3 Long-Term Denudation and Geomorphology in Scotland

Adrian M. Hall

Abstract

Long-term geomorphology has received little recent attention in Scotland. Palaeosurfaces and major landforms, including valleys and basins, can be linked to the sub-Caledonian and sub-Permian basement unconformities. The present topography was sculpted from the sub-Palaeocene unconformity after kilometre-scale uplift in response to Early Palaeogene magmatism. Recent results from thermochronology indicate an eastward decrease in denudation across Highland Scotland that is supported by landscape persistence in eastern areas since the Devonian. A sequence of planation surfaces developed from the Late Eocene onwards in intervals of slow uplift and high sea levels. The highest extensive surface, the Eastern Grampian Surface, has been uplifted to an elevation of 500–840 m. The surfaces formed by etch processes operating in response to changing base levels under warm-to-cool, humid environments, with extensive forests and widespread deep weathering. After uplift, each planation surface was modified through valley incision, backwearing of scarps and downwearing. Pliocene sea-level fall likely led to formation of coastal platforms that included precursors of the present Hebridean strandflat.

Keywords

Tectonics • Unconformity • Weathering • Denudation • Planation surfaces • Inselbergs • Topographic basins • Drainage patterns • Long-term relief development

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3.1 Introduction

The focus of this chapter is on the shaping of Scotland's scenery before the Pleistocene. The macro-scale topography has a long evolution, its inherited features remain prominent in today's scenery and its gross form has guided the build-up of glaciers and the pattern and intensity of glacial erosion through the Pleistocene. The origins of the present relief can be traced in erosional unconformities that emerge from beneath sedimentary and volcanic cover of Precambrian to Palaeocene age. The present topography was shaped during and after Palaeogene uplift in response to tectonic, climatic and sea-level forcing. The major landforms developed mainly in the Neogene through the interplay of base-level changes, differential weathering and fluvial erosion.

3.2 Deep Time: Unconformities, Erosion and Inherited Relief

Scotland has an unusually diverse geology for a small part of Earth's surface. Plate fragments, or terranes, with rocks that extend back in time to the Archaean, were assembled into their present configuration during the Palaeozoic (Chap. 2). The terranes are separated by major vertical structures in the crust, such as the Great Glen Fault (Fig. 3.1a), that have guided lateral and vertical displacement through the Phanerozoic. The geological terranes approximate to, but do not match, the main morpho-structural blocks that have conditioned denudation and relief development since the Cretaceous: the Orkney-Shetland Platform (OSP) , the Outer Hebrides Platform (OHP), the Northern Highlands, the Grampian Highlands, the Midland Valley and the Southern Uplands. The Palaeogene Hebridean Igneous Province (HIP), scattered across western Scotland, has its own distinctive topographic expression. The morpho-structural blocks stand above the upper Palaeozoic to Mesozoic rift basins of the Inner Hebrides and Moray Firth. Sediments in

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these basins, in the North Sea and on the North Atlantic shelf, were largely sourced from land areas centred on present-day Scotland during and after the Devonian (Trewin 2002).

The morpho-structural blocks carry extensive unconformities that mark the terminations of long periods of erosion and the onset of burial of basement by terrestrial and marine sediment. Collectively, the unconformities record the depth and pattern of erosion and burial over time (Fig. 3.1a). The oldest stack of unconformities is on the Lewisian foreland of the NW Highlands, with unconformities that lie beneath the Stoer Group (∼1.18 Ga) and Torridon Group (∼1.04 Ga) conglomerates and sandstones, Cambrian (∼540 Ma) quartzites, Permo-Triassic (∼265 Ma) sandstones and Palaeocene (∼63 Ma) basalt. The presence of five tiered unconformities in less than 1 km height range indicates that denudation of the Lewisian basement since ∼ 1.0 Ga has been limited. Despite kilometre-scale burial and loading by Precambrian sedimentary cover, the Moine Thrust nappes and younger sedimentary rocks, the basement has returned to approximately the same level after each period of erosion and unloading.

Across Scotland north of the Highland Boundary Fault, the Caledonian Orogeny is the starting point for relief development (Chap. 2). Profound erosion in the Moine and Dalradian gneisses and schists and rapid exhumation of plutonic intrusions in the Caledonian mountain belt culminated in the formation of the post-orogenic, sub-Caledonian (Devonian) unconformity. This unconformity is exposed extensively in eastern parts of the Northern and Grampian Highlands, with only a small core area lacking Devonian outliers (Fig. 3.1a); since ∼380 Ma, basement erosion has been limited (Hall 1991; Macdonald et al. 2007). Permo-Triassic sediments were deposited in rift basins

