Lewisian, Torridonian and Moine Rocks of Scotland

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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

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

Eon/Era	Age (Ma)	Orogeny/Event	Igneous intrusions and sedimentary depositional events	Tectonic activity
MESOZOIC	200			Formation of the Minch Fault marginal to Mesozoic basin
	300		Camptonite and monchiquite dykes Quartz-dolerite dykes	
	400		Appinitic diorite	Extensional faulting follows thrusting to the WNW in OHFZ
PALAEOZOIC		Caledonian		
	500			
— — —	— — —	— — —	— — —	— — —
	1000			Uplift and ductile movement along Langavat Belt. Possible early thrusting on OHFZ
MESO-PROTEROZOIC	1100	Grenvillian		
— — —	— — —	— — —	— — —	— — —
	1400		Microdiorite dykes (rare)	Uplift
MESO-PROTEROZOIC	1500	Late-Laxfordian	Pegmatitic granites	Laxfordian $D4_L$ deformation
	1600			
	1700		Granite sheets and dykes, mainly in Uig Hills–Harris Granite Vein-Complex	Laxfordian $D3_L$ deformation and metamorphism.
	1800	Main Laxfordian		
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	
	2600		Diorite and microdiorite	
	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.
ARCHAEAN	2800			
	2900		Deposition of sedimentary rocks and intrusion of 'Older Basic' Suite. Earliest granodioritic and tonalitic intrusions	Earlier $D1_S$ fabrics and structures.
	3000			
	3100			

— — — Dashed line represents time gap in column indicating no evidence of significant tectonic events or igneous activity.

