Chapter 2 Lewisian Gneiss Complex of the Outer Hebrides

Introduction

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The Outer Hebrides comprise a chain of islands some 210 km long, ranging from the largest, Lewis and Harris in the north, through North Uist, Benbecula, and South Uist, to Barra, Mingulay and finally Berneray in the south. They include a multitude of smaller islands, and the more-outlying Flannan Islands, Shiant Islands, Sula Sgeir and North Rona. Although most of the islands were strongly scoured during Quaternary glaciations, there has been significant post-glacial build-up of peat, notably thick in some rock basins, and of blown sand and machair on the western side of the Uists and Barra.

The bedrock geology of the Outer Hebrides is dominated by Archaean and Proterozoic gneissose and subsidiary schistose rocks collectively termed the 'Lewisian Gneiss Complex'. Originally called the 'fundamental gneisses' of Scotland, they were renamed by Murchison (1862) after the island of Lewis. Although of broadly similar age and origin to the mainland Lewisian rocks of north-west Scotland (Chapter 3), the exact geological relationships between the two areas remain somewhat contentious. The two basement areas are separated by a dominantly Mesozoic-age sedimentary basin, which lies mainly beneath the Sea of the Hebrides and the Minches. Recent isotopic dating of zircons from the Lewisian Gneiss Complex has shown that the ages of the gneiss protoliths and metasedimentary elements vary across the complex. Times of emplacement of the main igneous bodies and of reworking also span a much greater period than originally envisaged (Kinny and Friend, 1997; Friend and Kinny, 2001). The Lewisian rocks of the mainland and Outer Hebrides apparently had distinctly separate geological histories prior to *c.* 1500 Ma, but the two areas have been in fairly close proximity since *c.* 1100 Ma, and both acted as part of the foreland to the Caledonian Orogeny.

Geological history

The Lewisian Gneiss Complex is a product of a multi-phase depositional, intrusive, deformational and metamorphic history that spans the time period between some 3100 million years ago and some 400 million years ago. The main lithologies result from a combination of different age and type of protolith, and different amounts and degrees of structural and metamorphic reworking. The generalized history of the Lewisian Gneiss Complex in the Outer Hebrides is summarized in (Table 2.1).

Two major periods of tectonometamorphic activity have been recognized; the Scourian and Laxfordian events. During the Scourian event the main elements of the gneiss complex were formed. The bulk of the rocks were originally granodioritic, tonalitic and basaltic intrusions emplaced at mid- or lower crustal levels and subjected to deformation and metamorphism (gneiss formation) between 3100 Ma and 2500 Ma. Granite bodies and microdiorite sheets were intruded near the end of the Archaean in what is termed the 'late Scourian' at around 2600 Ma (Fettes *et al.,* 1992). There followed the widespread intrusion of the 'Younger Basic' Suite of dolerite and basalt dykes and lenticular sheets in the Palaeoproterozoic at around 2400 Ma. Significant later accretion of possibly arc-related metasedimentary and metavolcanic rocks and intrusion of the South Harris Igneous Complex occurred at around 1880 Ma. The gneisses and earlier igneous bodies were reworked significantly between 1850 Ma and 1600 Ma, during the Laxfordian event, and it is the resultant Laxfordian folds, fabrics and metamorphic mineralogy that dominate the Lewisian rocks of the Outer Hebrides.

Subsequently, the Hebridean block was subjected to considerable uplift and erosion, and was the site of the formation of the Outer Hebrides Fault Zone (OHFZ). This gently ESE-dipping, complex structure is the product of several periods of compressional, strike-slip and extensional movements. The fault zone coincides approximately with a suture resulting from Lewisian terrane amalgamation between *c.* 1500 Ma and 1100 Ma (Friend and Kinny, 2001), and may have formed originally as a Grenvillian (*c.* 1100 Ma) thrust belt (Fettes *et al.,* 1992; Imber *et al.,* 2002). It was reactivated as an extensional structure at the time of deposition of the later parts of the Torridonian succession (*c.* 1000 Ma). Subsequent reactivation and further development occurred near the end of the Caledonian Orogeny during the main Scandian

WNW-directed thrusting event at *c.* 435–425 Ma (Fettes *et al.,* 1992). This was rapidly followed by further extension, which gave rise to dip-slip movements. Development of the roughly coincident Minch Fault occurred in the Mesozoic, and this structure later controlled the nature of the Palaeogene basic igneous activity that peaked at around 58 Ma.

Previous work

The Outer Hebrides were first visited for geological purposes by J. MacCulloch (1819) who carried out a cursory survey. Unlike the Scottish mainland, the Geological Survey did not map the islands in the late 19th and early 20th centuries, and T.J. Jehu and R.M. Craig of the University of Edinburgh undertook the first systematic study in the 1920s. The results were described in a series of reports in the *Transactions of the Royal Society of Edinburgh* between 1923 and 1934. Jehu and Craig recognized the main elements of Hebridean geology including the South Harris Igneous Complex, the Outer Hebrides Fault Zone, the mafic and ultramafic bodies, and the main outcrops of granites. A further gap in research followed, and it was only following the publication of J. Sutton and J.V. Watson's (1951) seminal work on the mainland Lewisian that work resumed in the Outer Hebrides. R. Dearnley mapped parts of South Harris (Dearnley, 1963) and also attempted to correlate wider features of Hebridean geology with the mainland (Dearnley, 1962a). Later, together with F.W. Dunning, he recognized the importance of the deformation state of a suite of Palaeoproterozoic mafic dykes, here termed the 'Younger Basic' Suite, which are equivalent to the Scourie Dyke Suite of mainland north-west Scotland (Dearnley and Dunning, 1968). This work focused on detailed studies of well-exposed coastal sections in Benbecula and South Uist and first recognized the heterogeneity and rapid spatial variations in the Laxfordian strain patterns. Also in the 1960s, Janet Watson, assisted by numerous PhD students at Imperial College, London, carried out a programme of work to map and understand the solid geology of the Outer Hebrides. A co-operative project with the Geological Survey to produce maps and reports followed. Areas not covered by PhD theses were mapped at 1:10 000 scale, existing material was compiled, and petrographical studies and chemical analyses of the main lithologies were carried out. The end result was the compilation of four 1:100 000-scale maps (Institute of Geological Sciences, 1981) and an accompanying memoir that included separate structural maps at 1:100 000 scale (Fettes *et al.,* 1992).

In the 1970s differing views were put forward regarding the number of major basic dyke suites in the Outer Hebrides. Bowes and Hopgood (1975) and Taft (1978) argued for several suites, and Coward (1973a,b), Francis (1973) and Davies *et* al. (1975) suggested that there is effectively only a single suite. Fettes *et al.* (1992) discussed the problem and the latter viewpoint was upheld. More-recent work has focused on the Outer Hebrides Fault Zone (OHFZ), describing its long and complex structural history (Sibson, 1977a; Fettes and Mendum, 1987; Butler *et al.,* 1995; Imber *et al.*, 1997, 2001, 2002), and dating of the various elements in the Lewisian Gneiss Complex (Cliff *et al.,* 1998; Whitehouse, 1990a; Friend and Kinny, 2001; Whitehouse and Bridgwater, 2001; Mason *et* al., 2004a,b; Mason and Brewer, 2005). In addition there has been detailed mapping, and geochemical and metamorphic studies in the south-west part of South Harris, notably on the various elements of the South Harris Igneous Complex, but also on the Langavat and Leverburgh metasedimentary belts (e.g. Witty, 1975; Dickinson and Watson, 1976; Horsley, 1978; Baba, 1997; Mason and Brewer, 2005). Baba (1998, 1999a,b) carried out detailed mapping and petrographical studies of the Leverburgh metasedimentary rocks and has described very high-pressure metamorphic assemblages, indicative of deep subduction.

Major lithologies

Mapping out and delineating the various elements of the Lewisian Gneiss Complex is difficult, even in well-exposed ground. Hence, the overall gneiss is generally represented on maps as a single unit, but discrete elements can be mapped out in places (Figure 2.1). As in many structurally and metamorphically complex terrains, evidence of the later tectonometamorphic events is more easily recognized. However, evidence of earlier events can be deciphered where later reworking of the gneiss is weak or absent. Many of the Outer Hebrides GCR sites feature anomalous areas where Laxfordian deformation is either effectively absent, or at least of low enough intensity to allow a picture of earlier events and lithologies to emerge.

Scourian

The protoliths of the Lewisian Gneiss Complex formed during the Archaean between 3150 Ma and 2500 Ma, and the tectonometamorphic processes that affected them during this period are assigned to the Scourian event. The oldest protoliths are metasedimentary enclaves and banded mafic and ultramafic intrusions. By analogy with Greenland, and from isotopic considerations, these units are probably between 3150 million years old and 2850 million years old (Friend and Kinny, 2001). The metasedimentary rocks are mainly brownish-weathering, schistose semipelites or rusty impure quartzose psammites. They occur typically as lenticular zones 5–50 m wide and show poorly defined contacts with the surrounding banded orthogneisses. The semipelites are recognized by their biotite-garnet-bearing assemblages, although in parts they also include sillimanite, staurolite, cummingtonite-gedrite and anthophyllite (Coward *et al.,* 1969). Around Loch Sgioport (Skipport), Coward *et al.* (1969) also reported the rare occurrence of both clinopyroxene and orthopyroxene in metasedimentary rocks, although later work has failed to substantiate this mineralogy Anthophyllite is common in some of the quartzose gneisses, notably near Scolpaig in the North Uist Coast GCR site. The metasedimentary lithologies are intruded by Scourian felsic and mafic orthogneisses and are cross-cut locally by Scourian aplitic and pegmatitic granite veins. Discrete belts of more-variable metasedimentary rocks, for example those found in South Harris and around Nis in northern Lewis, were once assigned to the Archaean (see Fettes *et al.,* 1992), but are now known to be Palaeoproterozoic in age (Friend and Kinny, 2001; Whitehouse and Bridgwater, 2001).