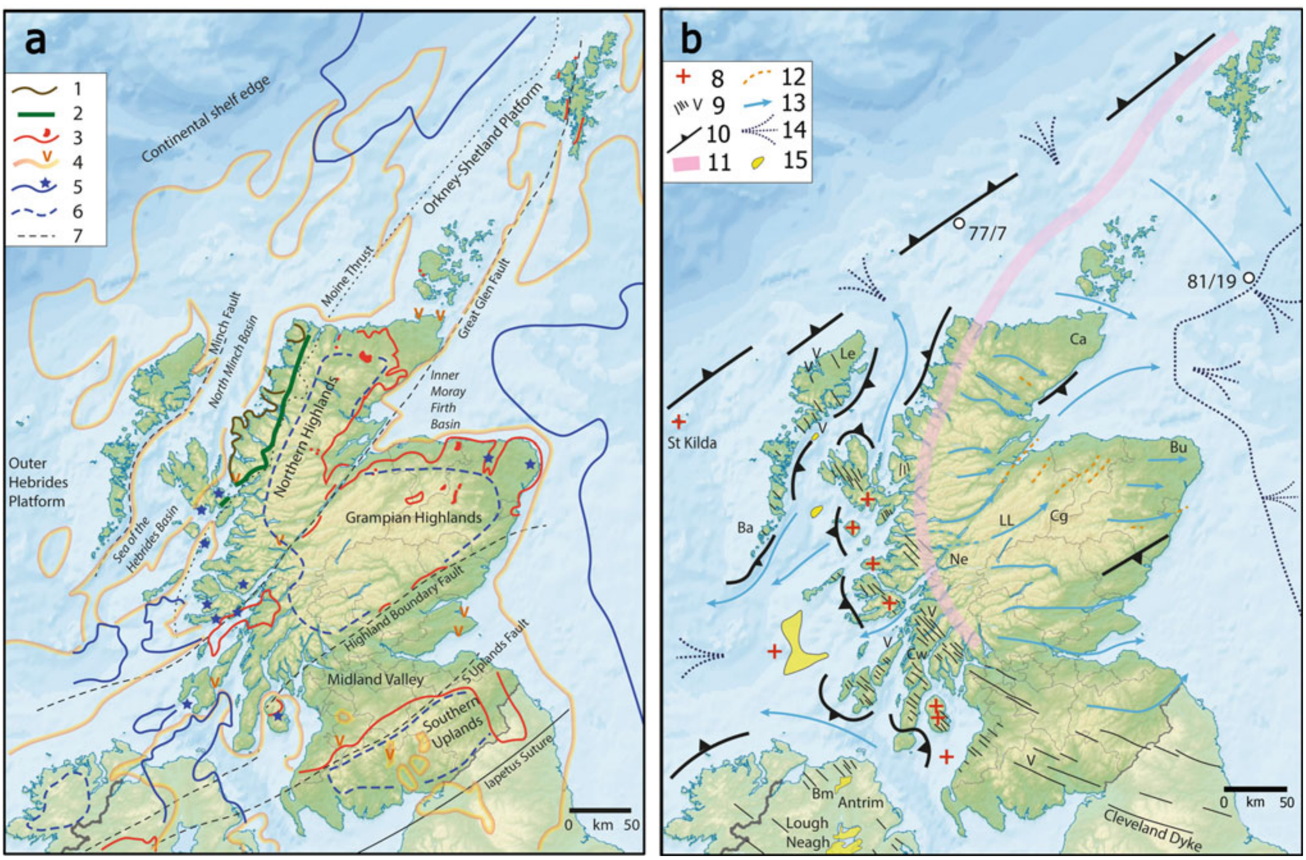

Fig. 3.1 Morpho-structural setting of Scotland. **a** Present limits of unconformities. 1: Sub-Torridonian unconformity. 2: Sub-Cambrian unconformity. 3: Sub-Caledonian (Devonian) unconformity and outliers. 4: Sub-Permian unconformity; V: Permian vent. 5: Sub-Palaeocene unconformity. 6: Approximate maximum limit of the Late Cretaceous transgression; Late Cretaceous outliers marked by stars. 7: Major fault. **b** Palaeogene uplift and drainage. Dotted line shows the position of the Early Eocene shoreline in the western North Sea, after Knox (2002). 8: Major intrusive igneous centre. 9: Palaeocene dykes; V: vesicular dykes. 10: Major scarp. 11: Main watershed. 12: Exhumed Devonian valley. 13: Major drainage routeway. 14: Sediment routeway. 15: Late Oligocene basin. Also shown are BGS boreholes (77/7 and 81/19) referred to in the text. Ba: Barra; Bm: Ballymoney; Bu: Buchan; Cg: Cairngorms; Le: Lewis; LL: Loch Laggan; Ne: Ben Nevis. (Base digital elevation map on a Creative Commons licence at CC-BY-SA-3.0, GFDL)

developed during crustal extension that heralded the opening of the proto-Atlantic. The edge of the Permian cover conforms largely to the present outline of the Scottish land area (Glennie 2002). Early Permian volcanic vents in Lochaber and Ayrshire (Fig. 3.1a) indicate that surrounding land surfaces remain close to Early Mesozoic erosion levels (Hall 1991). The offlap from the Devonian unconformity suggests that Devonian and Carboniferous sedimentary cover was thinned, locally removed and recycled by erosion in the Late Palaeozoic. Similarly, the farther offlap of the Late Cretaceous Chalk edge indicates removal of Permo-Triassic cover during and since the Mesozoic. The youngest unconformity is represented by the present land surface.

The sub-Torridon Group unconformity has low relief near Cape Wrath, whereas farther south the ancient land surface becomes hilly and, locally, mountainous (Stewart 1972). In contrast, the sub-Cambrian unconformity surface is remarkably planar for $\sim$150 km on the Lewisian foreland; it represents a fragment of the former Great Unconformity on Laurentia. The sub-Caledonian unconformity is generally hilly across the Northern and Grampian Highlands, but lower-relief pediment surfaces exist in Caithness (Chap. 8). The sub-Permian unconformity was strongly influenced by fault-block tectonics. For example, on the eastern flank of the Moffat basin in the Southern Uplands, the unconformity is buried beneath breccias originally deposited as scree at the base of steep fault scarps (Brookfield 1980). Hence, the buried unconformity surfaces differ widely in morphology.

Where unconformities are of high relief, inheritance of exhumed topography in the present landscape is generally confined to valley segments at the edges of outliers. Persistence of landforms is more widespread where major features have maintained their gross form and position during later denudation. Examples include sub-Torridonian gneiss hills and valleys around Loch Maree (Stewart 1972), sub-Devonian valleys in fracture zones around the Cairngorms (Hall and Gillespie 2016) and the sub-Cretaceous quartzite inselberg of Mormond Hill in Buchan (Chap. 21). The persistence of exhumed hills, valleys and basins in the Cenozoic topography is a consequence of the reactivation of the same rock controls on differential weathering and erosion that originally brought these features into existence.

3.3 Morphogenetic Setting for Palaeogene and Neogene Relief Development

Deposition of chalk continued in western Scotland, Northern Ireland and the North Sea Basin until $\sim$70 Ma (Hopson 2005). During the Late Cretaceous sea-level highstand, the Scottish land area was small and of low relief, contributing little clastic sediment to flanking basins (Fig. 3.1a). Similar conditions existed in SW Norway, where contemporary relief was <500 m (Sømme et al. 2013). The low relief of the sub-Palaeocene unconformity constrains the patterns and magnitude of uplift and denudation later in the Cenozoic. The timings of the main events that have shaped the scenery of Scotland through this time are summarised in Fig. 3.2.

