying shales, with localized rotation and toppling of segments as gaps opened between detached blocks.

10.6.2 Other Failures of Palaeogene Lavas

The structural configuration of stacked Palaeogene lava flows overlying weaker rocks that has favoured large-scale postglacial rock-slope failure on Trotternish is replicated at several other sites on Skye and on Mull. At Ben Tianavaig, 4 km southeast of Portree on Skye, Jurassic sedimentary rocks ~300 m thick are sandwiched between the overlying lavas and an underlying dolerite sill. The entire seaward face of the mountain has collapsed, forming a landslide complex ~2 km^2 in area that extends over a kilometre from the headscarp to terminate at coastal cliffs. Cheng (2013) has shown that the landslide consists of a series of largely intact, back-rotated lava blocks interrupted by localized toppling failures, and that the planform of the headscarp follows discontinuities (faults and dykes) that formed zones of weakness in the lava pile.

On Mull, the largest rock-slope failure involving Palaeogene lavas is the Coireachan Gorma landslide on Ardmeanach. The failed mass covers ~0.8 km^2 and extends up to 0.5 km from the cliffed headscarp to terminate at coastal cliffs up to 50 m high. The landslide is dominated by four large back-tilted blocks indicative of deep-seated rotational sliding that was probably seated in the underlying schists or sandstones. The interpretation of a large, multi-ridged steep-fronted rampart at the foot of the same lava scarp near Gribun has proved contentious. Dawson et al. (1987) concluded that the rampart is a moraine deposited by a niche glacier during the Loch Lomond Stade, but Ballantyne (2002) argued that the Gribun debris accumulation represents the runout of a postglacial rock-slope failure. Pollen-stratigraphic evidence suggests that the ridge formed prior to ~11.9 ka and possibly prior to ~12.5 ka.

10.6.3 Talus Accumulations and Debris Flows

Talus slopes formed through the incremental accumulation of rockfall debris at the foot of cliffs are common on the islands; most are paraglacial landforms that mainly accumulated soon after deglaciation. The most impressive taluses are those skirting cliffs in the Cuillin Hills, where the coarseness of rockfall debris has inhibited vegetation and soil development. By contrast, the talus slopes that skirt the foot of basalt cliffs, such as those near Gribun on Mull or at the foot of Ben Meabost on Skye, are completely vegetated.

Much of our understanding of the evolution of talus accumulations in Scotland stems from research on the Trotternish escarpment. These taluses support a complete cover of soil and vegetation but are incised by deep gullies, exposing sections that have permitted investigation of their structure, radiocarbon dating of buried organic soil horizons and reconstruction of their evolutionary history (Hinchliffe et al. 1998; Hinchliffe 1999).

The Trotternish taluses form rectilinear slopes resting at 36°–42° with short slope-foot concavities, and ~27–30% of the talus debris comprises fine sediment derived from granular weathering of the source rockwalls. Sections in gully walls have revealed in situ rockfall debris overlain by stacked debris-flow deposits intercalated with slopewash deposits and palaeosols. Radiocarbon dating of these palaeosols has shown that reworking of talus by debris flows has occurred episodically throughout the Holocene. Gully erosion and deposition of debris-flow deposits was apparently initiated at the crest of talus slopes, then extended downslope, ultimately resulting in the deposition of small debris cones at the slope foot. Calculations based on talus volume indicate that 4.3–7.8 m of cliff retreat has occurred since deglaciation (~16.5 ka). It is likely, however, that most of the talus accumulated during the Lateglacial period as a result of joint opening through paraglacial stress release and frost-wedging under severe periglacial conditions prior to ~11.7 ka (Hinchliffe and Ballantyne 1999). During the Holocene, gully erosion has replaced rockfall accumulation as the dominant process operating on the Trotternish taluses.

Recent debris-flow activity on the islands is evident from fresh flow tracks (marginal levées and terminal lobes) on many mountain slopes, particularly on granites that have weathered to produce sandy regolith. By far the highest density of debris-flow tracks (locally more than 30 per kilometre of slope) occurs in the Red Hills of Skye, where tracks originating in bedrock gullies on upper slopes terminate in mid-slope, at slope-foot debris cones or occasionally at valley-floor stream channels (Milne et al. 2015). The east slope of Beinn Dearg Mhòr (731 m) near Loch Ainort is a representative example. At this location at least four rainstorm-triggered debris-flow events occurred in the period 1981–2016, making this and neighbouring areas amongst the most active sites of debris-flow activity in Scotland.

