Scotland's denudational history: an integrated view of erosion and sedimentation at an uplifted passive margin

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Abstract: Denudational history is commonly reconstructed from basin sediments derived from the denuded source area, and less frequently from the source area itself. Northern Britain is an important source area for the surrounding sedimentary basins and this paper reviews the erosional history of Scotland from Devonian time to the present using evidence both from onshore geology and geomorphology and from patterns of sedimentation in surrounding basins. Cover rocks were extensive in Scotland during late Palaeozoic time but the persistence of sediment source areas within the upland areas of Scotland makes it unlikely that basement highs were ever completely buried, and depths of post-Devonian erosion of basement have been correspondingly modest (<1–2 km). During Mesozoic time, Scotland experienced several major erosional cycles, beginning with uplift, reactivation of relief and stripping of cover rocks, followed by progressive reduction of relief through etchplanation and culminating in extensive marine transgressions in Late Triassic, Late Jurassic and Late Cretaceous time. Mid-Paleocene pulses of coarse sediment to the Moray Firth Basin coincided with major uplift. This uplift was associated with major differential tectonics within the Highlands, with warping and faulting along the margins of the Minch and the inner Moray Firth Basins. Tectonic activity was renewed on a lesser scale in late Oligocene time and continued into Late Neogene time. Differential weathering and erosion under the warm to temperate humid climates of Neogene time created the major elements of the preglacial relief, with formation of valleys, basins, scarps and inselbergs, features often closely adjusted to lithostructural controls and, in some cases, with precursors that can be traced back to Devonian time. The history that can be 'read' from the onshore region complements the source area history interpreted from sedimentary basins derived from these areas.

The nature and rate of deposition of sedimentary basin sequences depend on many factors, including rates of basin subsidence, sea-level history and source area characteristics, such as climate history, lithology and uplift rates. Source area uplift is generally interpreted to be associated with an essentially instantaneous 'basin' signal of high rates of flux of sediments that have experienced limited chemical weathering. Although in some cases such a response may be demonstrable (e.g. Copeland & Harrison 1990), the degree to which major uplift is signalled by a sedimentary pulse depends on the extent to which the potential energy associated with high elevation can be converted into the kinetic energy (and hence the stream power) necessary to detach, entrain and transport high volumes of sediment. Two interrelated factors determine the extent to which potential energy provided by uplift can be converted to kinetic energy, namely, the geomorphological character of the source area, and the extent to which the source area 'knows' about the uplift event. A high-elevation, uplifting source area that is efficiently connected to base level will generate high volumes of sediment via a combination of river incision, mass movement from steep valley sides and efficient evacuation of sediment. The southwards draining rivers of the Himalayas offer excellent examples of such systems (e.g. Burbank *et al.* 1996; Hancock *et al.* 1998), which contrast markedly with the systems draining northwards from the Himalayas to the high-elevation, but low-energy and internally drained, Tibetan plateau (Summerfield & Brown 1998).

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The most rapidly uplifting areas, such as the Southern Alps (Hovius 2000; Tippett & Hovius 2000), Himalayas (Fielding 2000), Japan (Ohmori 2000) and Taiwan (Lin 2000), are associated with plate convergence zones. On the other hand, passive margin uplands, such as the southern African uplands (Brown *et al.* 2000), the Western Ghats in India (Gunnel & Fleitout 2000), the SE Australian highlands (Bishop & Goldrick 2000), and the Scottish Highlands portion of the western European Atlantic margin, are commonly associated with low to very low rates of denudation and sediment flux. Fleming *et al.* (1999) and Cockburn *et al.* (2000), for example, have reported very low rates of denudation from the southern African passive margin highlands, of the same order of magnitude as those reported from the SE Australian uplands from mass balance, geomorphological and thermochronological studies (Bishop 1985; Bishop & Goldrick 2000). Bishop & Goldrick (2000) also reported widespread and persistent disequilibria in SE Australian river long profiles, reflecting the low gradients and low stream power of this margin's drainage systems. These long profile disequilibria can be attributed to passive denudational rebound (Bishop & Brown 1992; Bishop & Goldrick 2000), with the margin evidently not having experienced active tectonic uplift during Cenozoic time apart from temporary uplift events related to transient thermal effects at the central volcanoes that mark eastern Australia's Cenozoic passage over mantle hotspots (Wellman & McDougall 1974; Wellman 1986; McDougall & Duncan 1988; Sun *et al.* 1989).

The tectonic character and histories of most of the passive margins descibed above have been reconstructed largely from subaerial terrestrial data, with relatively little reliance on the sedimentary basin record. The sedimentary record has been used mainly for mass balance studies of these margins to determine rates of source area subaerial denudation (e.g. Bishop 1985) or as a guide to the evolution of the river systems (e.g. Rust & Summerfield 1990). Rates of source area denudation may also be determined more directly from the source area itself using geomorphological studies (e.g. Bishop 1985; Nott *et al.* 1996), cosmogenic isotope analysis (Fleming *et al.* 1999; Cockburn *et al.* 2000), and low-temperature thermochronological techniques, such as apatite fission-track analysis (Gleadow & Brown 2000). Conflicts, which are not yet fully resolved, are often apparent, however, between geomorphological interpretations of source area history and thermochronological approaches to source area denudation (Kohn & Bishop 1999).

Reconstruction of the evolution of the Scottish Highlands (Fig. 1) on the Western European continental margin has relied on both offshore and onshore data, with often much greater emphasis on the offshore record, no doubt because of the wealth and quality of these data (see Jones *et al.* 2002). There is a corresponding wealth of data from onshore areas, and in this paper we re-examine the post-Palaeozoic geomorphological history of the Scottish Highlands as a source area for surrounding basins, especially the main sediment receiving area, the North Sea Basin. We have two aims: (1) to summarize critically the onshore data on the evolution of the Scottish Highlands, for a readership that might not be fully aware of the literature on this topic; (2) to assess the extent to which source area uplift, denudation and geomorphological development, and landscape antiquity, can be 'read' from the source area itself, thereby complementing the offshore record.

An outline of the history of the Highlands source region from Palaeozoic time to the present

The disposition and provenance of (often thin) remnants of Devonian sediments show that many key morphotectonic elements of the current Highlands relief were already established by the end of Devonian time (Fig. 2). These include the main Grampian watershed, the linear depression of the Great Glen, the large basins of NE Scotland and major valley systems draining NE towards the Moray Firth along the Caledonian fracture zones. The Caledonian mountains had been eroded, exposing many late Caledonian Newer Granites, together with some older intrusions (Watson 1985). The Caledonian granites were intruded into already stabilized crust or their intrusion completed the stabilization process (Leake & Cobbing 1993). Reconstruction of the sub-Devonian relief around the inner Moray Firth implies surfaces of high relief, with fault-bounded half-basins and fault-guided valleys partly infilled with conglomerates and sandstones. These Devonian fills were largely removed between late Palaeozoic time and the present so that the current level of erosion lies close to that at the end of Devonian time (see Leake & Cobbing 1993). A similar equivalence exists in the NW Highlands, where the present terrain lies at the same general elevation as the base of the Torridonian sequence (Watson 1985).

Fig. 1. Scotland, showing sites and features mentioned in the text.