3.3.1 Magmatism and Tectonics

Cenozoic tectonics involved a main phase of uplift in the Palaeogene driven initially by magmatism in the HIP and later by the passage of the Icelandic plume, with magmatic underplating of topography (Mudge 2014). Early magmatism in the HIP is recorded by the eruption of basalts at 61–58 Ma. Later volcanism was associated with the emplacement of major igneous centres in western Britain at 60–55 Ma (Bell and Williamson 2002; Chap. 10). Minor magmatic activity continued on the OHP until $\sim$45 Ma (Faithfull et al. 2012). In the HIP, the sub-Palaeocene surface was broken and warped by fault movements and uplift, with kilometre-scale displacement around igneous centres (Hall 1991). Combined uplift and lava accumulation raised Palaeocene basalt plateaux to elevations of 2 km or more on Skye (Jolley 1997) and Mull (Bell and Williamson 2002).

Regional uplift produced extensive emergence of the Scottish land area. Erosion stripped Permo-Triassic cover from the OSP (Morton et al. 2004) and large volumes of sand accumulated in the Faroe-Shetland and North Sea Basins. Eastward tilting in the inner Moray Firth Basin may have led to removal by erosion of $\sim$1.3 km of mainly Mesozoic section (Mackay et al. 2005), although the sub-Caledonian unconformity around the Moray Firth does not show tilting of this magnitude (Fig. 3.1a). Major uplift of the Southern Uplands and northern England also occurred at this time, with removal of $\geq$1.2 km of Mesozoic section across the English Lake District (Łuszczak et al. 2018). Present elevations across Scotland indicate that the mainland rose as a block, with minor tilt towards the east (Fig. 3.1b). The broad pattern of uplift across the northern Highlands is seen in its summit envelope surface (Fig. 3.3). Deformation has occurred towards block margins in NE Scotland, the eastern Midland Valley and towards the North Channel between NE Ireland and SW Scotland. The start of seafloor spreading in the NE Atlantic at $\sim$55 Ma led to basin subsidence along the Atlantic shelf and in the North Sea (Mackay et al. 2005). Rates of sediment input declined sharply in the North Sea (Liu and Galloway 1997), consistent with slowing of uplift and relief reduction on the OSP and in eastern Scotland. The OHP remained emergent (Evans et al. 1997).

Episodes of plate reorganisation in the North Atlantic led to further uplift during the Neogene (Stoker et al. 2005). Continuous flexural uplift and denudational isostasy likely also occurred, as on other Atlantic passive margins (Rouby

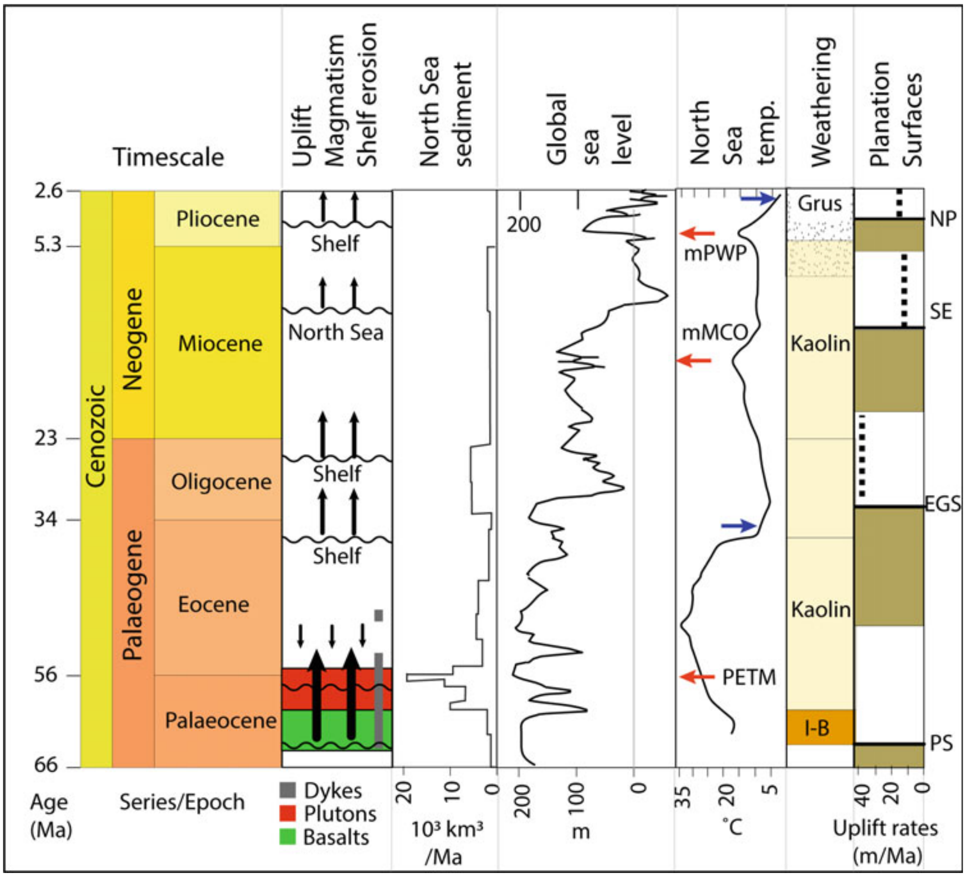

Fig. 3.2 Chronological framework for Cenozoic (Palaeogene and Neogene) environmental change. Main unconformities on the Atlantic shelf (wavy lines) from Stoker et al. (2010). See text for timing of magmatism in the Hebridean Igneous Province. North Sea sediment volumes from Liu and Galloway (1997). Global sea-level curve from Haq et al. (1987). North Sea temperatures from Buchardt (1978). PETM: Palaeocene–Eocene Thermal Maximum; mMCO: mid-Miocene Climatic Optimum; mPWP: mid-Pliocene Warm Period. Weathering types and planation surfaces modified after Hall (1991). NP: Niveau Pliocène; SE: Surface Écossaise; EGS: Eastern Grampian Surface; PS: sub-Palaeocene unconformity; I-B: Inter-basaltic lateritic horizons. Post-Eocene uplift rates (vertical dashed lines) are derived from the relative elevations of the outer edges of each surface since its uplift from base level

et al. 2013), induced by earlier and continuing erosion centred on western Scotland and the OSP and by sediment transfer to, and loading on, North Atlantic and North Sea shelves. In the Late Oligocene, uplift and erosion affected western Britain, with terrestrial sedimentation in small extensional basins (Evans et al. 1991). The edge of the North Atlantic shelf was transgressed in the Early Miocene (Evans et al. 1997). A younger, erosional unconformity developed on the shelf in the Early Pliocene (~4 Ma), with subsidence along the shelf edge and seaward tilting of the OHP (Stoker 2002). Large volumes of sediment were transferred to the North Atlantic shelf edge in the Miocene and Early Pliocene (Stoker et al. 2010), but in the North Sea, Scandinavian sources dominated sediment supply following uplift of the Scandic mountains in the mid-Miocene. Erosion of the OSP continued to supply material to adjacent shelves through the Pliocene (Ottesen et al. 2018); drowning of the OSP and the OHP occurred mainly during the Pleistocene.