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

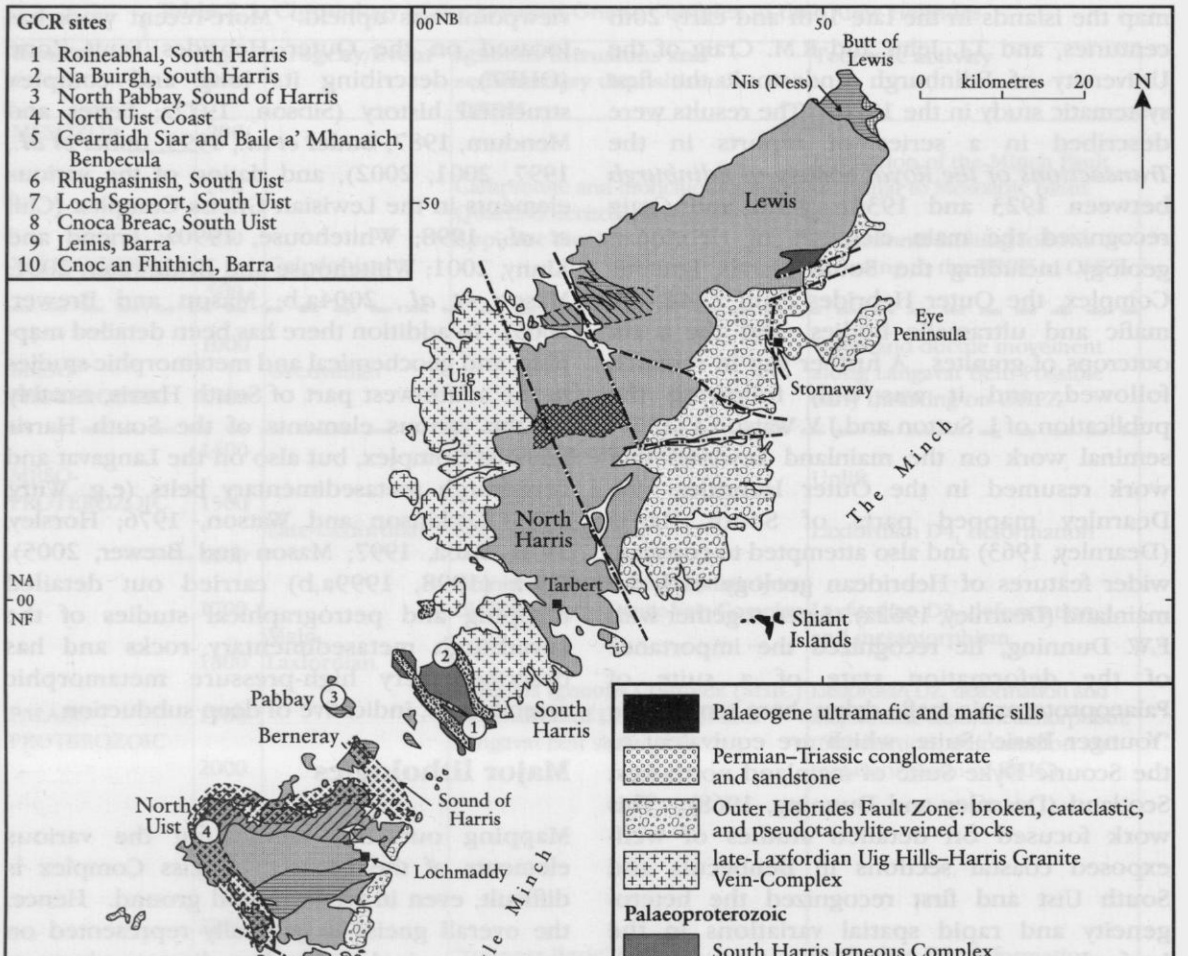


Figure 2.1 Simplified geological map of the Outer Hebrides.

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 semi-pelites 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 meta-sedimentary 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 (Garry-a-siar) 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 quartzo-feldspathic 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 north-west 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 (microcline 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 tectonothermal 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 'stratigraphical' 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 × 1 km, but most dykes lie in the range 1–3 m thick. They vary from undeformed coherent dykes (e.g. at the **Leinis** and **Gearraidh Siar and Baile 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 pre-existing shear zones, formed during the Inverian

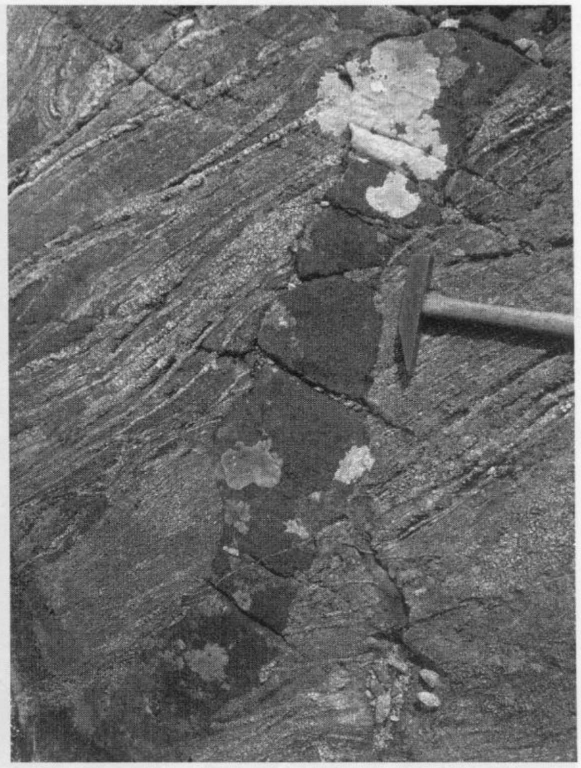


Figure 2.2 Photograph of a discordant 'Younger Basic' dyke cutting Scourian migmatitic felsic and subsidiary mafic gneisses, by Loch Leòsaid, North Harris (NB 055 083). The hammer head is 14 cm long. (Photo: British Geological Survey, No. P008271, reproduced with the permission of the Director, British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

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 ($D1_L$) 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 Baile 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 (Shìphoirt), 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 leucogabbro 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