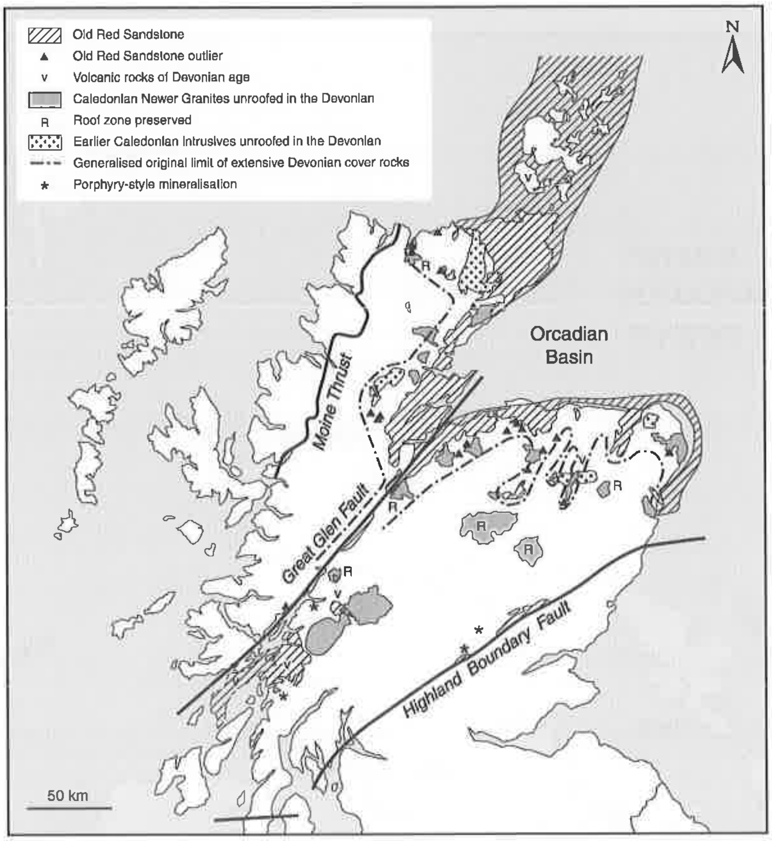

Fig. 2. Indicators of post-Devonian depths of denudation (after Hall 1991).

There is little direct evidence of events in the Highlands during the Carboniferous period, as rocks of this age are restricted to the marginal basins of the Midland Valley and the Moray Firth. The considerable thicknesses of Carboniferous sediments, with up to 4 km in the Midland Valley (Francis 1991) and 1.5 km in the outer Moray Firth (Andrews *et al.* 1990), were largely sourced from the Highlands. The Westphalian outliers in Morvern resting on the Moine sequence imply a former cover of Carboniferous rocks in parts of the SW Highlands (Francis 1991). A reworked Carboniferous microflora is present in Jurassic rocks as far west as the onshore outcrops in the inner Moray Firth Basin (Andrews *et al.* 1990).

The Highlands are generally shown as an emergent and exposed basement area in palaeogeographical maps of the Carboniferous period (Guion *et al.* 2000) but the extent and depth of Carboniferous denudation in the Highlands remain unclear. Recent apatite fission-track studies imply that as much as 3 km of late Palaeozoic cover rocks have been removed from the Highlands area (Thomson *et al.* 1999) but deep Late Palaeozoic erosion appears incompatible with the widespread survival of near-surface volcanic and intrusive rocks of late Carboniferous age (Watson 1985; Hall 1991). Volcanic activity continued throughout Permian time and is represented in the Highlands by the camptonite–monchiquite dyke swarms of Orkney and the Western Highlands (Francis 1991). Associated uplift was probably limited as the total volume of magma was small (Watson 1985). This accords with the survival of Carboniferous deep weathering mantles in northern Scotland that acted as a major source of kaolinitic detritus for Jurassic sediments in the inner Moray Firth (Hurst 1985a).

Alternating periods of moderate uplift, reduction of relief and marine transgression affected the Highlands during Mesozoic time (Hall 1991). Triassic sediments are up to 500 m thick against the Great Glen Fault but thin to 150 m around Elgin (Frostick *et al.* 1988). By the end of the Triassic period uplift had ceased and relief was considerably reduced, and the outer Moray Firth formed part of an extensive continental plain of low relief (Andrews *et al.* 1990). Calcretes and silcretes formed and the Rhaetic Sea transgressed close to the present margins of the inner Moray Firth. Continued transgression in Early Jurassic time saw the deposition of fluviatile sand around the margins of the Moray Firth. Sand and clay mineralogy suggests derivation dominantly from Devonian and Carboniferous cover rocks to the north (Hurst 1985a) and from Moinian chloritic metasediments to the south (Hurst 1985b). Thermal doming in Mid-Jurassic time in the Moray Firth Basin caused deep truncation of Early Jurassic and older sediments and sediment transfer to the Viking Graben and inner Moray Firth. Crustal collapse in the central North Sea in Callovian time was accompanied by rapid sedimentation in the inner Moray Firth and synsedimentary movements along the Helmsdale Fault (Anderton *et al.* 1979). Marginal marine sands overstepped the current basin margins and may have covered the axis of the Great Glen (Hallam & Sellwood 1976: Wignall & Pickering 1993). The faults controlling sedimentation in the inner Moray Forth appear to have also been active on the adjacent land area (Roberts & Holdsworth 1999).

Tectonic activity was renewed at the Jurassic–Cretaceous boundary in the Moray Firth Basin. Uplift of the Halibut Horst led to erosion of Carboniferous sandstones. Fault scarps along the northern margin of the inner Moray Firth generated coarse mass flow deposits (Anderton *et al.* 1979). Early Cretaceous sediments later overstepped the Helmsdale Fault north of Helmsdale to overlie Jurassic and Devonian sediments (Chesher & Lawson 1983). In Morvern, Cretaceous greensands rest on Moinian schists (George 1966). A small outlier of late Hauterivian–early Barremian glauconitic sandstone rests on Devonian and basement rocks in eastern Buchan (Hall & Jarvis 1994).

By Late Cretaceous time the Highlands had been reduced to an area of relatively low relief. Cretaceous sequences along the eastern margin of the Hebrides basin are thin, implying limited sediment supply, and lie close to sea level, implying tectonic stability (Hancock 2000). Terrigenous sedimentation ceased in the Moray Firth with the deposition of thick chalk sequences. On land, the sub-Cenomanian surface, before transgression, carried deep kaolinitic weathering mantles, later reworked to form the highly quartzose sands of Lochaline (Humphries 1961) and the kaolinitic Paleocene sands and muds of the inner Moray Firth (Carman & Young 1981). The extent of marine transgression in Late Cretaceous time is unclear but deposition of the chalk in depths of several hundred metres of water (Hancock 1975) suggests that only a small area of the Highlands can have escaped submergence.

Around 60 Ma, the passage of the Iceland plume was accompanied by major magmatic activity in western Scotland (Bell & Jolley 1997). Magmatism involved emplacement of igneous centres, extrusion of flood basalts well beyond the present outcrop and injection of regional dyke forms to form the Tertiary Igneous Province. The period of magmatism was brief, concentrated between 61 and 55 Ma (Jolley 1997), and in individual igneous centres volcanism was largely confined to single palaeomagnetic polarity intervals of 0.4–3 Ma (Musset 1984). Accelerated sand accumulation in the Moray Firth Basin (Liu & Galloway 1997) can be linked via sediment routeways and provenance to erosion of uplifted source areas on the Orkney–Shetland Platform and in the Highlands (Jones & Milton 1994). Sediment flux reached a maximum in Late Paleocene time and declined into Eocene time (Joy 1993; White & Lovell 1997).