3.3.2 Sea Level

Global sea levels were up to 200 m above present through much of the Palaeogene, with the North Sea reaching its largest extent during the Eocene (Anell et al. 2012), but fell sharply in the Oligocene and dropped again after the mid-Miocene and mid-Pliocene temperature highs (Fig. 3.2). Whilst the amplitude of these fluctuations was much less than the kilometre-scale uplift experienced on the land area, the effect of falling Neogene sea levels was likely profound on the shelves surrounding Scotland. First, shoreline positions shifted across gently inclined shelf surfaces (Mudge 2014). Second, large volumes of sediment released by Palaeogene erosion were likely stored on inner shelves under high Eocene sea levels and later transferred to the North Atlantic shelf edge during later emergence. Third, global sea-level fall in the Pliocene likely led to the development of extensive, emerged shoreline features, similar to the wide coastal ramps developed on Hercynian platforms that stand today at elevations up to 200 m above sea level in western France (Pedoja et al. 2018) and 115 m in SW England (Gunnell 2020). Such features in Scotland included precursors of the strandflat identified in the Inner and Outer Hebrides (Chaps. 9 and 11), later modified, lowered and locally erased by Pleistocene glacial and marine erosion (Dawson et al. 2013).

3.3.3 Climate, Vegetation and Weathering

The location of Scotland on the eastern North Atlantic margin maintained high precipitation throughout the Cenozoic. Mean annual temperatures (MATs) remained subtropical through the Palaeogene (Liu et al. 2018). Towards the Eocene–Oligocene boundary (~34 Ma), there was a step change towards the modern ice-house climate, with build-up of the Antarctic ice sheet and a sharp fall in sea-surface temperatures in the North Sea (Fig. 3.2). Temperatures recovered to reach 15.5–20 °C in Denmark (Larsson et al. 2011) for a period of ~12 Ma during the Late Oligocene and Miocene. By the Early Pliocene (4–5 Ma), MATs had fallen to −1 °C in the high Arctic (Csank et al. 2011). During the mid-Pliocene Warm Period at ~3 Ma, sea-surface temperatures in the southern North Sea rose briefly to levels similar to, or warmer than the present (Williams et al. 2009), before continued global cooling and the onset of pan-Arctic glaciation at ~3.6 Ma (Knies et al. 2014).

The Cenozoic vegetation record for Scotland is fragmentary. During the Palaeocene, vertical zonation of forest developed over a ~2 km elevation range in the HIP (Jolley 1997), and swamps containing broadleaved and evergreen taxa as well as *Taxodium* (swamp-cypress) covered the inner Moray Firth area (Kender et al. 2012). During the Late Oligocene, cool temperate swamps formed in lowland Antrim, in NE Ireland, with upland coniferous forest (Mitchell 2004), and a similar biome existed in the Inner Hebrides (Evans et al. 1991). Lignite layers of likely Early Pliocene age in BGS borehole 81/19 in the outer Moray Firth contain pollen of *Carya* (hickory) (Andrews et al. 1990). Late Pliocene deciduous forests in western Ireland were of high species diversity, with hickory accompanied by other species now exotic to the British Isles, such as swamp-cypress, *Liriodendron* (tulip tree) and *Nyssa* (sour-gum) (Coxon 2005). Dynamic forest biomes likely dominated throughout the Palaeogene and Neogene, modulating earth-surface processes.

Chemical weathering developed widely below forest floors under warm-to-temperate, humid climates but the character of weathering profiles changed as climates cooled through the Cenozoic. In the Palaeocene, laterite and iron crusts developed under humid subtropical monsoon climates in Antrim (Hill et al. 2000) and in the HIP (Bain et al. 1980). Basalts were weathered to clay to a depth of 80 m during the Eocene and Early Oligocene at Ballymoney in Antrim (Mitchell 2004). In borehole 77/7 near North Rona (Fig. 3.1b), kaolinite-rich, highly weathered basement occurs beneath Late Oligocene sediments (Evans et al. 1997). In Buchan, stable isotope ratios for kaolin clays in >25 m deep weathering profiles indicate groundwater temperatures of 23±5 °C, consistent with wider evidence for intense and deep Palaeogene weathering (Hall et al. 2015; Chap. 21). Clay mineral stratigraphic studies of North Sea sediments show abundant smectite in the Palaeocene and Eocene derived from alteration of volcanic ash sourced from the HIP and other eruptive centres (Huggett and Knox 2006). Climatic cooling from the Late Miocene onwards is associated with an increase in illite and chlorite in North Sea sediments (Nielsen et al. 2015). This change has been linked to the onset of formation of geochemically immature, grus-type weathering profiles in NE Scotland, characterised by low clay contents, retention of little-altered primary minerals such as feldspar and biotite, and varied clay mineral assemblages that remain strongly influenced by parent rock type (Hall et al. 1989). Saprolites and associated supergene minerals in Scotland currently lack absolute dating, unlike in other parts of Europe (Dill et al. 2010a, b), limiting our understanding of rates of long-term denudation and landform development.

3.4 Cenozoic Denudation

Patterns and rates of Cenozoic rock removal across Scotland may be reconstructed using evidence from thermochronology, sediment volumes and the landform record.