10.7 Coastal Geomorphology

Rock coasts dominate the littoral of Skye, Mull and Rùm, in the form of cliffs, ramps, boulder-strewn intertidal shore platforms and raised rock platforms, sometimes partly buried under Lateglacial or Holocene beach deposits. Sandy beaches and coastal dunes are rare, and machair deposits (windblown sediment composed mainly of shell fragments) are mainly limited to Iona and the Ross of Mull. The coastal geomorphology of Arran is more varied, with fewer coastal cliffs but extensive areas of intertidal or raised shore platforms, and several sandy beaches. Of these, the most interesting are those along the south coast of the island, where numerous Palaeogene basalt dykes have acted as natural groynes to trap small sandy beaches, one of which is sufficiently secluded to be designated one of Scotland's three naturist beaches.

10.7.1 Coastal Landslides

The cliffed coastlines of all four islands are scarred by landslides, including some historic failures attributable to undercutting by wave action, such as that at An Scriodan in northern Arran, which occurred about 300 years ago. The largest coastal landslides are those where lavas or sills overlie weaker rocks, and even some 'inland' rock-slope failures such as the Quiraing, Ben Tianavaig and Coireachan Gorma landslides terminate at the shoreline, where wave erosion is thought to contribute to ongoing local instability (Fenton et al. 2015).

At least 18 major coastal landslides occur along the cliffed coasts of northern Skye. The largest coastal landslide in Scotland is that at Scòre Horan, on the east coast of the Waternish peninsula. The headscarp of this landform coincides with the outcrop of Palaeogene lavas and is over 2 km long and up to 60 m high. The area of failed rock covers ~1.2 km^2 and is mainly underlain by Jurassic siltstone and mudstone, though a dolerite sill underlies the uppermost part of the failed mass and another crops out at its toe. The inner part of the slide consists of back-tilted blocks, but whereas those abutting the headscarp are angular, most are rounded, indicating that they have been modified by glacial abrasion and that postglacial failure has been limited to a narrow zone below the headscarp. A Lateglacial raised shore platform at 12.5–14.0 m OD (Ordnance Datum) cuts across the landslide toe and is overlain by raised beach deposits (Richards 1971). Another huge coastal landslide has occurred at Waterstein Head in NW Skye, where the 50–60 m high headscarp also coincides with the edge of the lava outcrop, and a failed mass of rock ~0.45 km^2 in area is seated on Jurassic sedimentary rocks. Multiple transverse ridges on the landslide suggest that multiple or successive rotational failures occurred within the sedimentary rocks. The toe of landslide terminates in a low cliff that is currently being eroded by wave action.

Not all coastal landslides caused by failure within sedimentary rocks overlain by lavas terminated on land. The

Fig. 10.13 Coastal landforms on Skye and Mull. **a** Coastal landslide at Carn Mòr, on the shores of Loch Scavaig, Skye. Failure seated in shales has caused collapse of the overlying cap of basalt lavas. **b** The Lateglacial rock platform in eastern Mull, which is thought to have formed through a combination of frost-wedging of rock and wave erosion during the Loch Lomond Stade. **c** High rock platform fragment ~19 m above sea level near Staffin Bay, northern Skye. **d** Postglacial raised beach, ~7 m above sea level, at the head of Loch Slapin, Skye. The moraines on the right were deposited by an outlet glacier of the Skye Icefield during the Loch Lomond Stade at ~12.4 ka. (Images: **a, d** Colin Ballantyne; **b** Murray Gray; **c** John Gordon)

runout zone of a coastal landslide on the seaward slopes of Ben Cleat, near Elgol in southern Skye (Fig. 10.13a) extends up to a kilometre offshore in the form of chaotic submarine hummocks and ridges (Small et al. 2016). Several large indentations in basalt or dolerite cliffs along the shores of Skye and Mull probably represent the sites of major coastal landslides where the runout zone is submerged or represented by low skerries.