Small outliers of thin Cretaceous sequences occur on both the western (Hancock 2000) and the eastern (Hall & Jarvis 1994) margins of the Highlands. As any emergent areas of the Highlands had been reduced to low relief by the end of Cretaceous time (Hall 1991), patterns of Tertiary uplift can be reconstructed using the present summit topography of the Highlands (Fig. 3). The distribution of summits above 800 m defines a zone of maximum uplift; terrain that now forms the main watersheds of the NW Highlands and of the Grampian Mountains. In Northern Scotland, high summits overlook the sedimentary basins of The Minch and the innermost Moray Firth, basins with margins that retain attenuated and localized sequences of Mesozoic sediments (Fig. 4). Major differential tectonics is implied between the Highlands and the surrounding basins. Early Tertiary reactivation of the Helmsdale Fault produced a major fault scarp, now marked by the line of hills between Ben Wyvis and Helmsdale. Another major escarpment existed in Early Tertiary time on the west coast of the Northern Highlands, stretching from the Cuillins to Cape Wrath. This escarpment is now dissected into a chain of isolated hills and hill groups, including the inselbergs of Suilven and Quinag. Its alignment runs parallel to the edge of the Minch Basin but it is not fault controlled, implying that uplift of the NW Highlands was associated with significant

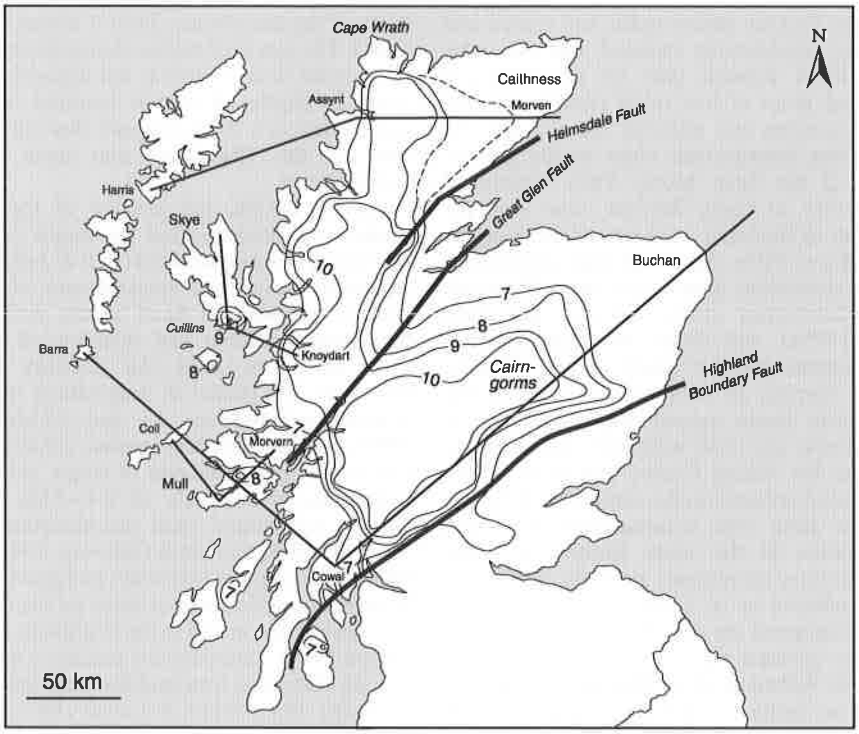

Fig. 3. Patterns of Tertiary uplift implied by Highland summit heights (in hundreds of metres). Fine lines give locations of diagrammatic cross-sections in Fig. 4 (longer section lines) and Fig. 5 (shorter section lines).

warping on its western margin. South of the Great Glen, there is also evidence of differential uplift. In Buchan the preservation of Cretaceous chalk flints and greensand demonstrates modest Tertiary uplift yet the Cairngorms, only 50 km to the west, even today reach 1300 m (Fig. 5). Differential movements are required, with possible downwarping towards the east in the Dalradian belt between Ballater and Keith (Ringrose & Migon 1997) and dislocation at the eastern edge of the Mounth and the Hill of Fare (Hall 1987). On the southwestern edge of the Western Grampians lies a zone of lower summits, centred on Cowal, where the presence of vesicular dykes (Gunn *et al.* 1897) suggests relative proximity to the Early Tertiary land surface (Fig. 4). The preservation on the Lorne Plateau of a small Carboniferous outlier at Bridge of Awe, resting on Devonian lavas (Johnstone 1966), is noteworthy, as are the fragments of sub-Triassic surfaces (Godard 1965) found in Morvern. These occurrences together imply that post-Caledonian vertical movements of the Cowal peninsula and adjacent areas have been modest when compared with those that have affected the main area of the SW Grampians.

In early Eocene time the Highland area foundered as it moved away from the Iceland plume (Nadin & Kusznir 1995) and sedimentation rates dropped in the North Sea (Liu & Galloway 1997). This coincided with the onset of a period, *c.* 20 Ma in duration, of humid and initially subtropical conditions, and apparently limited uplift. Deep kaolinitic weathering covers probably developed widely in association with extensive erosion surfaces (Hall 1991). Tectonic activity was resumed throughout NW Europe in Late Oligocene time, with the onset of major uplift of Fennoscandia (Rohrman *et al.* 1995) and basin development throughout western Britain, including the Hebridean region (Fyfe *et al.* 1993). The presence of depositional hiatuses west of the Shetlands (Ridd 1981), deltaic and lignitic sands east of the Shetlands (Johnson *et al.* 1993) and unconformities in the central North Sea (Gatliff *et al.* 1994) indicate significant uplift in the Scottish area and associated erosion and enhanced sediment supply (Liu & Galloway 1997).