Spatially associated with metasedimentary rocks, particularly in the Uists and Benbecula, are lithologically distinct, compositionally finely banded, planar and lenticular, mafic-ultramafic bodies. These are termed the 'Older Basic' Suite and show ultramafic to felsic banding on a centimetre- to metre-scale. They form bodies tens to hundreds of metres across, generally with interleaved felsic orthogneiss or metasedimentary units. In South Uist bodies occur in linear belts (Figure 2.1), but individual intrusions are not coherent over more than a few kilometres. A good example is exposed by Rubh' Aird-mhicheil at the Cnoca Breac GCR site. More-coherent banded mafic bodies crop out on Benbecula and North Uist. Examples are seen in the northern part of the Gearraidh Siar (Carry-a-liar) and Baile a' Mhanaich (Balivanich) GCR site and in the North Uist Coast GCR site. Few large banded 'Older Basic' bodies have been recognized in Harris and Lewis.

In the eastern part of South Uist a granulite-facies mafic metadiorite, the Corodale Gneiss (also called 'Eastern Gneiss'), occurs in the hangingwall of the Outer Hebrides Fault Zone (Coward, 1972; Fettes *et al.,* 1992). The body exhibits relict igneous, possibly cumulate, banding in parts. This ranges from ultramafic to felsic on a centimetre- to metre-scale. In addition there appears to be an overall gradation from lower, more-mafic, parts up into more-felsic diorite. Sm-Nd and Pb-Pb whole-rock dating gives ages of 2770 ± 140 Ma and 2900 ± 100 Ma respectively, implying that this distinctive lithology is also of Archaean age and formed during the Scourian event (Whitehouse, 1993). The gneiss is bounded on its western side by a prominent thrust feature defined mainly by pseudotachylite breccia. Cataclastic fabrics and features are common throughout the unit, but on its eastern side it also shows evidence of low-grade retrogression and mylonitization. It is bounded to the east by mylonites and 'mashed' felsic gneisses. Similar foliated and fractured garnet-bearing metadiorite lithologies occur around the Butt of Lewis adjacent to the Ness Anorthosite and metasedimentary units. Whitehouse and Bridgwater (2001) obtained ion-microprobe U-Th-Pb zircon ages from the diorite showing that their protolith formed at *c.* 2700–2800 Ma, with Pb loss at *c.* 2300 Ma, and new zircon rim growth during the early Laxfordian event at *c.* 1860 Ma. A partly foliated, uniform metadiorite body is also exposed along the coast north-east of the Abhainn Bhuirgh (Borve River) [NB 409 573] in sheared contact with the adjacent flaggy metasedimentary gneisses. Metadiorite has also been recorded within mafic rocks at the mouth of the Abhainn Dhail (Dell River) [NB 488 624].

These metasedimentary and basic meta-igneous units were intruded by voluminous Archaean tonalitic and granodioritic sheeted intrusions, which now form the bulk of the quartzofeldspathic gneisses. In the literature they have been termed 'grey gneisses', but in this volume they are generally termed 'felsic gneisses'. Numerous small- to medium-sized mafic and minor ultramafic intrusions also form part of this igneous suite. The intrusions were apparently emplaced at mid- to lower crustal levels (> 15 km), mainly between *c.* 2900 Ma and 2700 Ma, and soon after emplacement were subjected to recrystallization, migmatization and gneiss formation under middle-amphibolite- to granulite-facies conditions ($D1_s$ and $D2_s$ events). These Scourian gneisses are the ubiquitous, typically banded, coarse-grained, felsic and mafic orthogneisses that form the bulk of the Lewisian Gneiss Complex. They vary from white to shades of grey, reflecting their feldspar and quartz content, and generally contain thin layers or lenticular bands rich in black biotite and dark-green hornblende. Discrete amphibolite layers and pods that range from a few millimetres up to tens of metres thick are also abundant. No major fold structures can be recognized now in the gneisses, but they have a strong, pervasive gneissose foliation and minor folds are present. Larger Scourian unbanded foliated mafic bodies up to several hundred metres across, normally amphibolite, but now partly migmatized or agmatized, have been mapped at various localities in North Lewis. They occur between the Abhainn Chuil (River Coll) and Abhainn Ghriais (River Gress) north of Stornoway, on the Eye peninsula, and on Muirneag [NB 479 489]. Possible Scourian mafic bodies are also shown interleaved with the metasedimentary rocks at Nis (Ness) and the Butt of Lewis, but in the light of recent age dating of the South Harris rocks (Friend and Kinny, 2001) and the Palaeoproterozoic age of the nearby Ness Anorthosite (Whitehouse, 1990b) these mafic bodies may be of Proterozoic age (see below).

A further period of late-Scourian (*c.* 2600 Ma) igneous activity resulted in the intrusion of locally significant ultramafic, dioritic, monzonitic and granitic bodies in parts of the Outer Hebrides (Fettes *et al.,* 1992). These intrusions all apparently cross-cut the Scourian gneissose banding and are variably deformed by the later Laxfordian events. They are best seen in eastern Barra in the hangingwall of the Outer Hebrides Fault Zone. The relationships between the various elements are particularly well displayed around Earsairidh, notably at the Leinis (Leanish) GCR site. Here, microdiorite sheets and dykes, and monzodiorite, monzonites and granite bodies intrude granulite-facies Scourian felsic gneisses containing hornblendite pods. The intrusive lithologies show no manifest signs of Laxfordian reworking and are cut by undeformed 'Younger Basic' dykes. The microdiorites are fine- to medium-grained, and range from dark-grey, melanocratic to pale-grey, leucocratic varieties. They occur as discordant but folded sheets and dykes up to 1 m thick, commonly with internal flattened and tightly folded mafic schlieren and a prominent related biotite fabric. Good examples are seen farther north on the island of Fuday [NF 743 084] in the Sound of Barra, where they are cut by late-Scourian quartz-feldspar pegmatites and undeformed 'Younger Basic' dykes (Fettes *et al.,* 1992). Immediately east of Castlebay, more-massive, sheeted, coarser-grained metadiorites with an overall thickness of *c.* 1 km dip 50°–60° to the east. They intrude Scourian quartzofeldspathic gneisses and are in turn cross-cut by granite sheets. These metadiorites can be traced southwards from Barra to Uinessan and Sandray, and similar rocks are mapped on Flodday to the north-east. Late-Scourian metadiorites and monzonites are absent from the Uists, Benbecula and Harris but are found in northwest Lewis.

The late-Scourian 'granites' in Barra are of two distinct types: (a) pink, medium-grained equigranular monzonites that occur as irregular sheets up to 10 m thick around Earsairidh, and (b) pale-grey to salmon-pink, coarse-grained augen granites that form intrusive sheets in the metadiorites east of Castlebay. The monzonites consist of potash feldspar (string perthite), plagioclase, quartz (< 5%), foxy-red biotite, minor altered hornblende and magnetite/ilmenite. The augen granites are composed of potash-feldspar aggregates (microdine microperthite and string perthite) with quartz, plagioclase and biotite. Accessory iron oxides and apatite are common. Larger sheeted and lenticular late-Scourian granitic intrusions, in part porphyritic, are also found in the northern and western parts of North Uist, on Berneray, in north-west Lewis, and on the Eye peninsula.

All of these elements were deformed by a late-Scourian episode of deformation and metamorphism that resulted in the formation of asymmetrical folds and gave rise to the regional NNE trend of the overall gneiss foliation ($D3_s$). Shear zones that post-date these structures are also recognized ($D4_s$). Late-Scourian quartz-feldspar pegmatites and pegmatitic granites occur sporadically throughout the Outer Hebrides.

The 'Younger Basic' Suite

The Scourian events were followed by a period of localized deformation and metamorphism between *c.* 2500 Ma and 2250 Ma, termed the Inverian event', by analogy with the similar-age event documented on the mainland, notably around Scourie and Lochinver (see 'Introduction', Chapter 3). However, in the Outer Hebrides this event apparently pre-dates the 'Younger Basic' Suite and thus is Scourian ($D3_s$, $D4_s$) by definition, yet on the mainland it appears to be coeval with, and to post-date, the emplacement of the Scourie Dyke Suite. However, between 2500 Ma and 2000 Ma, the Outer Hebrides generally appears to have been a relatively stable area, although the currently exposed rocks still remained at mid-crustal levels. At around 2420 Ma the Scourian elements were intruded by a suite of mafic to ultramafic dykes, sheets and lenticular intrusions, with possible later phases of dyke intrusion up to *c.* 2000 Ma (see 'Introduction' to Chapter 3; Heaman and Tarney, 1989). This predominantly mafic intrusive suite, known in the Outer Hebrides as the 'Younger Basic' Suite, is broadly correlated with the Scourie Dyke Suite of the mainland (see Fettes *et al.,* 1992), although Mason and Brewer (2004) argue on geochemical grounds that they represent separate dyke-swarms. The dykes are concentrated in zones with an apparent east to south-east trend and form part of a wide zone of Palaeoproterozoic mafic dykes that has been mapped in Greenland and on Baffin Island. The dykes act as an important marker, here separating an early Scourian period of crustal accretion, deformation and metamorphism from a later Laxfordian period of pervasive tectono-thermal reworking and granite intrusion (Figure 2.2). This distinction was first recognized during the initial geological survey of the mainland of north-west Scotland (Teall in Peach *et al.,* 1907). However, Sutton and Watson (1951) emphasized the importance of the mafic dykes, and used igneous events as 'stratigraphicar markers to differentiate and classify separate parts of the gneissose complex in the Scourie-Laxford area (see 'Introduction', Chapter 3). Subsequent work, both on the mainland and in the Outer Hebrides, has amplified and altered the picture but the original assertions remain true.