Early models from apatite fission track and AHe thermochronometry have provided three contrasting scenarios for the cooling history of the Scottish Highlands: (i) cooling following Caledonian exhumation without significant burial (e.g. Persano et al. 2007); (ii) burial in the Late Palaeozoic to Early Mesozoic followed by uninterrupted cooling (e.g. Thomson et al. 1999); or (iii) multiple cycles of post-Caledonian burial and exhumation from the Late Palaeozoic through the Cenozoic (e.g. Holford et al. 2010). Recent work on low-temperature AHe and (U-Th-Sm)/He thermochronology in the west-central Highlands supports the last scenario, providing evidence for three main cooling phases: at the end of the Caledonian Orogeny, during Permo-Triassic extension and in the Early Palaeogene (Fame 2017; Amin 2020); these correspond with phases of uplift and rapid erosion identified in the geological record. Two main findings stand out for the Cenozoic cooling history: (i) widespread Early Palaeogene cooling is recorded in the HIP (Dobson et al. 2010), along the western edge of the

Highlands (Amin 2020) and in the Southern Uplands (Łuszczak et al. 2018); and (ii) Neogene cooling was limited but remains poorly constrained in magnitude, space and time (Fame 2017; Łuszczak et al. 2018; Amin 2020).

Estimates of the maximum depth of Cenozoic denudation around Ben Nevis in the western Highlands fall within the range 0.7–1.7 km (Fame 2017; Amin 2020). Estimated denudation depths decrease eastward towards the Cairngorms, where sub-Devonian landforms are preserved (Hall and Gillespie 2016). Cenozoic denudation was near zero in Buchan, where Cretaceous Chalk flints survive (Chap. 21). However, estimates based on different thermochronological techniques differ widely, with 0.3 km of Cenozoic denudation estimated at Loch Laggan in the Western Grampians (Fame 2017), but 0.9–1.5 km in the Cairngorms (Amin 2020). Moreover, apparent cooling ages also vary significantly over short (10–20 km) distances. For example, on the Outer Hebrides, estimated maximum Cenozoic denudation varies from 3 km on Barra to 1.5 km on Lewis (Amin 2020). Whilst differential denudation may be real and attributable in part to block movements, further research is needed.

Sediment volumes in the North Sea Basin indicate the loss of an average ~1.0 km of rock from the Scottish Highlands through the Cenozoic (Hall 1991). Similar estimates are derived from modelled subsidence histories for sedimentary basins around Scotland (Jones et al. 2002). Where the sub-Caledonian unconformity stands close to the present erosion level, losses were mainly through the removal of sedimentary cover. Revised calculations that include the Rockall and Faroe-Shetland basins have provided significantly higher estimates of 2.0–2.4 km for Highland denudation (Wilkinson 2017). However, taking account of the potential contributions to these basins from erosion in east Greenland, around Palaeogene igneous centres on the Atlantic shelf and after inversion of Mesozoic basins on the shelf, these estimates appear large. For example, removal of ~1.85 km thick Mesozoic cover is estimated for the West Orkney Basin through the Cenozoic (Evans 1997). Adoption of the higher estimates requires removal of great thicknesses of former Mesozoic cover from the Highlands for which independent evidence is lacking (Hudson 2011).

Palaeocene dyke swarms are exposed at elevations of up to 900 m in the western Highlands, 400 m in the Midland Valley and 600 m in the Southern Uplands (Fig. 3.1b). Where dykes lack evidence of near-surface emplacement, deep erosion below the sub-Palaeocene surface is likely (George 1966). However, where dykes show amygdales and segregation vesicles or are associated with small vents, cooling occurred within a few hundred metres of the present surface. Examples occur on Lewis (Chap. 9), Cowal in the SW Highlands (Hall 1991) and along the Cleveland Dyke in the Southern Uplands (Dagley et al. 2008); these areas experienced more limited uplift in the Palaeocene and less denudation thereafter.

On the OHP, uplift of mountains on Harris led to deep Palaeocene erosion but block movements across major faults maintained north Lewis at low elevations (Chap. 9). In NE Ireland, the preservation of Cretaceous Chalk below Palaeocene lavas indicates that later erosion in Antrim has been confined to the volcanic cover, amounting to the loss of 300–700 m of rock (Holford et al. 2009); depths of Cenozoic erosion across the SW Hebrides were likely comparable. The surface of the OSP has been entirely reshaped, with levelling of Palaeogene uplands after kilometre-scale erosion (Chap. 7). Across much of Scotland, the depth of Palaeocene-Early Eocene denudation requires that major epigene landforms are younger features.

3.5 Landforms

The scenery of Scotland includes four main generations of relief: the ancient exhumed elements (Sect. 3.2), the major pre-Pleistocene Cenozoic landforms, the Pleistocene glacial and marine features, and the landforms and sediments that post-date the Last Glacial Maximum (Chap. 4). The Cenozoic (Palaeogene and Neogene) landforms considered here were variously modified and dissected during Pleistocene cold stages. The form of the older features is most evident in eastern areas where the imprint of glacial erosion was lighter, but the gross form of the Neogene relief is evident everywhere.

3.5.1 Drainage Patterns and Major Valleys

The broad pattern of Palaeogene drainage across Scotland is indicated by sediment routeways to adjacent shelves and by broad straths set deep within the Highlands and Southern Uplands (Fig. 3.1b). During Palaeocene uplift, it is possible that the headwaters of eastward-draining rivers in the NW Highlands locally extended west of the Moine Thrust but firm evidence of a major sediment input from this source area is lacking from the heavy mineralogy of contemporaneous North Sea sandstones (Morton et al. 2004). The positions of the main watersheds are long established, with sediment transport routes indicating origins in the Devonian and Permian.