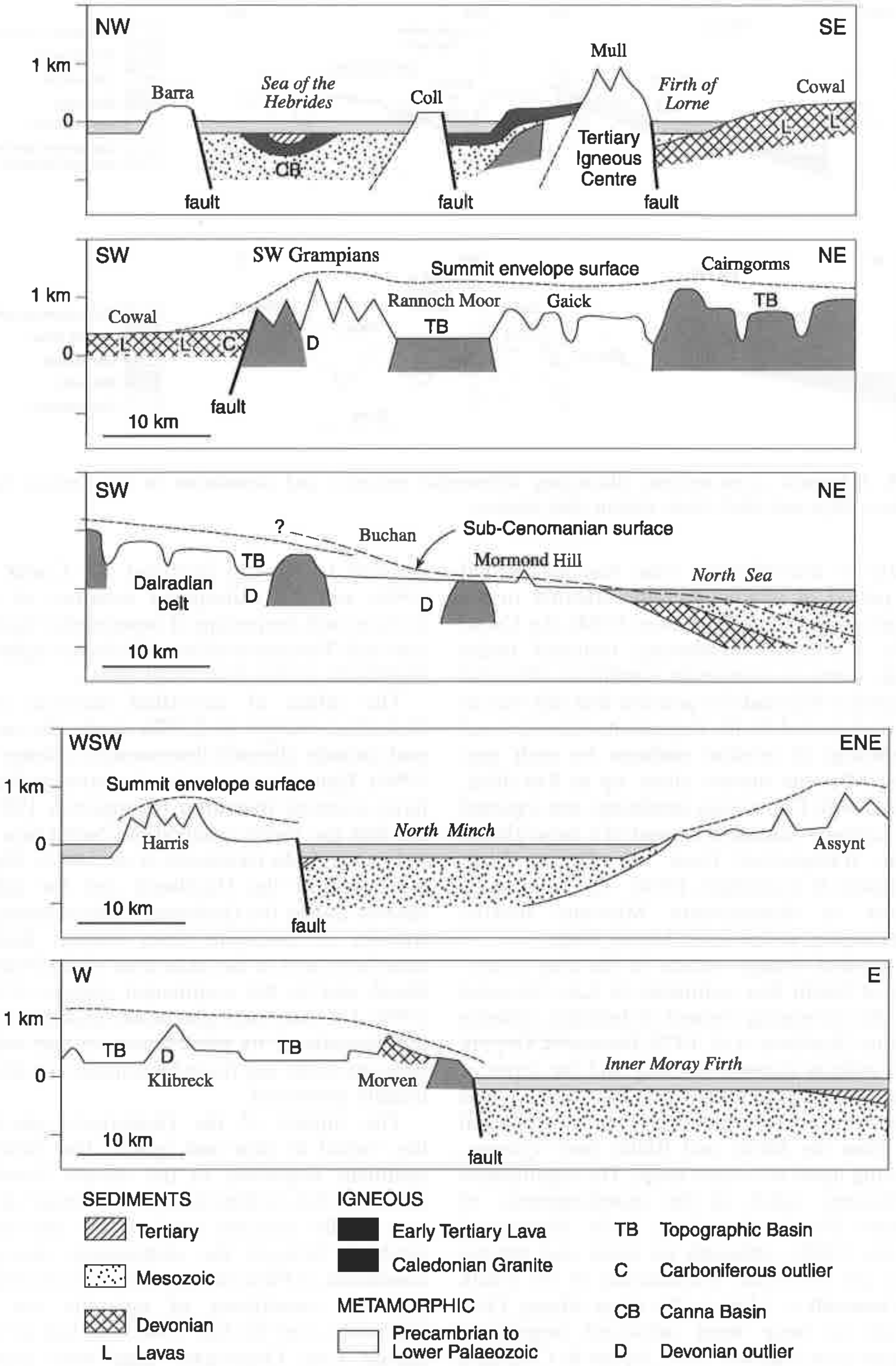

Fig. 4. Schematic cross-sections illustrating major morphotectonic units along two traverses across the Scottish Highlands.

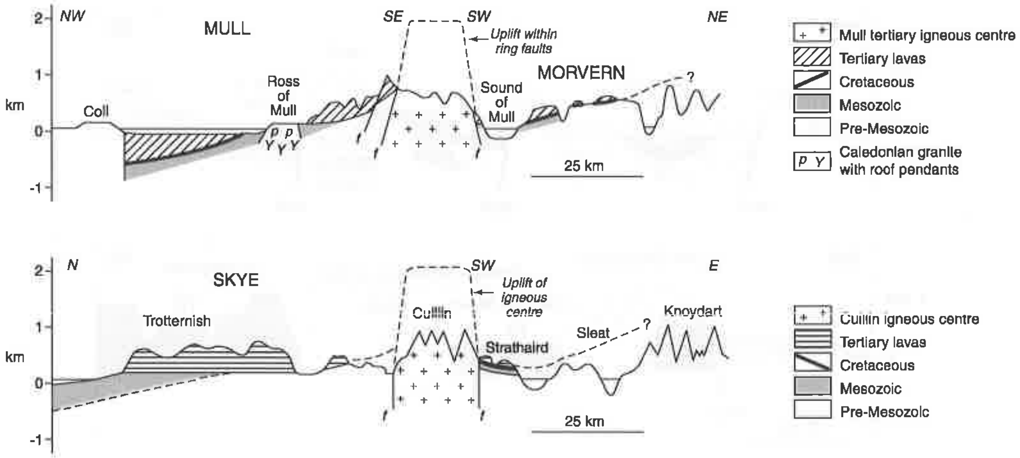

Fig. 5. Schematic cross-sections illustrating differential tectonics and deundation in the Tertiary Igneous Province: Skye and Mull (from various data sources).

Early to mid-Miocene time was the second long period of relative tectonic stability in the Tertiary period, lasting for over 10 Ma (Le Coeur 1999). Kaolinitic weathering resumed under humid, warm to temperate conditions (Berstad & Dypvik 1982) and it is possible that this was an important period for the formation, extension and remodelling of erosion surfaces by etch processes. Miocene marine clays, up to 8 m thick, together with Cretaceous sandstone, are reported from Leavad, Caithness, as part of a large glacial erratic transported from the Moray Firth (Crampton & Carruthers 1914). The occurrence appears to demonstrate Miocene marine sedimentation in the inner Moray Firth.

A marked change occurs in the clay mineralogy of North Sea sediments in Late Miocene time. An increasing content of feldspar, chlorite and illite (Karllson *et al.* 1979; Berstad & Dypvik 1982) reflects climatic cooling and the input of immature terrigenous material. This material was increasingly sourced first from Fennoscandia and later from the Rhine and Baltic river systems, reflecting uplift of source areas. The significance of Neogene uplift in the morphogenesis of northern Britain has long been recognized (George 1966), although its scale and pattern are as yet uncertain. Exhumation of the Chalk from beneath *c.* 1 km in the inner Moray Firth appears to have been achieved largely in Neogene time (Japsen 1997; Japsen & Chalmers 2000) and implies contemporaneous uplift of the Scottish Highlands. Geomorphological evidence for Late Tertiary tectonics is provided by the apparent warping of mid-Tertiary erosion surfaces in northern Scotland (Godard 1965), the uplift, warping and dislocation of Late Tertiary surfaces in western Scotland (Le Coeur 1988, 1999) and the widespread evidence of valley incision and deepening of topographic basins set into mid-Tertiary erosion surfaces throughout the Highlands at this time (Hall 1991).

The influx of ice-rafted material to the Hebridean margin at 2.5 Ma marks the onset of mid-latitude climatic deterioration (Stoker *et al.* 1994). Episodic mountain glaciation is likely to have occurred thereafter (Clapperton 1997) but the first ice sheets reached the North Sea Basin only after 1 Ma (Andrews *et al.* 1990). Multiple glaciation of the Highlands and the adjacent shelves during the Quaternary period brought the transfer of sediment from current land and nearshore area to the axial area of the North Sea Basin and to the continental shelves (Clayton 1996). On land, each glaciation tended to remove the deposits of its predecessor so that only the deposits of the last (Late Devensian) ice sheet are usually preserved.

The impact of the Quaternary glaciations has varied in time and space. The volume of sediment deposited in the central North Sea indicates that sedimentation, and hence denudation of the adjacent land masses and shelves, doubled between the dominantly non-glacial conditions of Pliocene and early Pleistocene time and the conditions of episodic ice sheet glaciation over the last 1 Ma. The last ice sheets during Late Quaternary time were also less effective agents of erosion and transportation than those of mid-Quaternary time, reflecting the earlier removal of pre-glacial weathered rock, the progressive adaptation of the glacier bed to the efficient evacuation of ice, and the greater thickness and extent of the Elsterian and Saalian ice sheets (Glasser & Hall 1997). The Scottish Highlands also exhibit a wide range of glacial landscapes, from the deeply dissected terrain of the western Highlands to the zones of selective linear erosion of the Cairngorms and the limited erosion of the Buchan lowlands (Linton 1959; Clayton 1974). The average depth of glacial erosion across Britain is estimated at 76 m, with 175 m in mountainous zones of intense erosion and as little as 15 m in zones of slow-moving or cold-based ice (Clayton 1996). This is equivalent to a volume less than the total amount of Quaternary sediment on the shelves surrounding Britain, implying that a significant component has been derived from the deep erosion of material from the inner shelves (Clayton 1996), including the inner Moray Firth and The Minch. Mass transfer on this scale must have caused isostatic uplift in the glaciated mountain areas of western and northern Britain. The depth of some of the west coast fjords may reflect glacial incision into the still-rising edge of the NW Highlands.

Former cover rocks in the Scottish Highlands

Palaeogeographical maps of the Highlands have tended to show the area as a persistent topographic high (e.g. Anderton *et al.* 1979; Ziegler 1981), but the extent and thickness of former cover rocks in the Scottish Highlands remain controversial. The region is routinely seen as a source area for sediments that have accumulated in the surrounding basins. This seems consistent with evidence of relatively modest depths (<1–2 km) of post-Devonian erosion of basement rocks (Watson 1985; Hall 1991). Yet in recent years, apatite fission-track thermochronology (AFTT), vitrinite reflectance and compaction studies have suggested that the Scottish Highlands have supported much greater thicknesses of overburden than previously thought and that depths of Tertiary erosion were as much as 3 km across northern Britain. The modelling of rates of cooling and the removal of overburden has the potential to provide valuable insights into the history of not only the offshore basins but also the adjacent source regions, yet it is currently often difficult to reconcile these models with onshore regional geology and geomorphology (Cope 1994; Holliday 1993; McCallan 1994; Smith *et al.* 1994). These are precisely the issues identified in parallel geomorphological and thermochronological studies of SE Australia (see Kohn & Bishop 1999).