The bulk of the 'Younger Basic' dykes are metadolerites of continental tholeiite affinity; locally, olivine metadolerites, metanorites and serpentinized picrite and pyroxenite pods also occur. The dykes, sheets and pods vary from a few centimetres to over tens of metres and more rarely to hundreds of metres in thickness. One particularly large lenticular body centred on Carra-crom [NF 734 735] in North Uist measures 3 km x 1 km, but most dykes lie in the range 1–3m thick. They vary from undeformed coherent dykes (e.g. at the Leinis and Gearraidh Siar and Bane a' Mhanaich GCR sites), to partly recrystallized and modified bodies (e.g. at the Loch Sgioport and North Pabbay GCR sites). In western North Harris, central South Uist, and parts of the North Uist Coast GCR site the dykes and pods are reduced in places to near-completely digested amphibolitic remnants within the Laxfordian mobilized gneisses (Figure 2.3). The bulk of the dykes are now parallel or sub-parallel to the gneissose banding, either because they were originally concordant or owing to the generally high Laxfordian strain and folding. Most dykes are lenticular along strike, generally resulting from a combination of original intrusive geometry and Laxfordian deformation effects. Fettes *et al.* (1992) described the full range of deformation states of the 'Younger Basic' Suite in the Outer Hebrides. They also noted that some dykes occur in preexisting shear zones, formed during the Inverian event, and marked by attenuation of the Scourian features under amphibolite-facies conditions. Some evidence suggests that dyke intrusion was synchronous with localized shearing and amphibolite-grade metamorphism. However, recent Sm-Nd dating of minerals and dykes in the mainland Lewisian around the Laxford Front suggests that the peak metamorphic conditions of the Inverian event post-dated dyke emplacement here by 100–150 million years (George, 2000). This event may be equivalent to the earliest Laxfordian events ($D1_1$) in the Outer Hebrides, which are normally manifest as internal fabrics within the amphibolitic 'Younger Basic' dykes (e.g. see North Pabbay GCR site report, this chapter). The thicker mafic bodies and weakly deformed dykes preserve igneous fabrics and locally show relict compositional banding, for example at the Rhughasinish GCR site. Locally they exhibit sharp discordant contacts with no obvious chilling at their margins. Small apophyses are common and are well seen at the Gearraidh Siar and Bane a' Mhanaich GCR site on Benbecula, and at Ardivachar Point [NF 740 462] in South Uist (Dearnley and Dunning, 1968; Coward, 1973a). Their mineralogies are consistent with granulite- to upper-amphibolite-facies conditions, with pyroxene and garnet present. The dyke geometry and mafic mineralogy reflect the prevailing crustal pressure and temperature conditions during emplacement and the degree of subsequent Laxfordian reworking. However, even in the most pristine-looking intrusions pyroxene (salite) and feldspar compositions lie within the metamorphic fields.

In addition to the metadolerites, the 'Younger Basic' Suite includes a suite of massive, coarse-grained, grey to brown, pitted weathering, norites and picrites, known as the 'Cleitichean Beag dykes' after their type locality (Fettes *et al.,* 1992). They are typically undeformed and form elongate pods with their long axes aligned north-west. Occurrences lie in two roughly E-trending zones, the more northerly extending east from Great Bernera to Cleitichean Beag [NB 271 367] and ranging from 6 km to 2.5 km wide. The more southerly zone is effectively restricted to the area of North Harris around Abhainn Suidhe (Amhuinnsuidhe) with an outlier body farther east at [NB 143 035] by Àird Asaig (Ardhasaig). The picritic intrusions consist of large orthopyroxene (enstatite) plates, fresh olivine (forsterite) and clouded plagioclase (labradorite) with secondary coronas of clinopyroxene, and later hornblende and biotite. They are similar to the olivine-gabbros and picrites of the Scourie Dyke Suite on the mainland (Tarney, 1973). The noritic rocks typically consist of orthopyroxene (enstatite) and plagioclase (labradorite-andesine) with secondary clinopyroxene, hornblende, garnet and biotite commonly present. In addition to the above belts, a norite dyke some 100–150 m wide can be traced east from the head of the Langabhat valley [NB 144 105] in south Lewis, to Loch Seaforth (Shiphoirt), where it appears to cut an 'Older Basic' amphibolite body. The Cleitichean Beag dyke was dated by K-Ar whole-rock methods at 2440 ± 60 Ma (Lambert *et al.,* 1970), and although such methods are no longer considered reliable, the age is similar to ones more recently obtained from the mainland on members of the Scourie Dyke Suite.

A number of ultramafic pods and several small ultramafic to mafic layered intrusions are also found in south and central Lewis and North Harris. These bodies are relatively fresh and the pods commonly form 'trails' across the Scourian gneisses. In fact 24 separate pods are mapped within a distinct 3 km-wide zone in central Lewis, which extends ENE from Loch Morsgail [NB 137 220] for some 10 km to Loch an Taobh Sear [NB 227 245]. In the southern islands these intrusions occur at more-scattered localities, mainly in North Uist (e.g. at Craig Hasten [NF 743 668]), and the northern part of South Uist (see Rhughasinish GCR site report, this chapter). Individually the pods range in size from a few metres across to 100 m by 50 m.

They are mainly peridotites but dunites and pyroxenites also occur. Typically they consist of olivine, partly serpentinized, and large orthopyroxene plates up to 3 cm or even 5 cm long.

Secondary hornblende and phlogopite are present, as are minor clinopyroxene and accessory magnetite, chromite and chrome-spinel (Fettes *et al.,* 1992). The layered intrusive bodies include the layered cumulate body at Maaruig [NB 202 062] in North Harris (mainly dunite and harzburgite), and the East Gerinish body in South Uist at [NF 822 447]. This latter body shows cumulate layering ranging from ultramafic (websterite) at the base, to gabbro and leuco-gabbro higher up. At the Rhughasinish GCR site a fine-grained garnetiferous mafic body is in contact with a coarse-grained pyroxenite body, but the exact affinities of the two intrusions are open to interpretation. Shear zones are present at both these South Uist localities, and are marked by retrogression of the ultramafic rocks to hornblende, and in part to anthophyllite.

Belts of metasedimentary rocks and the South Harris Igneous Complex

Following emplacement of the 'Younger Basic' Suite there is evidence for the existence of tectonically active volcanic arc environments, marked by the deposition of varied sedimentary and volcanic sequences in restricted, at least partly ocean-floored, basins. The resultant infill is now represented by the Leverburgh and Langavat belts of South Harris, and the Ness Belt of north Lewis. Park *et al.* (2001) documented a similar scenario for the formation of the Loch Maree Group metasedimentary succession near Gairloch at between 2200 Ma and 2000 Ma. SHRIMP U-Pb zircon ages from the Langavat and Leverburgh metasedimentary rocks (Friend and Kinny, 2001) showed a range from 2780–1880 Ma for the detrital cores, and *c.* 1885 Ma and 1875 Ma for metamorphic rims. Sm-Nd data obtained by Cliff *et al.* (1998) also indicated a post-Archaean origin for the metasedimentary rocks and ^{207}Pb-^{206}Pb detrital zircon ages obtained by Whitehouse and Bridgwater (2001) were in the range 2150–1830 Ma. The data suggest that the metasedimentary successions were deposited in a volcanic arc environment around 1890–1880 Ma, rapidly followed by subduction, deformation and intrusion of the South Harris Igneous Complex (SHIC), all accompanied by amphibolite- to granulite-facies metamorphism.

The Leverburgh Belt, 1–1.7 km wide (Figure 2.4), consists of a wide variety of metasedimentary lithologies. Quartzose psammites, commonly garnetiferous, are the most abundant rock-type, but gneissose to schistose semipelite and pelite units are also prominent. The pelitic lithologies contain spectacular garnet, kyanite and sillimanite porphyroblasts and are locally rich in perthitic microcline. Near Roghadal (Rodel) the pelites are locally highly graphitic. Lenticular beds of calc-silicate rock are common in several areas, for example on Ceapabhal (Dearnley, 1962b), and metalimestones are prominent around Roghadal and on the Stuaidh peninsula. Amphibolitic mafic pods and lenses are scattered throughout the succession and are mostly intrusive in origin. However, recognizable amphibolitic mafic pillow lavas are present on the Stuaidh peninsula. The Langavat Belt farther north-east contains fewer definitive metasedimentary lithologies and the units show higher degrees of deformation and metamorphism. Psammites, quartzites, and finely banded amphibolite–felsic gneiss units are the main rock-types, with this last lithology interpreted as possibly metavolcanic in origin (see Na Buirgh (Borve) GCR site report, this chapter). Metalimestones and gneissose semipelites and rare pelites are present, but only as minor components. Mason *et al.* (2004a) proposed that the Langavat Belt metasedimentary rocks are unrelated to those of the Leverburgh Belt. They argued that the Langavat Belt represented imbricated felsic and mafic orthogneisses and metasedimentary units, with both elements subsequently strongly sheared during Laxfordian events.

Both belts are intruded by elements of the SHIC, which consists of four major meta-igneous lithologies: metagabbro, meta-anorthosite, metanorite and metadiorite. Metagabbros are very abundant as sheets and pods, and also constitute a major part of the Roineabhal layered metagabbro–anorthosite body. The upper anorthositic part of this body is the largest occurrence of anorthosite in the UK and was proposed as a site for a superquarry to supply white aggregate for use mainly as reflective road-stone. However, in the light of the unique scenery, geology, ecology and culture of South Harris the proposed quarry site at Lingreabhagh (Lingarabay) became the subject of a public enquiry in the 1990s (see Roineabhal GCR site report, this chapter). The metanorite body lies partly in the Sound of Harris and bounds the Leverburgh Belt to the south-west. The meta-diorite is generally mafic, in parts verging on gabbroic, and is the largest individual intrusion of the SHIC at c. 30 km^2. It also contains an elongate body of metatonalite some 9 km long and 100–150 m wide near Bagh Steinigidh. There are also numerous associated ultramafic pods, including serpentinized lherzolites, meta-pyroxenites (websterites) and hornblendites, all metamorphosed under granulite-facies metamorphic conditions. This last event has been dated at *c.* 1870–1880 Ma using both U-Pb zircon techniques (Cliff *et al.,* 1998; Friend and Kinny, 2001; Whitehouse and Bridgwater, 2001) and Sm-Nd whole-rock methods (Cliff *et al.,* 1983). The SHIC was intruded at lower crustal levels and crystallized initially under medium-pressure granulite-facies conditions. The presence of sillimanite in the adjacent metasedimentary rocks implies pressures of *c.* 9 kbar (25–30 km depth) and temperatures of *c.* 850° C. Subsequently the rocks were further recrystallized under high-pressure granulite-facies conditions and locally sapphirine-orthopyroxene-kyanite-bearing assemblages were formed in the pelites. Baba (1998, 1999a) used the metamorphic mineralogies to construct a pressure–temperature path that reached a peak of 12–13 kbar and 8000–900° C. These conditions were attributed to a subduction-arc collision model, which would be consistent with the overall tholeiitic to calc-alkaline trends shown by the extensive geochemical data for the SHIC (Baba, 1999b).

Quartzose psammites and striped amphibolites, the latter again possibly metavolcanic in origin (cf. Langavat Belt lithologies), also occur in northern Lewis around Nis (Ness). They are intruded by a somewhat altered and strongly tectonized anorthosite. Whitehouse (1990b) obtained whole-rock Sm-Nd isotopic data and a Pb-Pb isochron from three samples of the Ness Anorthosite. These implied that the body was probably emplaced around 2300–2200 Ma and was affected by granulite-facies metamorphism at 1860 ± 240 Ma.