10.7.2 Rock Platforms

Rock platforms (coastal benches eroded in bedrock, often with a backing cliff) are present on all four islands. Sissons (1983) proposed that these fall into three categories: (i) low-level interglacial platforms; (ii) a glacio-isostatically tilted Lateglacial rock platform; and (iii) high rock platforms at altitudes above ~18 m OD. The first category consists of platform fragments close to the present tidal range that locally support glacially moulded rock outcrops and sometimes pass below till bluffs. Such low-level platforms were considered by Dawson (1980a) to be inherited landforms that developed during interglacials, locally modified by postglacial marine erosion. The Lateglacial rock platform (also referred to as the Main Rock Platform or Main Lateglacial Shoreline) is generally 50–150 m wide with backing cliffs typically 15–20 m high (Fig. 10.13b), and supports relict sea stacks and arches, indicating formation since ice-sheet deglaciation. This shoreline has a maximum altitude of 10–11 m OD in the Loch Linnhe area and eastern Mull, and declines away from the centre of glacio-isostatic uplift in the western Highlands at average gradients of 0.13–0.18 m km^{-1} (Gray 1974; Dawson 1988). It is consequently present as an intertidal feature in southern Skye, eastern Rùm and southern Arran. Because it occurs only outside the limits of the LLR, exhibits no evidence of glacial modification and is well developed in areas of limited fetch, several authors have argued that it formed rapidly under periglacial conditions during the Loch Lomond Stade through a combination of frost-wedging of bedrock and removal of debris by storm waves and sea ice (Sissons 1974, 1983; Dawson 1980b). This platform exhibits abrupt vertical dislocations of 1.0–2.7 m at sites on Mull, providing evidence of postglacial fault movements (Firth and Stewart 2000).

The high rock platform fragments of the Inner Hebrides are amongst the most intriguing landforms in Scotland. They are up to 700 m wide and are most extensively developed on the west coasts of Islay and Jura (Chap. 11); those on the coasts of western Mull and NW Rùm tend to be narrower (~20–200 m) but extend for several kilometres along the coastline. They range in altitude from ~18 m OD to ~51 m OD (~24–30 m on Skye; ~18–33 m on Rùm and ~25–51 m on Mull and adjacent islands; Fig. 10.13c), though some of the higher (>40 m OD) fragments mapped on Mull may be lava benches rather than the products of marine erosion. In some areas, platform fragments at different altitudes occur in proximity, indicating that they are not part of the same former shoreline. Some are reported to be ice-moulded or overlain by till, but others exhibit no evidence for glacial modification. High rock platforms are limited to west of a line that extends through Skye, Mull and Jura to eastern Islay (Fig. 10.14). This distribution prompted Sissons (1982, 1983) to argue that they represent fragments of glacio-isostatically-uplifted intertidal rock platforms that formed through frost action and storm-wave activity during successive glacial periods when ice-sheet margins lay east of the line depicted in Fig. 10.14. More radically, Dawson et al. (2013) have suggested that the high rock platforms are remnants of a formerly more extensive glaciated strandflat surface of Pliocene age. It is also possible that some of the high rock platform fragments of the Inner Hebrides were formed under periglacial conditions during the retreat of the last ice sheet. TCN dating has shown that retreat of the Hebrides Ice Stream was succeeded by a period of ~3000 years (~20–~17 ka) when an oscillating ice margin was located amid the islands of the Inner Hebrides (Small et al. 2017; Fig. 10.14). Palaeotidal modelling indicates that this zone experienced megatidal conditions during this period (Scourse et al. 2018), which would have favoured coastal erosion and removal of debris released by frost wedging of bedrock. Oscillation of the ice margin during this period may explain why some high-level platform fragments exhibit evidence for glacial modification, whereas others do not.

10.7.3 Other Raised Shorelines

Coastal terraces eroded in drift and raised depositional features on the islands fall into two groups: high Lateglacial shorelines and lower shorelines that represent Holocene marine transgressions. Both sets of features decline in elevation away from the centre of glacio-isostatic uplift in the western Highlands, though the gradient of the Holocene features is much gentler than that of the Lateglacial shorelines.