Current models of Highland source area evolution based on AFTT (Thomson *et al.* 1999) suggest that: (1) late Palaeozoic cover rocks up to 3 km thick formerly covered the basement rocks of the Highlands; (2) Tertiary erosion has removed 1–2 km of rock from above the current topography.

There is little doubt that late Palaeozoic rocks once covered considerably larger areas of the Highlands massif than at present. Devonian outliers occur widely around the coastal rim of the Moray Firth and reach thicknesses of several hundred metres in fault-bounded basins. Carboniferous rocks formerly extended across part of the SW Highlands (George 1960) and reach a thickness of over 1 km in the inner Moray Firth (Thomson *et al.* 1999). Yet it is unlikely that late Palaeozoic rocks once covered all of the Highlands and hence pre-Mesozoic overburden thicknesses of 2–3 km seem unreasonable. The Lower and Middle Old Red Sandstones around the Orcadian Basin were largely derived from mountains sited in the area of the current Eastern Grampians and Western Highlands (Mykura 1983) and there is little obvious sign that these mountain areas were eventually worn down sufficiently to be buried. Typically, a regional unconformity separates the Upper Old Red Sandstone from older sediments and this is ascribed to regional tectonics (Mykura 1983). In Morayshire, on the margin of the Orcadian Basin where uplift might be expected to be limited, the Upper Old Red Sandstone rests in places directly on the Moine sequence (Horne 1923), indicating removal of the Lower and Middle Old Red Sandstone before deposition. A similar situation occurs in the Midland Valley, where the Upper Old Red Sandstone, including conglomerates with pebbles of metamorphic rocks derived from the Southern Highlands, rests with marked angular unconformity on the Lower Old Red Sandstone (Francis *et al.* 1970). By implication, substantial removal of the Lower and Middle Old Red Sandstone had been achieved before the end of Devonian time.

The Highlands also acted as a source region for Carboniferous sediments in the Midland Valley (Francis 1991; Guion *et al.*, 2000) and Namurian–Westphalian sandstones in the Stirling district contain heavy minerals ultimately derived from low-grade metamorphic rocks north of the Highland Boundary Fault (Francis *et al.* 1970). Along the eastern margin of the Minch Basin numerous small outliers of Permo-Trias occur. Only at Inninmore on the Sound of Mull is Carboniferous sediment found underlying Trias units and here the Carboniferous rocks are only

100–160 m thick. Elsewhere the Permo-Trias sequence rests on older rocks (Johnstone & Mykura 1989). By implication, the Carboniferous rocks were removed before the start of the Trias period or were never laid down to any significant thickness along the western edge of the Northern Highlands.

The thick sequences of Mesozoic clastic sediments in the central North Sea, which might be taken to indicate deep erosion of the Highlands, derive only in part from the Scottish area. A major contribution of material from Fennoscandia occurred during Triassic and early Jurassic time (Ziegler 1981). Erosion of intrabasinal highs also provided sediment (Andrews *et al.* 1990). Yet the presence of igneous and metamorphic debris in sediments at the margins of the Highlands implies continuing erosion and thus exposure of the basement of the Highlands area (Hudson 1964; Hurst 1985a, 1985b). The volume of debris also implies a significant, but unknown depth of erosion. In the Minch Basin, it is possible to quantify depths of Permian to Jurassic erosion of the terrain surrounding the Sea of the Hebrides Trough. Preserved sediment volumes are close to the originally deposited volumes (Steel 1978: Fyfe *et al.* 1993) and suggest that *c.* 280 m of rock was removed in Permo-Trias time and *c.* 210 m in Jurassic time from the main contributing area of the southern Outer Hebrides Platform. These relatively low values are consistent with the removal of only thin cover from the Highlands.

Depths of Tertiary erosion from the source area of the Moray Firth Basin in the Highlands can be quantified using sediment volumes in the North Sea. The North Sea acted as a sediment trap throughout Tertiary time (Liu & Galloway 1997), with only a narrow and shallow connection to the Norwegian–Greenland Sea (Nielsen *et al.* 1986). In early Tertiary time the dominant sediment source was the Scottish Highlands and the Orkney–Shetland Platform but throughout Neogene time sediment was increasingly derived from Scandinavia and the great river systems of NW Europe. Rough calculations indicate the removal of 600–800 m of rock from the contributing area east of the main Scottish watershed during Tertiary time (Hall 1991). As only 25% of the Scottish land area now lies above 300 m (Haynes 1983), it appears that the summit envelope surface of the Highlands at 900–1200 m (Fig. 3) lies only a few hundred metres below the uplifted sub-Cretaceous land surface. On these estimates, there appears to be a good fit between the volume of rock removed by erosion from the Highlands and that received in the North Sea Basin. In the inner Moray Firth, sonic velocities in the Kimmeridge Clay indicate removal of around 1 km of overburden (Hillis *et al.* 1994; Thomson & Hillis 1995) and this seems generally compatible with the existence of hills, such as Ben Rinnes, at up to 800 m elevation on both the northern and southern margins of the basin. In contrast, the removal of over 1.1 km of rock from above the present terrain of Caithness and Sutherland (Thomson *et al.* 1999) seems excessive. On Morvern, AFTA data indicate *c.* 1.7 km of Tertiary erosion on the Strontian Granodiorite (Thomson *et al.* 1999), yet the current land surface nearby retains thin sequences of Mesozoic sediments buried beneath Early Tertiary lavas (Johnstone & Mykura 1989).

Further judgement on these issues must await continuing work using AFTT and (U–Th)/He thermochronology. None the less, onshore geological and geomorphological data from the passive margins of southern Africa (B.J. Bluck, pers. comm) and southeastern Australia (Kohn & Bishop 1999; Bishop & Goldrick, 2000) seem to suggest that AFTT may overestimate the depths of former cover rocks and of denudation. Of course, the regional pattern of AFTT data, and the denudation that they imply, cannot be taken to provide a detailed history of any particular locality. The lavas of 100 Ma age on the south coast of New South Wales, for example, are inconsistent with deep denudation having occurred along and across the whole of the coastal strip below the SE Australian escarpment, an interpretation that has been implicit in much of the AFTT discussion. Likewise, there are many areas throughout the SE Australian highlands, as in the Scottish Highlands, where ancient landscape elements (dating from Mesozoic time in the SE Australian case) have been identified (Young 1981; Bird & Chivas 1989; Twidale 1994; Twidale & Campbell 1995; Hill 1999). Hill (1999) has argued that variations in relief in the SE Australian highlands and across the coastal strip below the escarpment, and differential preservation of Mesozoic landscape elements, may explain the apparent conundrum in SE Australia of kilometre-scale denudation in Late Mesozoic time and the preservation of Mesozoic landscape elements. Where local, detailed AFTT data are available in SE Australia, particularly in areas where the regional structure is dominated by individual fault blocks, differential fault block movement is clearly indicated by the AFTT data (Kohn & Bishop 1999; Kohn *et al.* 1999). Elevated geothermal gradients would also assist in minimizing the amounts of denudation required for Late Mesozoic fission-track ages to crop out at the present ground surface in SE Australia, but there is currently a