Laxfordian events

The pervasive Laxfordian reworking of the Archaean (Scourian) and Palaeoproterozoic elements of the Lewisian Gneiss Complex took place under amphibolite-facies conditions between 1800 Ma and 1550 Ma. It resulted in folding, imposition of locally pervasive planar and linear fabrics, and migmatization. It terminated with the intrusion of late-stage granite sheets and veins and pegmatitic rocks, accompanied by significant uplift. In the Outer Hebrides the state of the generally abundant 'Younger Basic' dykes allows the intensity of the Laxfordian deformational and metamorphic effects to be assessed. In contrast to the mainland where Laxfordian reworking is effectively absent over wide areas, Laxfordian reworking is pervasive in the Outer Hebrides with the exception of parts of eastern Barra and local low-strain areas, notably in the Uists and Benbecula. It is these exceptional areas that are described in several of the GCR site reports (e.g. Leinis, Gearraidh Siar and Baile a' Mhanaich, North Pabbay, North Uist Coast).

The folding and metamorphism occurred early in the Laxfordian event and two main phases can be distinguished (Coward *et al.,* 1970; Fettes *et al.,* 1992). The earlier event ($D2_l$) resulted in pervasive gently dipping foliation and variably developed lineation. Close to tight folding on both small- and larger-scales is common, and F2 fold axes plunge gently to the north-west and south-east in the Uists and Benbecula, but more steeply to the SSE to south-west in South Harris. In northern Lewis F2 fold axes are more generally east or west plunging and are commonly subhorizontal. The later phase ($D3_1$) resulted in regional asymmetrical folding with broad hinge zones and attenuated steep limbs. The kilometre-scale F3 broad asymmetrical open antiforms and tight pinched-in synforms define the overall structural pattern of the gneissose foliation and pre-Laxfordian elements of the Lewisian Gneiss Complex in the Uists and Barra. Here, fold axes typically plunge gently to moderately to the north-west or south-east, with subvertical axial planes striking north-west or NNW The related S3 foliation/schistosity is well developed on attenuated fold limbs and in some fold hinge zones but is absent over large areas. The North Uist Coast and North Pabbay GCR sites amply illustrate the range of Laxfordian fold styles and related strain variations. In South Harris F3 fold axes plunge south-east, possibly controlled by the pre-existing orientation of the metasedimentary belts and the SHIC. However, in western North Harris they plunge at shallow angles to the west or to the ESE with F3 axial planes striking east–west and generally dipping steeply south. The sparse data in Lewis shows that, where present, F3 fold axes normally plunge gently north-east, and related axial planes dip moderately to steeply eastwards.

The Palaeoproterozoic metasedimentary belts show abundant tight folding and fabric development attributed to $D2_L$ and $D3_L$, with any pre-Laxfordian angular relationships strongly modified. Friend and Kinny (2001) showed that the metamorphic event in the adjacent reworked Scourian quartzofeldspathic gneisses occurred at *c.* 1680 Ma, just prior to the emplacement of the abundant Laxfordian granites. However, as at least part of the deformation in the Langavat Belt post-dates these granites, some of the deformation and metamorphism must be post-Laxfordian. The SHIC does show regional inversion and subsequent large-scale folding, both generally attributed to Laxfordian tectonometamorphic events (Coward *et al.,* 1970; Witty, 1975; Horsley, 1978). These tectonic events are early in the local structural chronology and may in fact be coeval with the early granulite-/upper-amphibolite-facies metamorphism at *c.* 1875 Ma. However, the extensive development of shear zones and amphibolite-facies retrogression, both marginal to and within the main SHIC bodies, is certainly attributable to Laxfordian events.

In the more water-deficient granulite-facies gneisses and the larger 'Younger Basic' bodies, Laxfordian reworking is normally limited to both small- and large-scale shear-zone development (e.g. Caisteal Odair in the North Uist Coast GCR site), and locally the formation of pseudotachylite. In places Laxfordian recrystallization and migmatization has resulted in the development of a coarse-grained gneissosity grading locally into a pegmatitic or agmatitic texture, with the original Scourian elements being masked or even erased. However, in many areas it is difficult to separate the earlier Scourian migmatitic textures from the Laxfordian effects unless 'Younger Basic' dykes are present. Laxfordian migmatization is best seen in the quartzofeldspathic gneisses in the western parts of Harris and south-west Lewis. Its occurrence relates to the development of Laxfordian granites, but migmatization normally pre-dates emplacement of the granite sheets and dykes. Where agmatization is well developed, F3 folding is locally associated with the generation of pegmatite. Farther north and east in Lewis migmatitic textures are not abundant. Here, $D2_L$ deformation and metamorphic features are dominant and $D3_L$ effects are apparently restricted to small-scale shear-zones and minor open folding. In South Uist and Barra, Laxfordian migmatization also occurs sporadically to the west of the Outer Hebrides Fault Zone, although here Scourian effects are normally dominant (Fettes *et al.,* 1992).

Laxfordian granites

The Laxfordian granites post-date the main deformation episodes and are best developed in the western part of North Harris and southwestern Lewis where they form the Uig Hills-Harris Granite Vein-Complex (Fettes *et al.,* 1992). Here, granite, porphyritic granite and leucogranite form a complex intermixture of sheets, veins and lenses up to several hundred metres thick. The granites are typically white to pink, medium-grained, biotite monzogranites, but the leucogranites range from aplitic to pegmatitic in texture. A development of late-stage aplitic granites and quartz-feldspar pegmatites is manifest as both discrete veins and more-diffuse zones at the margins of sheets and at granite-country rock contacts. In the Uig Hills the granites locally contain abundant microcline phenocrysts; this appears to be a late-stage magmatic effect. In parts the granites here are foliated and even mylonitic, particularly toward the margins of the granite complex. Fettes *et al.* (1992) reported several instances of aplitic and pegmatitic granites cross-cutting foliated granite, suggesting that deformation closely followed intrusion (e.g. west of Mangersta at [NB 003 314]). The granite complex extends south to Scarp, North Harris, Taransay and to the central part of South Harris. These areas typically contain thinner granite sheets than the Uig Hills. Adjacent to the Langavat Belt, Friend and Kinny (2001) recorded that granite sheets become mylonitic in the contact zone.

The granites have silica values between 68% and 75% and their geochemistry is typical of calc-alkaline suites. The restricted compositional range of the exposed granites is compatible with fractionation from more-basic parental magmas at *c.* 5 kbar. Aside from the Uig Hills-Harris Granite Vein-Complex, small Laxfordian granite bodies are found on An Cliseam (Clisham) and east of Aird Asaig in North Harris, at Dail Beag (Dalbeg) in west Lewis, and on the lower northern slopes of Beinn Mhòr in South Uist. They also occur as smaller veins scattered throughout the Outer Hebrides.

Granites from South Harris were dated by van Breemen *et al.* (1971), who obtained an Rb-Sr isochron age of 1713 Ma and a U-Pb bulk zircon age of 1678 Ma (recalculated). More recently, Friend and Kinny (2001) obtained U-Pb SHRIMP zircon ages of 1674 Ma and 1683 Ma from granite sheets in South and North Harris respectively, which they interpreted as the age of emplacement. They drew attention to the age difference between the Laxfordian granites on the mainland (1854 Ma) and those in the Outer Hebrides.

Late-Laxfordian pegmatitic granites and quartz-feldspar pegmatites are also widespread, with notable large examples at Sletteval and Ceapabhal (Chaipaval) in South Harris, which were worked for feldspar during the 1939–1945 war. The pegmatites occur generally in small swarms, with individual veins typically 1–2m across, although they do range up to 25 m wide. On Taransay, pegmatitic granites form between 25% and 75% of the exposed rock. They are generally white and pink, very coarse grained, and consist of perthitic microcline, quartz, albitic plagioclase, and biotite. Accessory minerals include magnetite (abundant), zircon, allanite, tourmaline, uraniferous minerals and in places garnet. Numerous other accessory minerals have been documented (Knorring and Dearnley, 1960; Knorring, 1959). In the Leverburgh Belt the pegmatitic granites are muscovite bearing. In South Harris they have been dated by various methods and were intruded mainly between 1700 Ma and 1500 Ma (Giletti *et al.,* 1961; Bowie, 1964; Mason and Brewer, 2005).

Post-Laxfordian uplift

A history of progressive uplift and metamorphism at shallower crustal levels during the Laxfordian event has been documented from the meta-igneous bodies within the SHIC and the adjacent Leverburgh and Langavat belts (Dickinson and Watson, 1976; Horsley, 1978; Cliff *et al.,* 1983; Baba, 1998). Elsewhere, only parts of the uplift history are preserved. Following Laxfordian deformation, metamorphism, and granite and pegmatite emplacement, the Lewisian Gneiss Complex was further exhumed by significant uplift and erosion. Kelley *et al.* (1994) obtained laser-probe Ar-Ar ages of 1430 ± 30 Ma and 1450 ± 50 Ma from biotites in the orthogneisses below the OHFZ on Grimsay. These date the closure of the Ar isotopic system in biotite by cooling, reflecting the rate and timing of post-Laxfordian uplift. By *c.* 1000 Ma the level of erosion was probably not greatly different to that at present.

It is unclear as to whether compressional episodes relating to parts of the Grenvillian orogenic event affected the Lewisian Gneiss Complex of the Hebrides. It certainly strongly affected pre-existing gneissose complexes in Canada and Sweden. Cliff and Rex (1989) obtained Rb-Sr biotite ages from 25 samples taken mostly from South and North Harris, but extending into central Lewis as far north as Carloway. These showed a range of closure ages between 1655 Ma and 954 Ma, mostly reflecting the post-Laxfordian uplift. In the granulite-facies rocks of the SHIC biotite ages are older, ranging from 1628 Ma to 1346 Ma, but north-east of the Langavat Belt the Rb-Sr ages generally cluster around 1200–1000 Ma. Mason and Brewer (2005) suggested that dextral-normal movements may have occurred at this time, focused on the later mylonitic rocks in the Langavat Belt. Older ages are recorded in Harris and Lewis from granulite-facies gneisses, the Maaruig ultramafic body and Laxfordian quartzofeldspathic pegmatites. Cliff and Rex (1989) suggested that the ages were compatible with uplift of the Outer Hebridean Lewisian rocks at the time of Torridonian deposition and that they may well have acted as a source of sedimentary material.