Early models of Cenozoic drainage evolution identified discordance between drainage routes and regional structural trends. This discordance was attributed to: (i) superimposition of drainage from a formerly extensive cover of Cretaceous rocks, following uplift (Bremner 1942; Linton 1951); and (ii) drainage development consequent to the emergence of tilted marine erosion surfaces in the Eocene (George

1966). Current understanding of the history of uplift and denudation indicates that the present summit surface of the Highlands stands below the sub-Palaeocene surface and that Scotland remained emergent throughout the Cenozoic. The emphasis on discordance was likely also overstated as major faults and shears in Scotland have multiple orientations and the centripetal drainage around the inner Moray Firth includes partly exhumed sub-Devonian valley systems aligned along SW–NE Caledonian structural trends (Hall 1991; Fig. 3.1b). Drainage towards the North Sea and inner Moray Firth developed mainly in response to patterns of Palaeogene uplift. In the Inner Hebrides, drainage was away from igneous centres and across down-faulted and down-warped basalts now found on the seabed (Fyfe et al. 1993). In the Northern Highlands, precursors of the present Shin, Brora and Helmsdale rivers became incised into the uplifted shoulder facing the Moray Firth (Hall 1991). The existence of proto-Dee and proto-Don river systems is indicated by the distinctive Dalradian garnet assemblage of Late Palaeocene sands offshore (Morton et al. 2004). The proto-Tay-Forth drainage fed sediment to deltas in the west-central North Sea (Gatliff et al. 1994).

3.5.2 Planation Surfaces

Stepped sequences of planation surfaces are ubiquitous features on passive margins and provide important insights into long-term relief development (Picart et al. 2019). The outstanding early analysis of Godard (1965) established that a staircase of surfaces exists in the Scottish Highlands, separated locally by scarps, but his landscape models have received little detailed attention by geologists (Jarman 2007). Also, unlike in Scandinavia (Ebert et al. 2011), no detailed GIS analyses exist of the regional topography in Scotland. Here we focus on three well-preserved surfaces in Scotland, north of the Highland Boundary Fault (Fig. 3.3).

- The Niveau Pliocène (90–180 m above sea level) is a peripheral surface that extends inland along valleys. The surface incorporates inherited Palaeogene facets in Lewis and Buchan, but widespread grus-type weathering indicates a mainly Pliocene reshaping. The Niveau Pliocène has been raised along the Minch, Helmsdale and Banff Faults and disrupted by later block faulting in Lewis (Chap. 9), the Sea of the Hebrides (Le Coeur 1999) and Orkney (Chap. 8).
- The Surface Écossaise (180–300 m) is more extensive, penetrating deep into the Northern Highlands and extending towards the main watershed. Similar headward extension along straths and basins occurs in the Central and Eastern Grampians. The Surface Écossaise has been raised along the Minch and Helmsdale Faults, but regional tilting is limited.
- The Eastern Grampian Surface (500–840 m) includes extensive high plateaux around the Cairngorms (Hall 1991; Fig. 3.4a; Chap. 20). On the Monadhliath, this surface was dislocated by later faulting (Ringrose and Migoń 1997). On the Mounth (SE Grampians), this surface has been gently tilted towards the North Sea.

Remnants of the Niveau Pliocène and the Surface Écossaise indicate initiation at base level, followed by extension inland along river valleys, and subsequent uplift and dissection. As the highest fragments of planation surfaces cross-cut Palaeocene dykes in western Scotland (Godard 1965), all surfaces postdate Palaeogene magmatism. Dating controls on surface initiation remain limited. Correlation with offshore unconformities that mark the terminations of phases of erosion after uplift suggests initial formation of the Eastern Grampian Surface in the ~15 Ma long period of relative tectonic stability in the late Eocene to mid-Oligocene, the Surface Écossaise in the mid-Miocene and the Niveau Pliocène by ~ 4 Ma (Fig. 3.2).

3.5.3 Hills

Isolated hills or inselbergs occur widely in the Highlands, either singly or as groups. Some inselbergs reflect localised rock resistance, whereas others appear to be products of backwearing of surrounding slopes. A few exhumed inselbergs also occur, notably the sub-Devonian inselberg of Scaraben in Caithness (Chap. 8). Inselbergs of resistance are most common on quartzites and include the Paps of Jura (Chap. 11) and Schiehallion and numerous hills in the lowlands of NE Scotland (Hall 1986). Inselbergs of this type are also found, however, on a range of other rocks, including volcanic necks in the Midland Valley, metamorphosed grits of the Highland Border Complex (e.g. Ben Ledi), slates (e.g. Hills of Foudland in Buchan) and Devonian conglomerates (e.g. Ben Griam Mòr in Sutherland). The considerable heights of many of these hills indicate prolonged differential denudation. The quartzite inselberg of Mormond Hill in Buchan is, in outline, a Mesozoic relic (Merritt et al. 2003). The most spectacular examples of inselbergs of position occur in the NW Highlands, where a chain of isolated hills in Torridonian sandstone and, towards the north, Cambrian quartzite, stretches from Stac Pollaidh to Cranstackie, rising steeply above the Niveau Pliocène on the surrounding Lewisian lowlands (Fig. 3.4b; Chap. 12). Most inselbergs of position, however, are developed wholly in crystalline rocks. Notable examples include Morven and Mount Keen, rising above the plateaux flanking the Dee valley, and the larger hill masses of Ben Hope and Ben Hee in the Northern