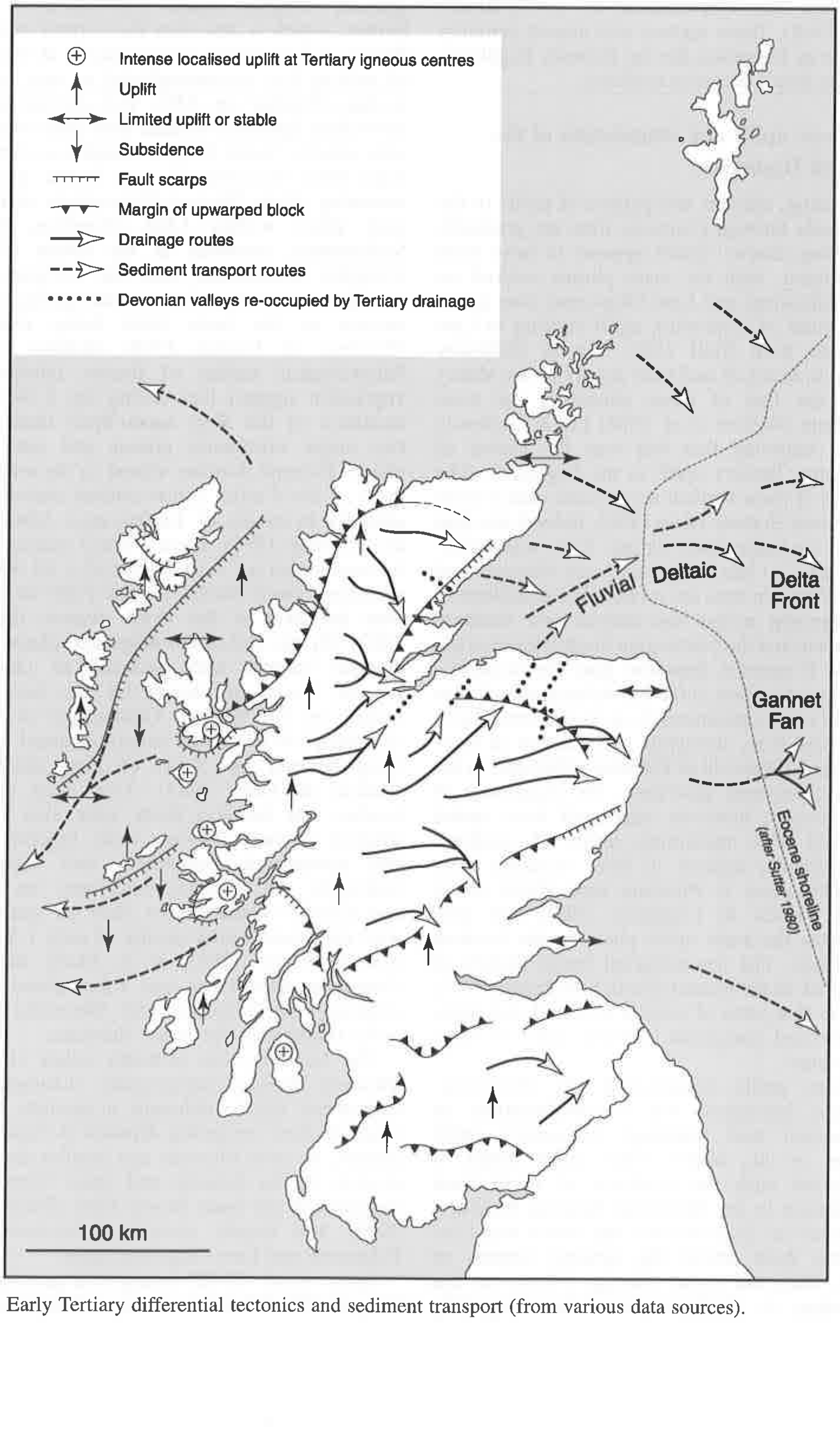

Fig. 6. Early Tertiary differential tectonics and sediment transport (from various data sources).

strong consensus among AFTT researchers that geothermal gradients along the SE Australian continental margin were probably not significantly greater than 25–30 °C km^{-1} in Late Mesozoic time (Dumitru *et al.* 1991; Brown *et al.* 1994). These matters will almost certainly emerge as important for the Scottish Highlands as more detail becomes available.

Cenozoic uplift and denudation of the Scottish Highlands

The timing, amount and pattern of uplift in the Highlands through Cenozoic time are gradually becoming clearer. Uplift appears to have been intermittent, with the main phases centred on Late Paleocene and Late Oligocene time and a later phase of continuing uplift starting in Late Miocene time (Hall 1991; Liu & Galloway 1997). In terms of sediment supply to the Moray Firth, the first of these phases is the most important (Nielsen *et al.* 1986; Liu & Galloway 1997), implying that this was the period of maximum Tertiary uplift in the Highlands. The timings of these vertical movements match those in western Norway (Riis 1996). Indeed, the four major unconformities dating from mid-Paleocene, mid- to late Oligocene, mid-Miocene and latest Pliocene time are remarkably consistent in development across the central and northern North Sea and the Norwegian Shelf (Huuse *et al.*, 2001). It appears therefore that the Scottish–Norwegian section of the NE Atlantic margin has reacted contemporaneously to crustal break-up in Paleocene time, intraplate deformation in Neogene time (Stuevold & Eldholm 1996) and to the onset of regional glaciation. The magnitude of these events, however, may well have varied spatially. The maximum uplift of southern Fennoscandia appears to have occurred from late Oligocene to Pliocene time (Doré *et al.* 1998; Japsen & Chalmers 2000) and thus postdates the main uplift phase in the Scottish Highlands. The reconstructed burial history of the Chalk in the western North Sea (Japsen 1997) implies that parts of eastern Scotland may have experienced maximum Tertiary uplift in Neogene time.

Major uplift occurred at the Paleocene-Eocene boundary via a combination of permanent and transient (dynamic) uplift (Jones *et al.* 2002). This uplift event is consistent with the evidence of rapid local denudation in the Hebridean Igneous Province. As much as 2 km of roof and cover rocks are missing from above the igneous centres of Skye, Mull and Arran (George 1966), but this unroofing is likely to have been spatially variable (Fig. 6) (see foregoing discussion of SE Australia). Holness (1999), for example, has argued that the metamorphic grade of the Torridonian arkose intruded by the Rhum Igneous Complex implies 500–550 m of overburden, which is less than the current relief on Rhum, and 'points to a topography at the time of melting [i.e. metamorphism] as very similar to that of today' (p. 538). This erosion of the Hebridean Igneous Province took place remarkably quickly. Some 2 km of basalt was removed from Mull between 58 and 56 Ma and the unroofing of the Western Granophyre of Rhum took place within 3 Ma (Emeleus 1983). Sedimentary interbeds in the Rhum Central Complex demonstrate that the complex was already unroofed and was undergoing active erosion as the lavas were being extruded (Emeleus & Forster 1979; Holness 1999). Palynological studies of former interbasaltic vegetation suggest that during the 0.24 Ma of existence of the Skye Lava Field there were two major subsidence phases and one uplift phase. Thermal doming related to the emplacement of the Cuillin centre caused elevation to altitudes in excess of 1200 m a.s.l. (above sea level; Jolley 1997). Lava erupted mainly from fissures spread out over an area of *c.* 40 000 km^2 stretching from Harris to the Firth of Clyde over the axis of the dyke swarms (Preston 1982). By the end of the magmatic phase many igneous centres were reduced to close to present levels, as shown by the late lavas resting on the Western Granophyre of Rhum (Emeleus 1983) and the deeply denuded basalts lying beneath the Sgurr of Eigg pitchstone (Dickin & Jones 1983). This deep erosion implies that the lava fields were also largely stripped in early Tertiary time, together with any underlying Palaeozoic and Mesozoic sediments. As Permian sandstones on Lewis and Jurassic sandstones on Skye are associated with maximum burial depths of only 1.5–2 km (Carter *et al.* 1995), it is likely that the Paleogene uplift event was a key phase in the stripping of Paleozoic and Mesozoic cover rocks throughout the Inner Hebrides.