Lateglacial shorelines occur at various altitudes up to 34 m OD on all four islands, mainly at the heads of sheltered bays, and are absent at coastal sites on Skye and Mull where LLR glaciers entered the sea. In some locations, abrupt drops in the Lateglacial marine limit are associated with stillstands or readvances that interrupted the retreat of the last ice sheet. At the mouth of Glen Brittle on Skye, for example, terraces marking the marine limit at 18–20 m OD terminate abruptly upvalley and the marine limit drops to ~7 m OD (Walker et al. 1988). This fall in the marine limit coincides with the maximum extent of a readvance of glacier ice in Glen Brittle, represented by end and lateral moraines that have been TCN-dated to ~17.6 ka (Small et al. 2016), though as noted in Sect. 10.3.1 an age of ~15.5 ka seems more probable. Similarly, on Arran, the Lateglacial marine limit is represented by raised beaches and raised deltas in sheltered bays, such as Brodick Bay and Drumadoon Bay, and rises northwards from ~27 m in the south of the island to ~32 m farther north (Gemmell 1973). In the northernmost part of the island, however, it occurs no higher than ~18 m, suggesting that glacier ice continued to occupy northern Arran after the rest of the coastline was exposed to the high Lateglacial sea.

Some of the most impressive raised shoreline features are of Lateglacial age. On Skye, these include a well-developed erosional platform up to 500 m wide cut across till at ~18 m OD at the head of Staffin Bay, and a raised tombolo, up to 30 m above present sea level, that connects a small offshore island to the coastline at The Braes near the mouth of Loch Sligachan. At Harris on the west coast of Rùm, superb Lateglacial shingle and cobble ridges rest at up to 29 m OD on the high rock platform (McCann and Richards 1969). On Mull, the most striking Lateglacial depositional coastal feature is a raised delta at the head of Loch Don, which was deposited at the retreating ice-sheet margin when relative sea level stood at an altitude of ~34 m OD and was later partly modified by ice advance during the Loch Lomond Stade (Benn and Evans 1993). On Arran, the most impressive Lateglacial coastal feature is a raised delta at Dougarie on the west coast, which occupies an area ~0.3 km^2, slopes seaward from ~32 m to ~30 m OD and formed when glacier ice occupied adjacent Glen Iorsa (Finlayson et al. 2014).

Because of oscillations in relative sea level at a time of continuing glacio-isostatic uplift, Holocene raised shorelines around Scotland are not all of the same age (Smith et al. 2012, 2019). In the Inner Hebrides, the Holocene marine limit is thought to have been reached between 5.8 ka and