Outer Hebrides Fault Zone

The Outer Hebrides Fault Zone (OHFZ) is a coherent, but complex, zone of ductile and brittle high-strain rocks and fault rocks that extends down the eastern side of the Outer Hebrides. It stretches for over 170 km from Tolsta Bay in Lewis, to Sandray, south of Barra (Figure 2.1). Many of the fault rocks tend to be massive and resistant to erosion, and commonly define positive topographical features. The most obvious examples form the prominent hilly eastern spine of North and South Uist. Here, the Lees (Lì a Thath, 251 m and Lì a Deas, 281 m), Eaval (347 m) (Figure 2.5), Thacla (Hecla) (606 m), Beinn Mhòr (620 m) and Triuirebheinn (357 m) represent the scarp and dip-slope of the OHFZ. Similar features are seen on Barra (Sheabhal (Heaval), 383 m) and more rarely in Lewis (Beinn Mholach, 292 m). The fault zone represents a major crustal structure similar in magnitude to the Moine Thrust Belt but located entirely within the Caledonian Foreland. However, it does appear to show evidence of a longer, more-complex, geological history stretching from the end Mesoproterozoic Grenvillian event to the late Silurian Scandian Event. There are no GCR sites within the OHFZ itself, although several impinge on its outcrop (e.g. Roineabhal and Cnoc an Fhithich (Aird Grèin) GCR sites). In view of this, the fault zone is given a fuller description in this introductory section than other parts of the geology of the Outer Hebrides.

The OHFZ includes gently to moderately SSE-dipping thrusts and extensional fault-zones, marked by pseudotachylite breccia, mylonites, ultramylonites, and phyllonites. Fault gouge is found along later along-strike and across-strike faults. Between the thrusts and faults are significant thicknesses of more-massive cataclastic gneisses and protomylonitic gneisses, aptly termed 'Mashed Gneiss' by Jehu and Craig (1925). The zone is unique in the UK in that it contains abundant examples of pseudotachylite. The different elements range in age from post-Laxfordian (*c.* 1650–1100 Ma) to Caledonian (Scandian *c.* 430–420 Ma) and Mesozoic (in part Permo-Triassic). The history of the zone has been summarized by Fettes *et al.* (1992) and more recently by Imber *et al.* (2001, 2002).

Rock types

Pseudotachylite is a black glassy rock when fresh, which results from localized frictional melting of the relatively dry country rock along fault planes during seismic movements. Subsequently the glass is typically devitrified and retrogressed to a grey or brown, very fine-grained material as in the Outer Hebrides examples. Its melt origin is indicated in places by feldspar microlites, and it commonly includes angular to rounded fragments of quartz, feldspar and more rarely hornblende. Once frictional heat has generated a melt, there is a sudden release of the pent-up energy and the melt cools very rapidly; the process lasts only seconds. Hence, the thickness of melt produced along generation planes is limited during individual seismic movements. Thicker zones are due to migration of melt away from the generation surface and/or multiple seismic movements. Jehu and Craig (1923), Sibson (1975, 1977a) and Fettes *et al.* (1992) *all* noted the features and occurrences of pseudotachylite, which are particularly well displayed in South Uist and Barra. The Cnoc an Fhithich GCR site in north-west Barra provides excellent examples.

In the Outer Hebrides pseudotachylite is commonly intermixed with cataclasite, an aphanitic, structureless, cohesive, fragmental breccia with the fragments < 0.2 mm across, which results from rock comminution in fault-or shear-zones. It commonly weathers grey or brown. Where fluids are present and the deformation processes have been more ductile, mylonite results. This forms distinct planar zones up to 30 m or 40 m thick consisting of fissile to flaggy, typically finely colour-banded, pale-green to fawn and even cream, fine-grained rock. Quartz, muscovite, chlorite, epidote and sericite are the dominant minerals that define the banding, whereas plagioclase feldspar and hornblende generally form more-resistant augen. Titanite (after ilmenite) is common in the more-mafic rock-types. In contrast to pseudotachylite, mylonites formed along mostly aseismic shear- and fault-zones by ductile processes, involving mainly recrystallization and grain-size reduction, grain-boundary sliding, and concomitant metamorphic changes of mineralogy. If the degree of strain was very high, the mylonites can be extremely fine grained and are termed 'ultramylonite'. The mineralogy and textures vary, dependent on the ambient pressure and temperature conditions. Lower amphibolite-facies mylonites have been found locally in south-east Lewis around Ceann Shiphoirt (Seaforth Head) [NB 295 158] and in the Baile Ailein (Balallan) area [NB 305 219], but mylonites normally have a greenschist-facies mineralogy. Where they have enhanced sericite contents and lower greenschist-facies mineralogies (quartz, albite, chlorite, sericite/phengitic muscovite), the mylonites are more finely laminated, schistose and normally fissile; they are termed 'phyllonites' (Higgins, 1971; Sibson, 1977a). Their typical appearance is as dark- to pale-green, grey and cream, millimetre- to centimetre-scale banded rocks with sharp internal colour boundaries. In parts they are developed preferentially in the mafic or more biotite-rich quartzofeldspathic gneisses, but they are primarily a product of an enhanced fluid flux and related retrogression that accompanied shear-zone formation (see Imber *et al.,* 2001).

The term 'Mashed Gneiss' encompasses the brecciated, partially cataclastic, and protomylonitic orthogneisses that make up much of the OHFZ. In many places the gneissic foliation has become disorientated to such an extent that the rock resembles a fine to coarse breccia. Pseudotachylite is common in this zone, as is cataclasite, but the gneiss and the fault rocks are typically retrograded.

Fault zones are marked by locally intense fracturing and in parts by clay-rich fault gouge. Good examples are documented in Barra and the adjacent small islands (MacInnes *et al.,* 2000), where they range from SE-dipping brittle thrust planes to more generally steep structures that offset the mylonitic fabrics and earlier thrust features. In South Uist, just south of Rubha Bholuim (Bolum) [NF 829 283], Osinski *et al.* (2001) recorded that soft, clay-rich gouge marks gentle E-dipping faults that bound the phyllonites.

Relationships between the various rock-types are clear in some areas but local examples cannot necessarily be translated to the fault zone as a whole. Good relationships are exposed in the notably wide outcrop of the OHFZ in southeast Lewis. Here, pseudotachylite veins cut early-formed amphibolite-facies mylonites in the Baile Ailein area [NB 305 219], and pseudotachylite breccia and 'Mashed Gneiss' are in turn commonly overprinted by a mylonitic foliation.

Similarly, thin planar ultramylonite zones crosscut pseudotachylite veining and 'Mashed Gneiss' fabrics in the Eisgein (Eisken) (NB 32 11) and Ceann Shiphoirt areas of south-east Lewis. Comparable relationships can be found in the Lochportain–Crogearraidh na Thobha (Crogarry na Hoe) and Eaval–Eigneig Bheag areas of North Uist. Around Loch Bhalamuis [NB 295 011] in south-east Lewis two sets of thrusts or faults with related mylonitic fabrics are observed, with later steeper dipping faults cross-cutting earlier low-angle structures. Altered, crushed and sheared gneisses also underlie the pseudotachylite breccia on Roinebhal [NF 813 139] in South Uist and appear to represent a later low-grade brittle reactivation of the western margin of the OHFZ. Folding is observed in several parts of the OHFZ, generally affecting the mylonites. The folds normally have chevron or kink styles, but in parts a related strong crenulation cleavage is developed. Dislocations related to the fold geometry are also present, testifying to the reactivation of the fault zone. Most of the folds appear to link to down-to-the-E extensional movements. Excellent examples are seen at Rubha Bhrolluim [NB 241 037] in south-east Lewis, and at Eigneig Bheag [NF 924 601] in North Uist. In South Uist, at Bàgh Uisinis (Usinish Bay) [NF 853 335] and on Stulaigh (Stuley) Island [NF 830 235], Coward (1972) reported small-scale tight folds in the mylonites. These probably formed as an integral part of the mylonitization, rather than during a later episode of movement as seen farther north.

Distribution of features and rock types of the Outer Hebrides Fault Zone (OHFZ)

The features recognized along the length of the OHFZ vary markedly and are best considered geographically as typical of either Lewis and Harris or the Uists and Barra. (Figure 2.6) shows the distribution of OHFZ-related rock-types and main features, whereas (Table 2.2) lists the various characteristics and interpreted kinematic history of the northern and southern regions of the OHFZ and their possible age.

In Lewis and Harris the OHFZ affects the mainly felsic orthogneisses and a significant thickness of 'Mashed Gneiss' and gneisses with protomylonitic and cataclastic fabrics is developed. This zone extends for *c.* 8 km west of Stornoway and is 15 km wide in the Park district of south-east Lewis. Its western limit is marked by a thick cataclasite + retrograde pseudotachylite breccia zone that dips gently to the southeast. When traced southwards this bounding zone becomes more diffuse, and mylonites and pseudotachylite-rich zones are widespread within the OHFZ. These are well seen around Ceann Shiphoirt [NB 295 158] and farther south around Loch Claidh and Caiteseal (Caiteshal) [NB 242 044]. Here, the zone of retrogression lies east of the thrust front and corresponds to the appearance of mylonites and phyllonites. Hence, the pseudotachylite, early mylonites and 'Mashed Gneiss' lack the pervasive hydrous alteration typical of most of the thrust zone. Farther south on Scalpay there is an extensive thickness of mylonites and mylonitic gneisses that Lailey *et al.* (1989) interpreted as partly predating the 'Younger Basic' Suite intrusions and the late-Laxfordian pegmatites. The field and petrographical relationships have been reinterpreted by Imber *et al.* (2002) to show that the mylonitic deformation post-dates all these intrusions. On South Harris the zone of retrogression extends up to 3 km west of the OHFZ. Within it the plagioclase feldspars are pervasively altered to sericite and epidote, hornblende is altered to epidote and chlorite, and biotite to chlorite. Perthitic microcline feldspar and muscovite have grown locally, titanite (after ilmenite) is abundant, and epidote is commonly found on joint planes. Farther south the OHFZ affects the south-east end of the meta-anorthosite outcrop resulting in extensive brecciation and saussuritization (in which plagioclase goes to zoisite, paragonite and quartz).