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

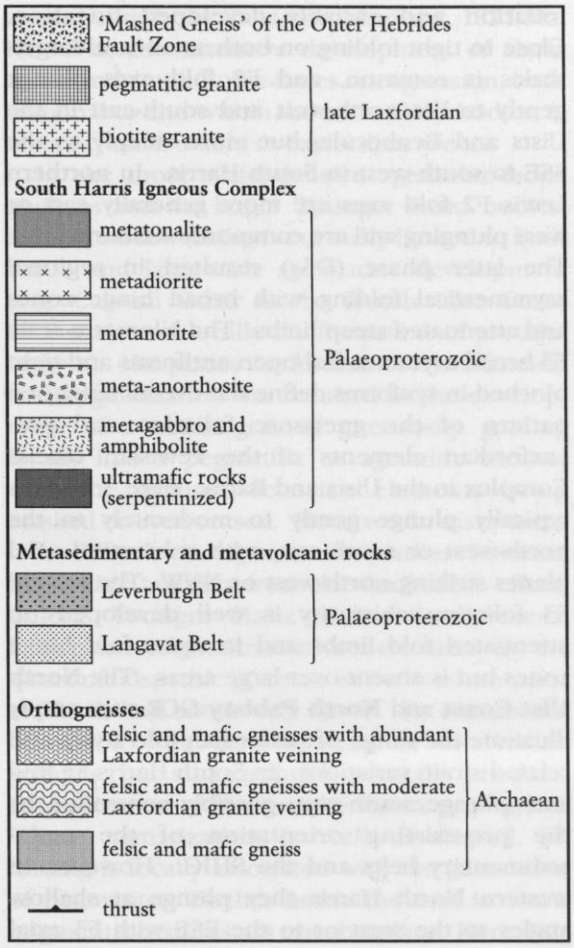


Figure 2.4 – *continued*.

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 roadstone. 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 metadiorite 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 Bàgh Steinigidh. There are also numerous associated ultramafic pods, including serpentinized lherzolites, metapyroxenites (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 800°–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 ($D3_L$) 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 meta-sedimentary 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 tectono-metamorphic 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 south-western 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 Àird 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 1–2 m 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 Tuath, 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,

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.)

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 Shìphoirt (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 proto-mylonitic 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 south-east Lewis. Here, pseudotachylite veins cut early-formed amphibolite-facies mylonites in the Baile Ailein area (NB 305 219), and pseudo-tachylite breccia and 'Mashed Gneiss' are in turn commonly overprinted by a mylonitic foliation. Similarly, thin planar ultramylonite zones cross-cut pseudotachylite veining and 'Mashed Gneiss' fabrics in the Eisgein (Eisken) (NB 32 11) and Ceann Shìphoirt areas of south-east Lewis. Comparable relationships can be found in the Lochportain–Crògearraidh 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 Ròinebhal (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 south-east. 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 Shìphoirt (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 pre-dating the 'Younger Basic' Suite intrusions and the late-Laxfordian pegmatites. The field and petrographical relationships have been re-interpreted 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