The Leavad clays probably relate to early Miocene marine transgression (Crampton & Carruthers 1914), although a modern faunal study of these intriguing deposits is required. If correct, an early Miocene age implies that deep erosion of the Jurassic and lower Cretaceous sequence in the inner Moray Firth (Hillis *et al.* 1994) was largely completed between Late Paleocene and Late Oligocene time.

Jones *et al.* (2002) interpreted gravity data from the NE Atlantic in terms of Neogene uplift but because of the absence of later Tertiary rocks from much of the Highlands area it is not easy to assess amounts of subsequent uplift and denudation. The small fault-bounded Late Oligocene basins of The Minch and the NW Scottish shelf provide important evidence of a phase of tectonic activity that can be traced throughout western Britain and may be related to minor plate reorganization (Evans *et al.* 1991, 1997). It may be significant that the Late Oligocene floodplain and swamp deposits in these basins do not rest on Eocene sediments but on kaolinized basement, implying prolonged weathering under humid conditions in Eocene time. On the NW Scottish shelf, the Oligocene sediments are succeeded by Miocene shallow marine sands (Evans *et al.* 1997). The sequence implies that despite Eocene crustal collapse The Minch and the adjacent shelf remained above sea level until marine transgression in Miocene time.

Crustal movement resumed in Late Miocene time (Stoker *et al.* 1994). Japsen (1997) considered that the amount of exhumation during Neogene uplift was equivalent in Britain to that achieved in Late Paleocene–Early Eocene time (see also Japsen & Chalmers, 2000). This seems unlikely, as Neogene sediments in the North Sea are largely sourced from Scandinavia and NW Europe, rather than Britain (Jordt *et al.* 1995). Moreover, the large volumes of coarse clastic sediments of Late Paleocene and early Eocene age in the Moray Firth contrast markedly with the more restricted sequences of Neogene muds (Liu & Galloway 1997). The increasing resolution of the Neogene succession in the central and northern North Sea and on the Norwegian shelf helps to constrain the timing of this late uplift, with pulses of terrigenous sediments evident in Late Miocene time and, coincident with the first Scandinavian ice sheets, in Late Pliocene time (Eidvin *et al.* 2000).

The thick Neogene sequences in the Faeroe–Shetland basin system (Stoker *et al.* 1993) are more difficult to account for. Likewise, Jones *et al.* (2002) reported that the volume of Paleocene sediment in the Faeroe–Shetland basins cannot be accounted for by denudation of a source area in NW Scotland. They suggested that Faeroe–Shetland basin sediments may also have been derived from source areas other than NW Scotland, such as the Faeroe Islands region or more widely in northern and western Scotland, and a similar explanation may have to be invoked to reconcile the thickness of the Neogene sequence in the Faeroe–Shetland basin systems and the apparently minor Neogene uplift of Scotland.

The signature of these Neogene vertical movements is recorded by elements of the Highland topography. In the Northern Highlands, Godard (1965) recognized three major erosion surfaces: a surface between 400 and 550 m, which cuts across parts of the Tertiary igneous centres and so is post-Paleocene and possibly Eocene in age; an intermediate and extensive Scottish Surface at *c.* 300 m of possible Oligocene age; the low coastal plateau of the Niveau Pliocène at *c.* 100 m. Assuming that these erosion surfaces originated close to sea level, it has been estimated that uplift in the NW Highlands is of the order of 400 m in the last 40 Ma (Le Coeur 1999).

The long-term trend has been towards the progressive tilting or downwarping of the Highlands towards the inner Moray Firth Basin. Despite a degree of glacial diversion and disruption the main drainage routes continue to flow towards the Moray Firth, just as in Early Tertiary and Late Devonian time. The most extensive erosion surface recognized south of the Moray Firth is the Eastern Grampians Surface, comprising the ramp-like interfluves of the Monadliath, the Dee–Don watershed and the Mounth. These surfaces slope from their inner margins around the Cairngorms at around 800 m towards the inner Moray Firth and the North Sea, dropping to elevations of *c.* 500 m at the outer margins (Hall 1991).

Recent morphometric analysis has confirmed that regional tilting was far from uniform. Erosion surfaces between 200 and 600 m on the Monadliath are strongly influenced by the Great Glen Fault and the Ericht–Laidon Fault. This may imply a significant tectonic event in mid- to late Tertiary time in which an extensive medium-level erosion surface was disrupted by block movement (Ringrose & Migon 1997). Ringrose & Migon also identified a possible zone of flexure located in the Dalradian belt between the high tops of the Cairngorms and the lowlands of Buchan. Late Neogene faulting has also been proposed along the SE coasts of Rhum and Coll along the Camasunary–Skerryvore Fault (Le Coeur 1988) and in the Elgin area (Hall 1991) and may represent part of a continuing patterns of neotectonic activity (Muir Wood 1989).

Denudation and landscape evolution

The main morphotectonic units in the Scottish area were already in existence by the end of the Palaeozoic era. The Orkney–Shetland Platform, the Highlands and Southern Uplands massifs have remained above sea level for most of post-Palaeozoic time and have shed sediment to surrounding basins. The persistence of differential movements between basement massifs and sedimentary basins has allowed conservation, during surface lowering, of major topographic features from as long ago as Devonian time, including watershed zones, drainage patterns and, especially, the scarps at the margins of the buoyant basement massifs. The Helmsdale Fault, for example, has been intermittently active throughout Mesozoic and Cenozoic time (Andrews *et al.* 1990).

Superimposed on this physiographic framework are the main Tertiary landforms. The magnitude of Paleocene uplift and denudation means that these Tertiary landforms are of mid- to late Tertiary age. Only in areas of minimal displacement, such as Buchan and Caithness, is the preservation of extensive Mesozoic landforms feasible.

Exhumed terrains are of restricted extent in Scotland. They include the rugged sub-Torridonian surface in NW Scotland (Godard 1957; Stewart 1972) and the equally irregular sub-Devonian surface exposed beneath the outliers around the margins of the Moray Firth Basin (Godard 1965). Aside from areas such as these, the oldest landforms recognized in Scotland occur in the lowlands of Buchan. This is an area of long-term relative stability where typical Highland rocks are associated with surfaces of low relief (Clayton & Shamoon 1999). It is also an area of very limited glacial erosion. The antiquity of the landscape is demonstrated by the Cretaceous residues in the form of chalk flints within the quartzite- and kaolin-rich Buchan Gravels (Hall 1987) and an outlier of Lower Cretaceous greensand (Hall & Jarvis 1994). These residues rest on weathered igneous and metamorphic rocks, known in boreholes to extend to depths of many tens of metres (Hall 1986). Largely by correlation with clay minerals in North Sea sediments, the spatially restricted kaolin-rich weathering profiles have been assigned to pre-Pliocene time and the less mature, but still deep sandy weathering profiles to Pliocene and Pleistocene time (Hall 1985; Hall *et al.* 1989). Given the apparent stability of the area, it is conceivable that some of the kaolinitic weathered materials are older, surviving from Paleogene time or exhumed from beneath Late Cretaceous cover rocks (Hall 1993).

Deep weathering is of fundamental importance in understanding the nature and evolution of the pre-Quaternary relief throughout Scotland and NW Europe (Godard 1965; Thomas 1989; Migon & Lidmar-Bergstrom 2001). Its presence has been used widely as an indicator of the preservation or limited modification of preglacial forms (Linton 1951; Godard 1961; Hall & Sugden 1987). There is often a close correspondence between pre-glacial morphology, levels of rock resistance to chemical weathering (Godard 1962) and deep weathering patterns (Hall 1986). The Tertiary period in Scotland was a time of warm to temperate humid climates when most, if not all, of the country stood above base level, conditions favouring the deep penetration of weathering.