In the Uists, the zone of alteration is again roughly coincident with the incoming of mylonites and phyllonites. Hence, it is only the western parts of the OHFZ outcrop that are largely unaffected by the hydrous retrogression. The fault zone is formed in the Laxfordian gneisses in North Uist and shows a broad transition from the early-formed pseudotachylite breccias at lower structural levels in the west to the later mylonites, phyllonites and folded phyllonites farther east. Note that the thrust products are out-of-sequence (cf. Moine Thrust Belt) and here reflect progressively younger periods of fault-zone activity eastwards at higher structural levels.

'Mashed Gneiss' is extensively developed on North Uist, for example east of Lochportain [NF 963 724] and on Eaval [NF 897 606], but is not abundant on South Uist. Here, the Corodale Gneiss lies directly above a *c.* 50 m-thick zone of pseudotachylite breccia marking the base of the thrust zone. Although this massive metadiorite body is partly cataclased, particularly near its base and top, it largely retains its original coherence. It is structurally overlain to the east on the Uisinis (Usinish) peninsula (NF 86 34) by thick mylonites and 'Mashed Gneiss'. 'Mashed Gneiss' also occurs to the south around Maol na h-Ordaig [NF 838 148]. Mylonites are common in the OHFZ of North Uist, and are notably thick along its eastern coastline, but in South Uist they lie mostly offshore.

On Barra the thrust at the base of the OHFZ is marked by 25–75 m of pseudotachylite, cataclasite and breccia and forms a prominent relief feature. However, the gneisses in the hanging-wall are virtually unaffected by deformation, brecciation, and so on. Laxfordian structures have been interpreted as being displaced across the thrust (Francis, 1973; Sibson, 1977a,b), and granulite-facies orthogneisses are present both above and below the thrust. Matching of features implies only limited displacement and the exposed thrust feature possibly represents a forethrust of the main OHFZ that itself lies offshore to the east in the Sea of the Hebrides.

Faulting

In addition to the dominant E-dipping thrust and extensional structures that dominate the OHFZ, normal and strike-slip faulting have also occurred at various stages of development. Stein (1988) used two-dimensional seismic reflection lines from the Minches to show that the interpreted Torridonian succession thickens westwards, and suggested that a bounding low-angle fault was active during deposition at *c.* 1000 Ma, at least adjacent to Lewis and Harris (see Imber *et al.,* 2001). Butler *et al.* (1995) suggested that sinistral strike-slip movement took place along the OHFZ as part of its main development. They based this on the recognition of near-strike-parallel mineral lineations, quartz-feldspar porphyroblast shapes (0-type and 8-type), and shear bands in phyllonites from North Uist (Eaval–Eigneig Bheag area), the Park district of south-east Lewis, and from Scalpay. The lineations are subhorizontal to gently NE-and SW-plunging. They argued that such movement was focused along the pre-existing weak phyllonite zones, which were reactivated again in Mesozoic times to form the steeper Minch Fault that lies immediately offshore to the east of the Outer Hebrides. In the Sound of Barra, Maclnnes *et al.* (2000) have documented a range of faults that relate both to thrust and extensional movements on the OHFZ and to later WNW-trending sinistral faults of probable Mesozoic age that cross-cut all the earlier OHFZ structures and fabrics. Similarly orientated late faults also cut the gneisses on Barra itself and are mapped farther north in the Uists and into the Sound of Harris where they trend north-west. WNW- and NW-trending faults also form prominent features in Harris and Lewis, for example the Tarbert and Loch Liurboist (Leurbost) faults, but although some show sinistral offsets of OHFZ features, others appear to be normal or reverse faults. A 10–12 km-wide zone of NNW-trending subvertical faults stretches from Loch Seaforth (Shiphoirt) and Loch Claidh in southeast Lewis up to West and East Loch Roag in west Lewis. The faults cut OHFZ features but there is evidence of earlier more-ductile movements and areas of steep foliation within this zone.

Although the OHFZ generally has a distinct western bounding structure, pseudotachylite veins, breccias, and mylonitic gneisses related to the main fault-zone also occur extensively farther west in the Outer Hebrides (Fettes and Mendum, 1987) (Figure 2.6). In places they lie along subsidiary thrusts that cut across the gneissose foliation and Laxfordian structures, but more generally they form patches or lenticular zones. A prominent N- to NW-trending zone of pseudotachylite breccia can be traced for some 13 km across central North Uist. More-diffuse zones of pseudotachylite breccia occur widely in the Uists and Barra, and an excellent example is seen at the Cnoc an Fhithich GCR site. In central and south Lewis the numerous pseudotachylite, ultramylonite and mylonitic zones west of the OHFZ generally represent small thrusts. In the Uig Hills of south-west Lewis, SE-dipping granite sheets commonly show sheared and even mylonitic margins (Fettes *et al.,* 1992, fig. 29). The Lewisian orthogneisses of much of northern and western Lewis also contain minor but locally pervasive cataclastic or protomylonitic fabrics.

Tectonic history of the Outer Hebrides Fault Zone (OHFZ)

The age and mechanisms of generation of the OHFZ are not fully known. What is clear is that the fault zone has seen a long and varied history, now represented by the various fault rocks found along its length ((Table 2.2); Imber *et al.,* 2001, 2002).

Fettes *et al.* (1992) suggested that the foliations in the late-Laxfordian granite sheets of the Uig Hills were generated approximately coeval with their intrusion. They noted several instances of pegmatites cutting foliated granite sheets. If indeed this is the case, and the OHFZ initiation is related to this NW-directed shearing deformation, its initiation must have occurred around *c.* 1670 Ma. The granite sheets certainly have acted as loci for WNW-directed thrust movements, but these movements may be mainly of later age, possibly Grenvillian (*c.* 1100 Ma) as suggested by Imber *et al.* (2002).

However, both time-periods record apparent uplift and extension of the gneiss complex, as shown by intrusion of granite sheets and the Grenvillian Rb-Sr closure ages (Cliff and Rex, 1989) respectively. Such conditions are not reconciled easily with compressional NW-directed thrust movements. Initial thrust movements on the OHFZ may link to transcurrent movements along major shear-zones, such as the Langavat Belt or possibly along a major structure that now lies offshore to the east in the Minches and Sea of the Hebrides. However, no compelling evidence points to a linked thrust–transcurrent faulting pattern. If Grenvillian or earlier movements did occur it is likely they resulted in the amphibolite-grade mylonites and possibly the generation of at least some of the pseudotachylite breccia zones that represent major westward thrusting.

Kelley *et al.* (1994) obtained laser-probe Ar-Ar ages from the matrix of a pseudotachylite vein in the immediate footwall of the OHFZ on Grimsay that gave a weighted mean of 430 ± 6 Ma. This is broadly compatible with whole-rock K-Ar dates obtained by D.C. Rex (in Sibson, 1977b) from various thrust rocks in the Uists and Barra. Pseudotachylite and cataclasite ages ranged from 2056 Ma to 442 Ma and mylonites from 471 Ma to 394 Ma. Errors are quite large and the possibility of excess radiogenic Ar from the adjacent gneisses or from included clasts is likely. S. Moorbath (also in Sibson, 1977b) reported K-Ar ages of 1120 Ma and 1140 Ma from pseudotachylite west of the OHFZ in South Uist. Again errors are large (± 44 Ma). The isotopic ages allow for movements at several periods ranging from Grenvillian to Scandian. They strongly imply that WNW-directed thrust movements did occur at around 430 Ma, coeval with major Scandian movements on the similarly orientated Moine Thrust Belt on the Scottish mainland and its northward continuation in Greenland. Deeper-level structures with similar trends and dips are interpreted on the MOIST (Moine and Outer Isles Seismic Traverse) and other BIRPS (British Institutions Reflection Profiling Syndicate) deep seismic reflection profiles that lie offshore from the Outer Hebrides (Smythe *et al.,* 1982; Stoker *et al.,* 1993). These Scandian tectonic movements relate primarily to the collision of Baltica and Greenland, but extended southwards to encompass the foreland areas of north-west Scotland and the Outer Hebrides. In the OHFZ these resulted in low-grade mylonites and phyllonites, first formed during WNW-directed thrusting and subsequently by WNW–ESE extension.

However, the role of the pseudotachylite breccias and 'Mashed Gneiss' is unclear. In parts they may represent Scandian compressive events that occurred prior to the ingress of fluid that culminated in mylonite formation. In other areas they may well be Grenvillian or even earlier in age as discussed above. Imber *et al.* (2001) and Fettes *et al.* (1992) postulated that the OHFZ may reflect pre-1100 Ma thrusting resulting in early mylonites, Grenvillian dextral shearing, and later dip-slip faulting at the time of Torridonian sediment deposition. This last event, at *c.* 1000 Ma, would have extensionally reactivated the already formed moderately ESE-dipping OHFZ thrust structure. However, Imber *et al.* (2001) suggested that the main episode of pseudotachylite and cataclasite formation accompanied WNW-thrusting during the Scandian Event (*c.* 430 Ma), followed by significant sinistral strike-slip movements focused on the phyllonite zones and later dip-slip movement in extension at *c.* 400 Ma. A phase of Carboniferous- to Cenozoic-age faulting is also recognized.

The magnitude of the postulated Silurian sinistral strike-slip movement is unclear. Butler *et al.* (1995) and Imber *et al.* (2001) proposed that some 90 km of relative movement occurred, distributed on the phyllonite belts throughout the Outer Hebrides. However, MacInnes *et al.* (2000) found no evidence for such movements in Barra and the adjacent islands, and the proposed linking of Lewisian features between the Outer Hebrides and the mainland (e.g. Dearnley, 1962a; Lisle, 1993) may well be invalid (see Friend and Kinny, 2001). The lack of any coherent major steep structure along the OHFZ at this time, except possibly for an embryo Minch Fault offshore, would appear to make it difficult to have lateral movements on the scale envisaged.