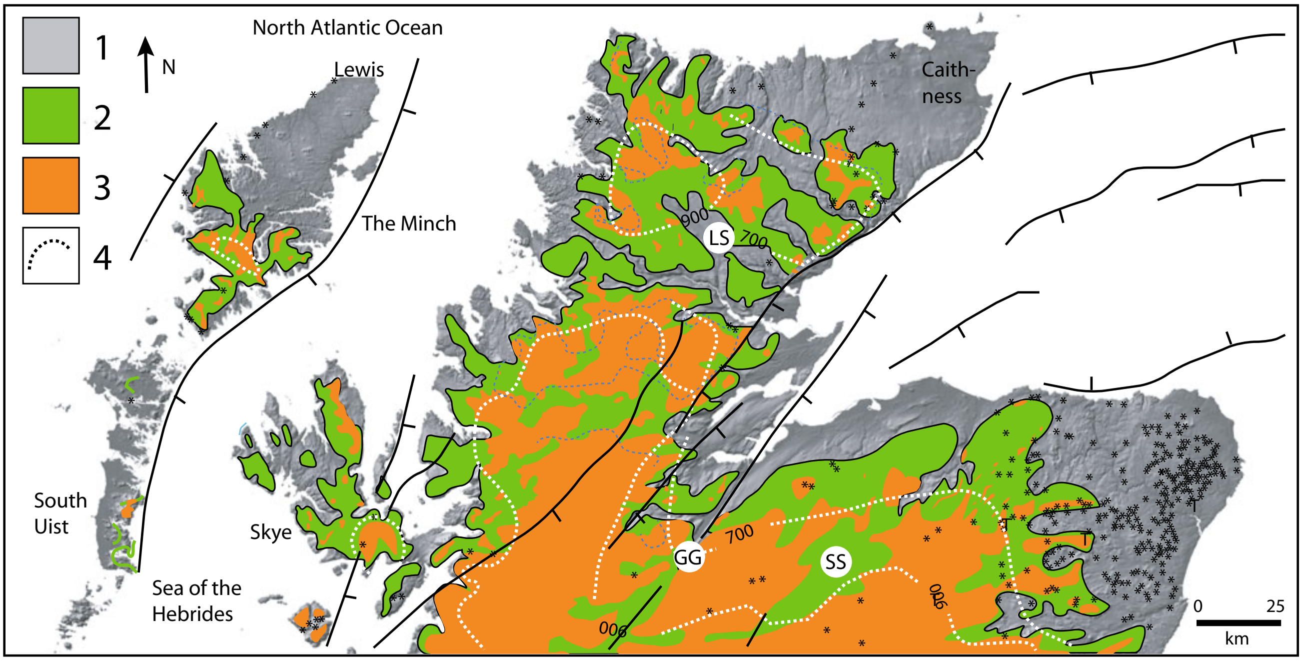

Fig. 3.3 Denudation and planation in the northern Highlands. 1: Niveau Pliocène. 2: Surface Écossaise. 3: Relief standing above the Surface Écossaise. 4: Summit envelope surface contours. *: Relict saprolite. GG: Great Glen; LS: Loch Shin; SS: Strathspey

Highlands. These inselbergs often occur within areas of rocks of relatively uniform resistance where their elevation cannot be accounted for by Neogene fault movements, and isolation through the encroachment of surrounding planation surfaces is likely (Godard 1965).

3.5.4 Basins

Topographic basins typically have broad floors of low relief enclosed by inward-facing slopes broken only by narrow drainage exits. Basins are a major element of the Highland scenery and are found at elevations from close to sea level to over 900 m in the Cairngorms. Basins also occur in the Howe of Fife in the Midland Valley and in upper Nithsdale in the Southern Uplands. The large basins of the Northern Highlands (Jarman 2007; Fig. 3.4c) and the Central Grampians (Hall 1991), including Rannoch Moor (Chap. 17), contain or are flanked by stepped planation surfaces and so have a development that spans at least the Neogene period. In NE Scotland, the basins are smaller, with floor areas of 10–60 km^2. Many basin floors are dissected and where the floors lie well above present valley floors, as in the Atholl basin, dissection began before the Pleistocene. Basins are rare west of the main watershed, where steep valley gradients encouraged pre-glacial valley incision and intense glacial dissection of relief (Haynes 1983; Chap. 4).

Many basins are long-established features, set deeply within the surrounding hills. The Cabrach basin is an exhumed Devonian form. Elsewhere in NE Scotland, basins up to 300 m deep are developed largely in biotite-bearing basic and granitic rocks that are susceptible to chemical weathering (Fig. 3.4d). Basin margins commonly coincide with litho-structural boundaries (Hall 1991). Grus is common beneath basin floors and linear weathering zones up to 50 m deep are preserved at the base of bounding scarps (Hall 1986). However, the large topographic basins around Lochs Naver and Shin do not show simple litho-structural controls on their positions and forms (Godard 1965). Whilst these basins were perhaps initiated by deep weathering, scarps at basin margins appear to have retreated across more resistant lithologies during Neogene basin-floor lowering.

3.6 Models of Long-Term Relief Development

The Scottish and Norwegian sections of the North Atlantic passive margin have broadly similar Phanerozoic tectonic histories, but with a dominance of Palaeogene uplift in Scotland versus Mio-Pliocene uplift in Norway. Debate over the long-term development of the Norwegian margin is currently polarised around two end-member models: (i) persistence of mountains since the Caledonian Orogeny with long-term denudation of dynamic topography modulated through variations in eustasy and climate (e.g. Huuse 2002; Nielsen et al. 2009; Pedersen et al. 2018); and (ii) episodic tectonism and uplift of the continental margin after