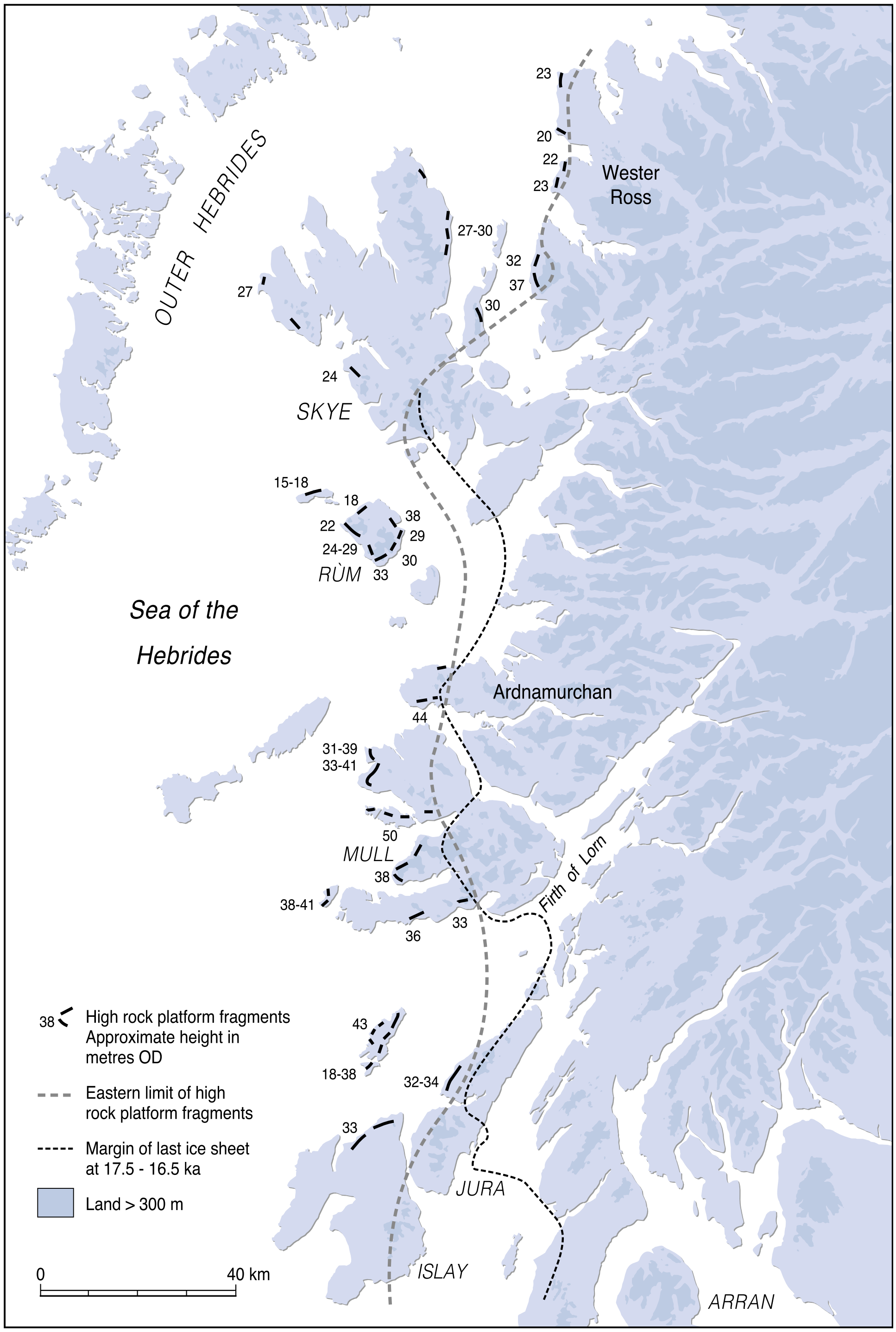


Fig. 10.14 Altitudes of high rock platform fragments in the Inner Hebrides, showing the eastern limit of platform occurrence. (After Sissons 1983) and the position of the margin of the last ice sheet at ~17.5–16.5 ka as depicted by Small et al. (2017)

3.6 ka (Selby and Smith 2007, 2016), whereas on Arran the Holocene marine limit is represented by the Main Postglacial Shoreline, which formed at 7.8–6.2 ka. Around the coasts of Skye and Rùm, Holocene raised beaches up to ~7 m OD occur in sheltered locations, mainly at fjord heads (Fig. 10.13d). The Main Postglacial Shoreline on Arran, however, takes the form of a raised beach that extends around the island at up to ~7–10 m OD (Gemmell 1973), one of the finest examples of a Holocene raised shoreline in Scotland.

10.8 Conclusion

It is difficult to describe the landscapes and landforms of the islands of the Hebridean Igneous Province without resorting to superlatives. They contain the finest igneous geology in Scotland, the most striking alpine scenery, glaciated landscapes dominated by radial outflow of ice, deep, cliffed cirques, numerous end, lateral and recessional moraines deposited by glaciers during the Loch Lomond Stade, an exceptional range of high-level periglacial and aeolian features, the largest and most spectacular landslides in the British Isles, and an unsurpassed range of coastal landforms. They include some of the most striking, internationally important and most-visited geological and geomorphological sites in Scotland and continue to yield new insights into both their long-term geological evolution and Quaternary environmental history. Geomorphologically, the four islands are unique in Scotland in illustrating the effects of successive Pleistocene glaciations on terrain underlain by complex igneous geology, and the aftermath of glaciation in terms of postglacial landscape evolution on such terrain.

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