Sibson (1977a, 1983) and Scholz (1988) suggested that major fault-zones such as the OHFZ consist of an upper crustal-seismogenic zone deforming by frictional processes, which passes down to a lower aseismic zone, deforming predominantly by viscous processes. However, Imber *et al.* (2001) rejected the Sibson–Scholz model, and pointed out that the various fault rocks of the OHFZ record a lengthy and complex history of thrusting and extension. They proposed an alternative model, whereby early formation of a crustal-scale hydrous phyllonite–mylonite zone acted as a locus for subsequent tectonic movements. If Friend and Kinny (2001) are correct in identifying different Archaean and Proterozoic terrains within the Lewisian Gneiss Complex of the Outer Hebrides and mainland north-west Scotland, then it is possible that the OHFZ is roughly coincident with an earlier Proterozoic-age suture that separates crustal blocks with disparate histories. The isotopic ages for the various Lewisian elements would constrain the formation of this suture to between *c.* 1500 Ma and 1100 Ma.

Post-Lewisian minor intrusions and sedimentary rocks

Late Caledonian intrusions are largely absent from the Outer Hebrides but an isolated appinitic diorite dyke occurs in the Uig Hills–Loch Roag area and a small diorite exposure occurs at Loch Fada in North Uist (Fettes *et al.,* 1992).

WNW-trending, late Carboniferous, quartz-dolerite dykes occur in Barra and South Uist; where Fettes *et al.* (1992) reported some 10 dykes, ranging from 3 m to 45 m thick. Later thin camptonite and monchiquite dykes, of latest Carboniferous to Permian age, that also trend WNW, are found more widely through the Outer Hebrides, but are only common in South Uist.

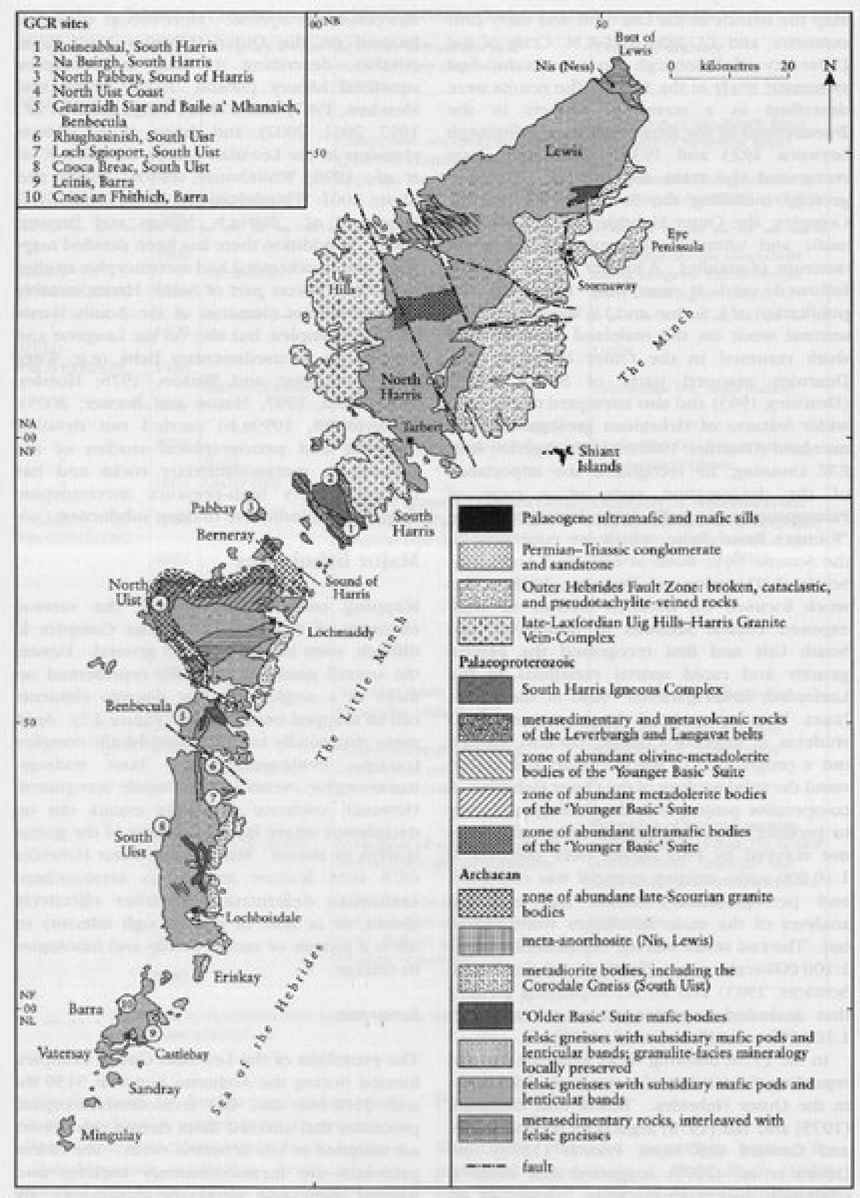
The bulk of the minor intrusions in the Outer Hebrides are the NW-trending dolerite dykes of Palaeogene age. They are seen in many of the GCR sites. Their concentrations are such that in Barra, South Harris and Lewis, distinct swarms have been recognized (Speight *et* al., 1982; Fettes *et al.,* 1992).

Post-Lewisian sedimentary rocks are limited to red-brown conglomerates and sandstones of Permo–Triassic age that occur around Stornaway and on the Eye peninsula of Lewis (Figure 2.1), (Figure 2.6). They are fault-bounded and link to a thick Mesozoic sequence found offshore in the Minch. Steel and Wilson (1975) and Fettes *et al.* (1992) give further details of the Stornaway Beds.

References

Eon/Era	Age (Ma)	Orogeny/Event	Igneous intrusions and sedimentary depositional events	Tectonic activity
MESOZOIC	200			
	300		Camptonite and monchiquite dykes Quartz-dolerite dykes	Formation of the Minch Fault marginal to Mesozoic basin
PALAEOZOIC	400	Caledonian	Appinitic diorite	Extensional faulting follows thrusting to the WNW in OHFZ
	500			
MESO-PROTEROZOIC	1000	Grenvillian		Uplift and ductile movement along Langavat Belt. Possible early thrusting on OHFZ
	1100			
MESO-PROTEROZOIC	1400		Microdiorite dykes (rare)	Uplift
	1500	Late-Laxfordian	Pegmatitic granites	Laxfordian $D4_L$ deformation
	1600			
	1700	Main Laxfordian	Granite sheets and dykes, mainly in Uig Hills–Harris Granite Vein-Complex	Laxfordian $D3_L$ deformation and metamorphism.
	1800			
PALAEO-PROTEROZOIC	1900		S. Harris Igneous Complex (SHIC) Deposition of Leverburgh and Langavat belt sediments	Laxfordian $D2_L$ deformation and amphibolite-facies metamorphism. (Subduction, deformation and metamorphism of SHIC)
	2000			
	2100			
	2200			
	2300		'Younger Basic' Suite (= Scourie Dyke Suite)	Laxfordian $D1_L$ deformation
	2400			Scourian $D4_S$ deformation Scourian $D3_S$ deformation
	2500	Late-Scourian	Quartz-feldspar pegmatite Granite and monzonite Diorite and microdiorite	
	2600			
	2700	Main Scourian	Formation of main granodioritic and tonalitic gneiss protoliths	Formation of Scourian gneisses and generation of main $D2_S$ fabrics and structures. Granulite- and amphibolite-facies metamorphism.
	2800			
ARCHAEAN	2900		Deposition of sedimentary rocks and intrusion of 'Older Basic' Suite. Earliest granodioritic and tonalitic intrusions	Earlier $D1_S$ fabrics and structures.
	3000			
	3100			

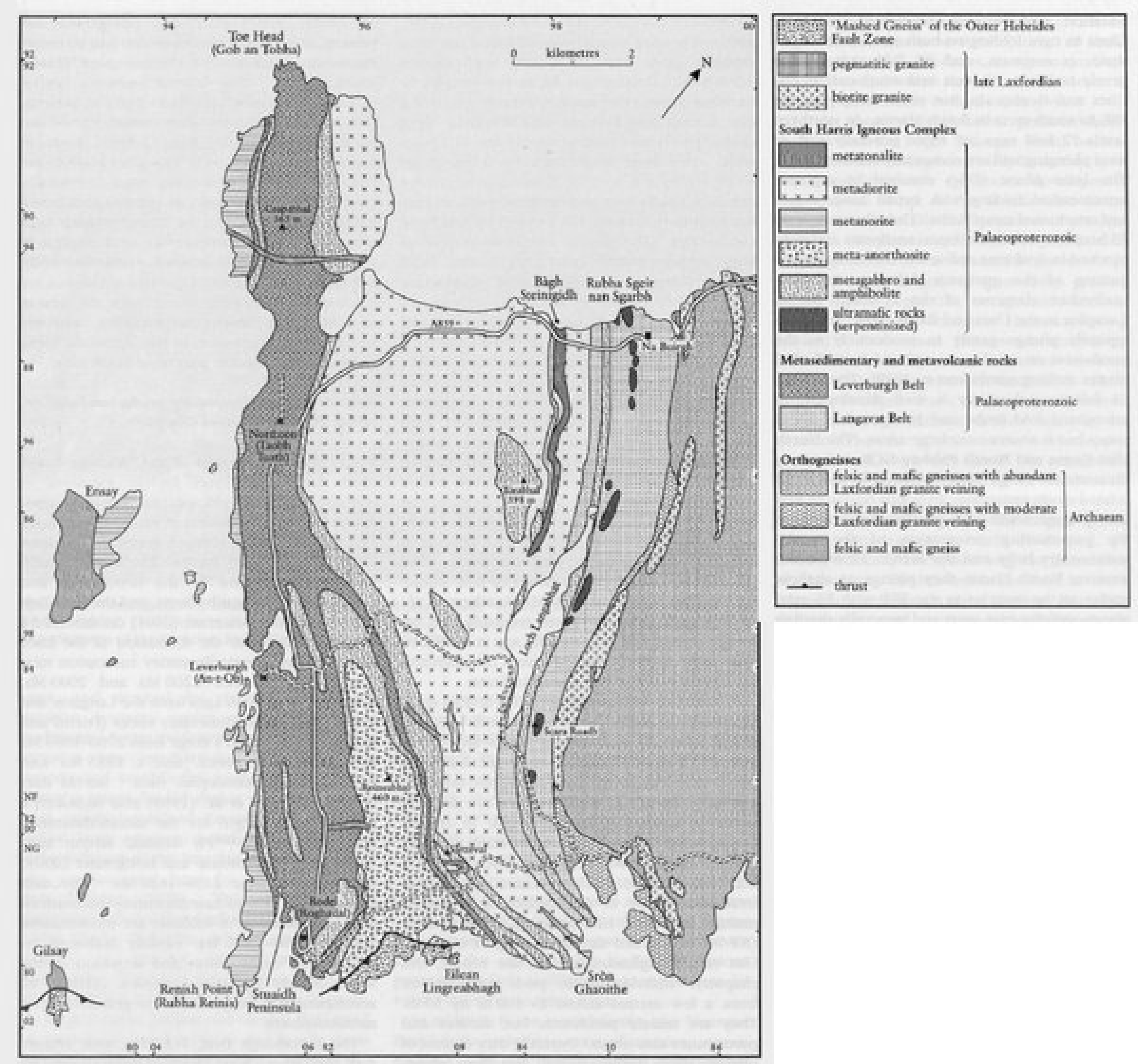
(Table 2.1) Chronology of the Lewisian Gneiss Complex in the Outer Hebrides.