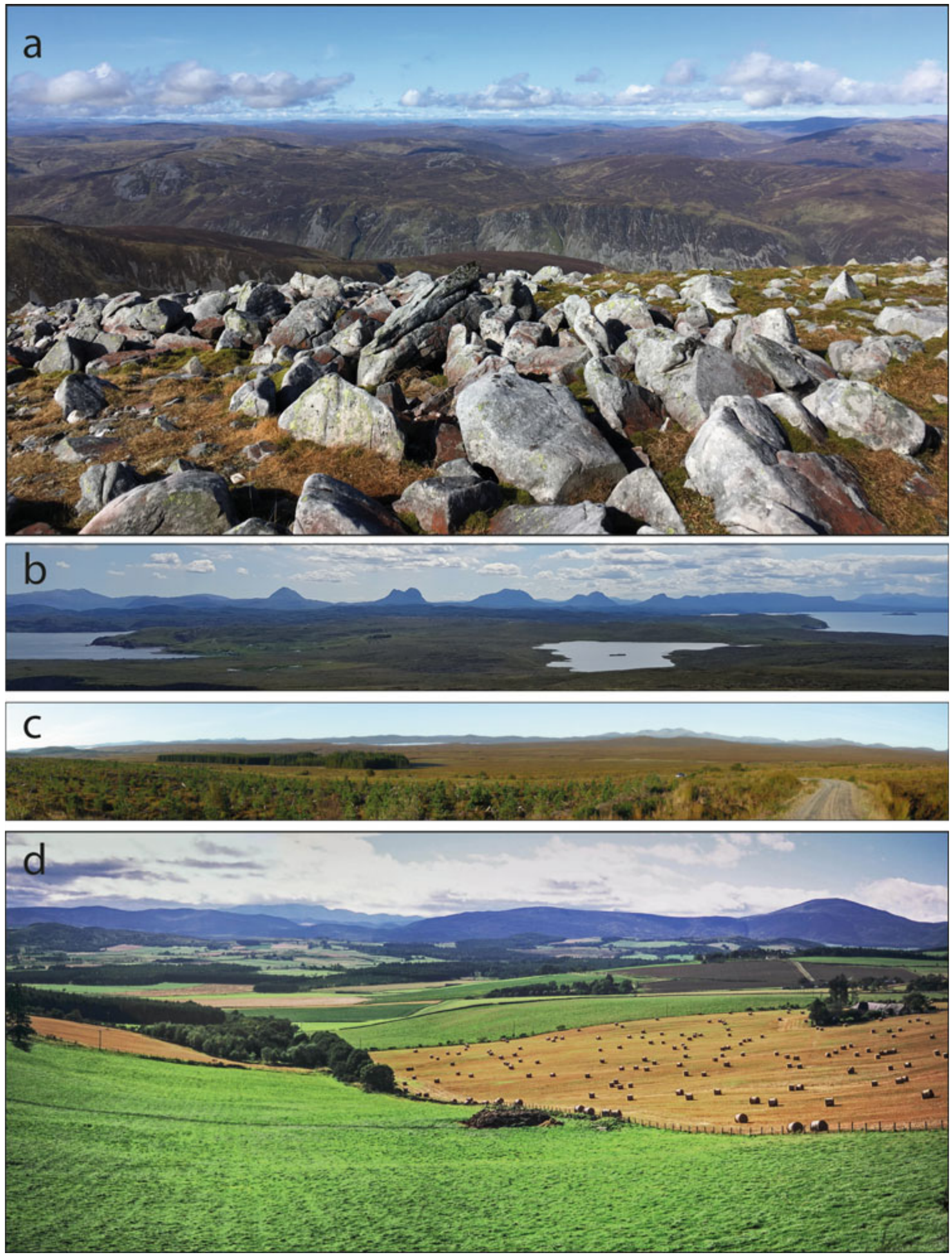

Fig. 3.4 Erosion surfaces and landforms. **a** View northwest from the highest point on Beinn a' Ghlo across the Eastern Grampian Surface on the Gaick plateau. **b** View southeast from Point of Stoer towards the chain of inselbergs of position that rise above the glacially eroded surface of the Niveau Pliocène. **c** Panoramic view west from near Crask across the Surface Écossaise on the floor of the Loch Shin basin and towards the main watershed. **d** View southeast across the Tarland basin towards the inselberg, Morven (right), that rises above the Eastern Grampian Surface. (Images: **a** Colin Ballantyne; **b**, **c** Adrian Hall; **d** John Gordon)

Mesozoic rifting, with formation of peneplains at base level, later uplifted but not significantly eroded (e.g. Lidmar-Bergström and Näslund 2002; Japsen et al. 2018). How does Scotland compare?

The post-Caledonian history of Scotland is not one of simple persistence of topography. Major episodes of uplift, mountain building and cooling associated with deep erosion occurred in the Early Devonian and Late Permian. By the Late Devonian and Late Triassic, the relief had been much reduced, allowing marine transgression of basin margins in the Early Carboniferous and Early Jurassic (Hall 1991). Persistence is seen, however, through the Mesozoic in palaeogeographic reconstructions of Scotland, when the Outer Hebrides, the Northern and Grampian Highlands and the Southern Uplands remain buoyant and shed sediment to surrounding basins (Hudson and Trewin 2002). However, by the culmination of the Late Cretaceous marine transgression, the residual land area of Scotland was small and low lying (Fig. 3.1b); no mountain topography remained from the Palaeozoic.

After kilometre-scale uplift in the Early Palaeocene, later uplift was episodic. The focus of deep erosion in western Scotland and its eastward decline across the Highlands, as indicated by thermochronology, is consistent, however, with additional, but subordinate flexural uplift of the western shoulder of Scotland driven by denudational isostasy (Fame et al. 2018). The elevation of the Eastern Grampian Surface at its eastern edge indicates minimum uplift of ~500 m since the mid-Eocene in parts of the Eastern Grampians. The younger surfaces indicate Neogene uplift rates of 13–22 m Ma^{-1} (Fig. 3.2), comparable to those in England and Ireland (Walsh et al. 1999). Generally, however, Cenozoic uplift and erosion depths in Scotland remain poorly constrained, falling between the temporal and spatial resolutions of low-temperature thermochronology (>10 Ma and >0.5 km depth) and cosmogenic isotope inventories (<1 Ma and <10 m depth).

Planation surfaces were initiated at base level during periods of relative tectonic stability and high eustatic sea level (Fig. 3.2). Surfaces were extended inland by headward erosion along short (100–250 km) river systems in southern Scotland (Sissons 1960), the Grampian Highlands (Hall and Bishop 2002) and the Northern Highlands (Godard 1965). Remnants of deep weathering covers and kaolinitic terrestrial sediments in basins around Scotland indicate that etch processes were fundamental in development of low-relief surfaces (Thomas 1995). Topography often became closely adjusted to litho-structural controls, principally mineralogy and fracturing, which influenced patterns and rates of chemical weathering (Godard 1962; Hall 1986). Planation surfaces, however, were subjected to continued weathering after uplift, as shown by the presence of deep grusses at elevations up to 800 m in the Cairngorms (Hall and Mellor 1988), and to significant erosion, with minimum rates of 10 m Ma^{-1} in western Scotland (Le Coeur 1999). Internal relief of hills and basins developed on uplifted surfaces during downwearing. Hence, the present upland surfaces are not preserved uplifted base-level peneplains, but instead represent dynamic etchsurfaces, modified after uplift during 2–20 Ma long periods of downwearing and headward extension, and largely stripped of regolith by Pleistocene glacial erosion (Chap. 4).

3.7 Conclusions

Problems of denudation and relief development over the last 400 Ma in Scotland have received little attention. Tiered unconformities indicate limited erosion of crystalline basement since the Devonian. By the end of the Cretaceous, relief was low. Major uplift along the North Atlantic margin, driven mainly by Palaeogene magmatism, produced contemporaneous kilometre-scale erosion in the western Highlands, but depths of Cenozoic erosion thinned eastwards. A staircase of younger etchplains developed close to base level in the late Eocene, mid-Miocene and Pliocene. Each surface was uplifted after formation, dissected, lowered and modified by weathering and erosion. Coastal platforms developed under falling sea levels in the Pliocene, including precursors of the Hebridean strandflat.

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