The sustained etching out of contrasts in rock resistance by chemical processes led to the formation of major landforms of differential weathering and erosion. These include valley systems, such as the pre-glacial headwaters of the Spey, Don and Dee, where there is pervasive litho-structural controls on valley alignment (Threlfall 1981). Deep topographic basins, some floored by Devonian sediments, are strung out along many of the valleys that drained east from the main watersheds in the NW Highlands and Grampian Highlands towards the Moray Firth (Fig. 4). The largest examples include the Rannoch, Atholl and Naver basins, with areas of more than 500 km^2 (Linton 1951). In NE Scotland, the basin floors are preferentially located on biotite-bearing granite and gabbro and boreholes show widespread deep weathering, reaching depths of as much as 50 m (Hall 1986, 1991). These susceptible rocks have provided the foci for weathering and erosion as the surrounding terrain was uplifted. In counterpoint stand inselbergs. These isolated hills include those of resistance, notably quartzite hills such as Schiehallion. Inselbergs of position also occur (Godard 1965), where the isolation of the hill mass appears to be a result of backwearing of slopes. A few exhumed hills occur, notably the sub-Devonian inselberg of Scaraben in Caithness (Crampton & Carruthers 1914). The quartzite inselberg of Mormond Hill in Buchan may be a Mesozoic relic, as it is associated with deep kaolinization and lies close to or at the level of the sub-Cenomanian surface (Hall 1987).

The landforms of differential weathering and erosion occur as mesoscale features as part of major erosion surfaces. The Buchan Surface, at an elevation of *c.* 100 m, includes most of the lowlands of NE Scotland, apart from the glacially modified coastal strip. It is an etch surface, where subtle differences in rock resistance give rise to hills and depressions and deep weathering is widespread. The origins of the eastern part of the surface date back to late Mesozoic time, for Late Cretaceous greensand and chalk were deposited on its surface, but it has a long history and its various elements are of different age. The preservation of unworn flints at the base of the flint gravels in Buchan testifies to the proximity of the sub-Cenomanian surface (Bridgland *et al.* 1997; Merritt *et al.* 2002). On the high ground of central Buchan at 100–150 m highly kaolinitic saprolites and the flint gravels themselves have been ascribed a pre-Pliocene age (Hall 1985). The lower tiers of the terrain support deep sandy weathering covers and appear to be of Plio-Pleistocene age.

It is likely that high-level erosion surfaces are also polycyclic and spatially diachronous. The surfaces at 800 m in the Gaick Forest (Hall & Mellor 1988) and at high elevations in the Cairngorms (Hall 1996) retain pockets of deep sandy weathering dating from the latest Plio-Pleistocene phase of etching. Within the Cairngorms mountains are a range of major paleic forms which have a longer history, including high-level basins and open valleys (Hall 1996) and the major depression of the Upper Avon Embayment (Linton 1950). The precursors of the major Tertiary rivers of NE Scotland, the Dee and the Don, were already established in Paleocene time and fed material to the Gannet Fan in the North Sea (Morton 1979). The Cairngorms and the Eastern Grampians have been an area of positive relief since at least the start of Tertiary time and these headwater erosion surfaces have evolved far above sea level. Phases of valley incision, indicated by benches on valley and basin sides, are likely to have been driven by changes in local base levels rather than in response to regional uplift.

Discussion and conclusions

Variations in the character and rate of supply of sediments to the offshore region has generally been interpreted in terms of source area responses to Cenozoic regional tectonics. Indeed, Liu & Galloway (1997) were explicit about the link between uplift and erosion in the North Sea Basin: 'Tectonic uplift of source areas exercises the commanding role in modulating long term sediment supply to the North Sea' (p. 1506). The precise process linkages between uplift and enhanced denudation are, however, not always as clear as is implied by the assumed link between uplift and enhanced sediment flux (see Introduction).

White & Lovell (1997) acknowledged that a simple process link between an increase in offshore sedimentation rate and the uplift of Scotland cannot be assumed, and suggested that uplift may be linked closely in time to increases in offshore sedimentation via an uplift-driven fall in relative sea level and an associated mobilization of sediments that were in storage in the nearshore area and on the continental shelf. It seems clear, none the less, that parts of Scotland, for example, the Tertiary Igneous Province, have responded rapidly to presumed uplift events. This is probably because these western areas are composed of small catchments that are well connected to base level and that, therefore, would be expected to respond rapidly to a fall in relative sea level. The preservation of ancient landscape elements throughout Scotland demonstrates, however, that such rapid response cannot be assumed for all areas, and that not all areas are equally sensitive to base-level changes. Variations in lithology will also be expected to be associated with variations in landscape sensitivity (see Brunsden & Thornes 1979); lithological variations in the response to Cenozoic weathering regimes in the Scottish Highlands point to a variant of such sensitivity. In the case of the Tertiary Igneous Province, it is also worth noting that construction of the Province's central volcanic edifices and the extrusion of the regional lava fields must have caused a relative elevation of the land surface, in turn triggering incision and enhanced denudation. The relative magnitudes of this latter effect and uplift remain to be quantified.

Many problems remain in understanding long-term landscape development in Scotland and yet there are many promising lines of enquiry. There is an urgent need for detailed morphometric analysis of the relief comparable with that available in southern Fennoscandia (e.g. Lidmar-Bergström *et al.* 2000). The scattered outliers of sedimentary rocks of Devonian to possible Miocene age that occur on land in Scotland are important archives of information regarding the evolution of the terrain, both via provenance studies and by investigation of burial histories. The dyke systems of late Caledonian, Carboniferous, Permian and Paleogene age that criss-cross much of Scotland have yet to be examined in detail with regard to depths of emplacement beneath contemporary land surfaces. Saprolites occur throughout Scotland, including buried and formerly buried pre-Cenozoic weathering mantles and Cenozoic deep weathering profiles. These saprolites await detailed mineralogical study and dating (Hall 1993), using techniques such as K–Ar dating of mica clays (Sturt *et al.* 1979) and D–H analysis of kaolins (Gilg 2000). Finally, there are opportunities to tie in the uplift and denudational histories of regional source areas within Scotland with sub-basins and fans in the offshore area, such as the Tertiary Barra Fan NW of The Minch (Stoker *et al.* 1993) and the Early Tertiary Gannet Fan fed by rivers draining the Eastern Grampians (Gatliff *et al.* 1994).

The preservation of ancient landscape remnants of varying spatial extent in the Scottish Highlands points to the types of spatial variability of denudation that have been identified in more detailed studies in southeastern Australia. Jones *et al.* (2002) has called for improved quantitative understanding of the Cenozoic denudation of northern Britain and it is therefore timely for thermochronologically based studies of the denudation of Scotland: (1) to move beyond regional denudational studies to more focused AFTT studies and (U–Th)/He analysis in apatite (Zeitler *et al.* 1987) to identify spatial variability in denudation; (2) to use AFTT and (U–Th)/He analysis to assess the extent of differential movements of crustal blocks; (3) to use the (U–Th)/He system to assess the age(s) of major landscape elements features (e.g. House *et al.* 1998); (4) to use cosmogenic isotope analysis to assess in more detail the spatial and temporal variations in Quaternary denudation.

Despite the advent of these various recently developed techniques, the major challenges of dating landscapes and landforms, and of determining the timing of uplift and denudation, remain. So far, the excellent temporal resolution available in the offshore record eludes us in studying the onshore, source area record, but this shortcoming does not justify, for example, oversimplified assumptions concerning the relationships between uplift and denudation.

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