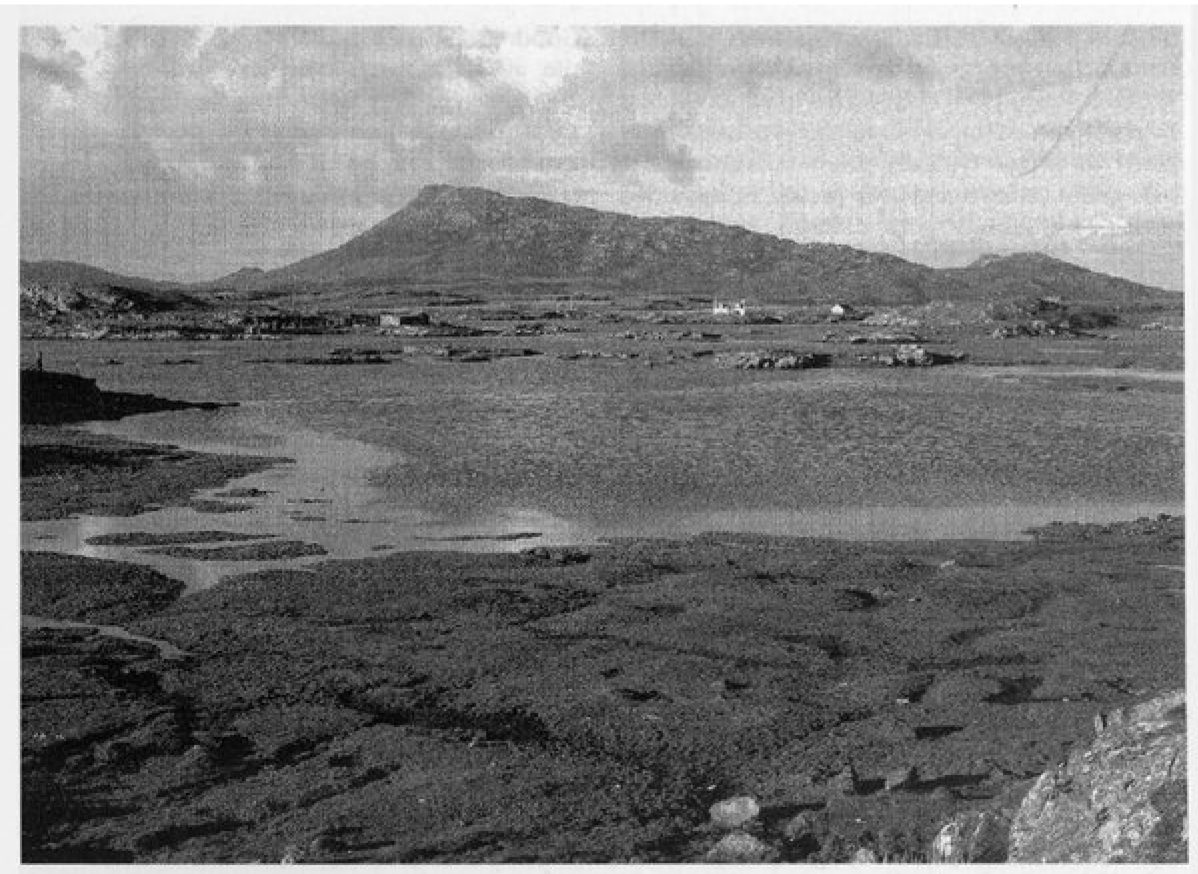
(Figure 2.1) Simplified geological map of the Outer Hebrides.

(Figure 2.2) Photograph of a discordant 'Younger Basic' dyke cutting Scourian migmatitic felsic and subsidiary mafic gneisses, by Loch Leòsaid, North Harris [NB 055 083]. The hammer head is 14 cm long. (Photo: British Geological Survey, No. P008271, reproduced with the permission of the Director, British Geological Survey, © NERC.)

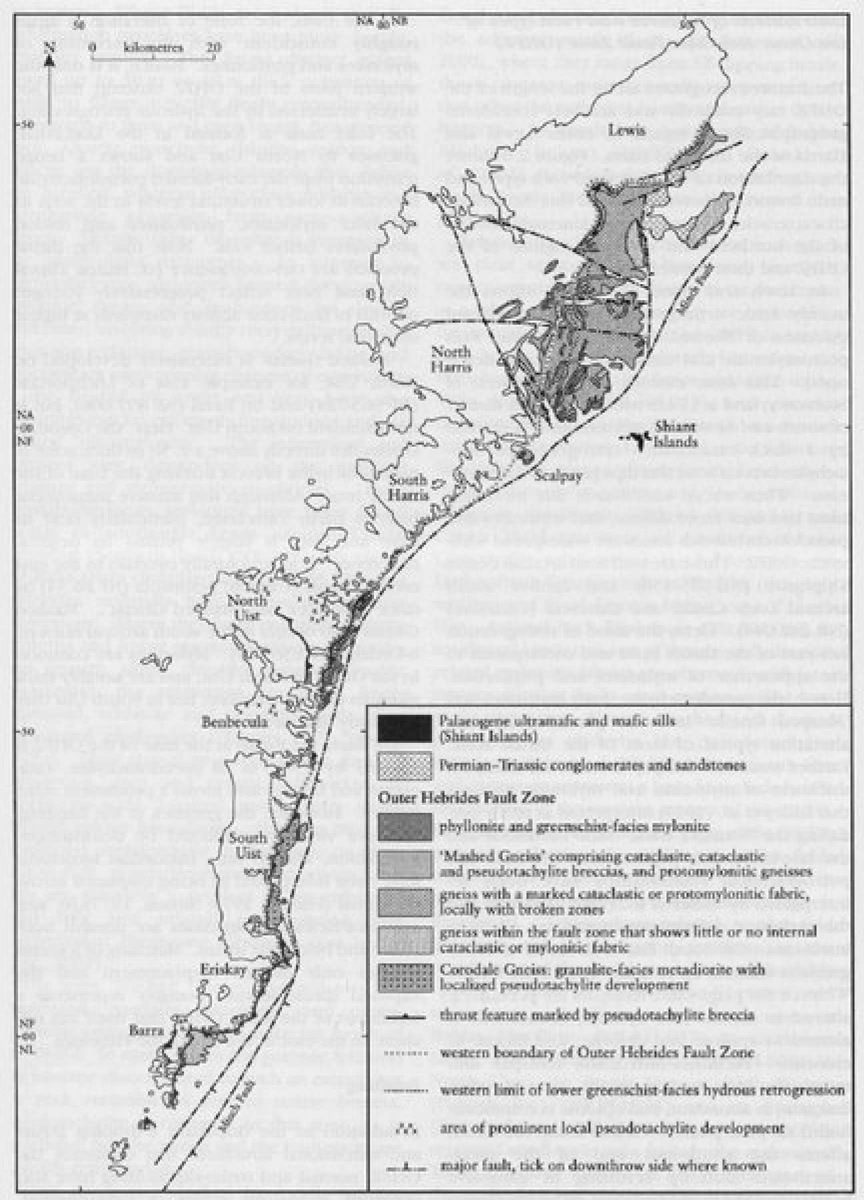
(Figure 2.3) Photograph of folded and boudinaged 'Younger Basic' dykes, Howmore Quarry, South Uist [NF 7659 3645]. The hammer is 42 cm long. (Photo: British Geological Survey, No. P008305, reproduced with the permission of the Director, British Geological Survey, © NERC.)



(Figure 2.4) Simplified geological map of South Harris. After Fettes et al. (1992).



(Figure 2.5) Eaval (347 m), North Uist, showing the dip-slope of the Outer Hebrides Fault Zone. View from Grimsay. (Photo: British Geological Survey, No. P001011, reproduced with the permission of the Director, British Geological Survey, © NERC.)



(Figure 2.6) The distribution of rock types and features related to the Outer Hebrides Fault Zone.

Event	Northern region	Central region	Reference
Laxfordian metamorphism	1750–1670 Ma	1750–1670 Ma	Corfu *et al.* (1994); Kinny and Friend (1997); Zhu *et al.* (1997a,b)
granite sheets	1855 Ma		Friend and Kinny (2001)
Scourie dyke emplacement	no age data	2020–1920 Ma	Heaman and Tarney (1989); Waters *et al.* (1990)
		2420–2400 Ma	Heaman and Tarney (1989); Corfu *et al.* (1994)
Inverian metamorphism and deformation	no evidence found for Inverian event	Scourie 2490–2480 Ma 2530 Ma	Corfu *et al.* (1994); Friend and Kinny (1995); Kinny and Friend (1997); Zhu *et al.* (1997a,b)
		Gruinard Bay no evidence found of Inverian event	Corfu *et al.* (1998); Kinny and Friend (1997)
Badcallian deformation and granulite-facies metamorphism		Scourie 2760–2710 Ma	Corfu *et al.* (1994); Zhu *et al.* (1997a,b)
igneous protolith (TTG)	2680 Ma (diorite)	Scourie 3030–2960 Ma	Friend and Kinny (2001); Friend and Kinny (1995)
	2840–2800 Ma	Gruinard Bay 2736–2726 Ma ('trondhjemite')	Corfu *et al.* (1998)
		2825–2790 Ma (mafic rocks)	Kinny and Friend (1997)
		2850–2750 Ma	Whitehouse *et al.* (1997) Love *et al.* (2004)

(Table 3.1) Summary of isotopic ages from the Lewisian Gneiss Complex of the Northern and Central regions of mainland Scotland.