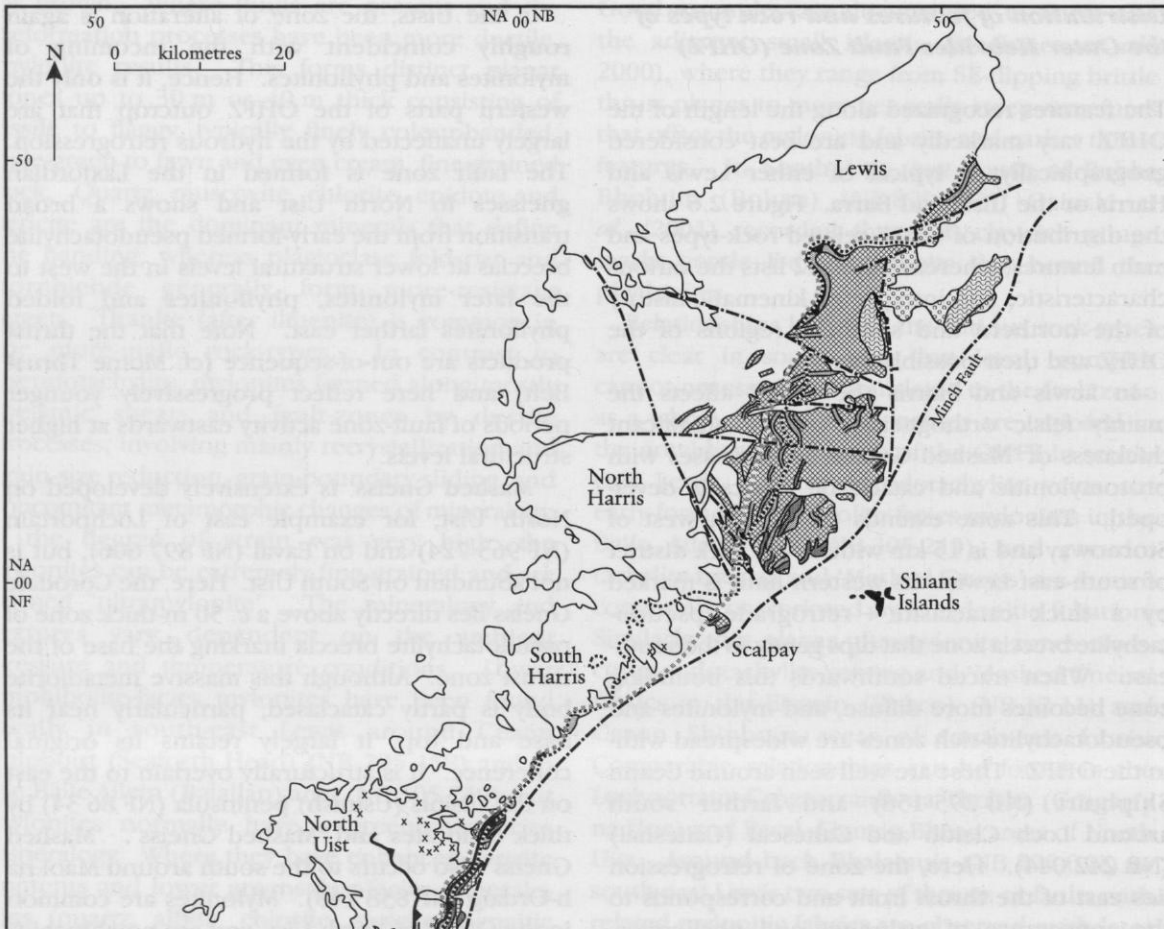


Figure 2.6 The distribution of rock types and features related to the Outer Hebrides Fault Zone.

Table 2.2 Rock types and kinematic history of the Outer Hebrides Fault Zone (OHFZ). Based on information from Fettes *et al.* (1992), MacInnes *et al.* (2000) and Imber *et al.* (2001).

Lewis and Harris		North and South Uist, Barra	
Rock type	***Structure and tectonic event***	***Rock type***	***Structure and tectonic event***
Fault gouge, breccia, some cataclasite.	Steep faulting of Devonian, Carboniferous and Mesozoic age related to uplift and basin formation. Formation of Minch Fault.	Fault gouge, breccia, some cataclasite.	Steep faulting related to uplift and basin formation in the Devonian and Carboniferous. Dextral strike-slip on WNW-trending faults of Mesozoic age.
Phyllonite and mylonite. Folding of pre-existing mylonites. Crenulation cleavage. Lower greenschist-facies mineralogies.	Extension with top-to-the-E movements down-dip of mylonite belts. Probably of late Silurian or Early Devonian age. Related hydrous retrogression in OHFZ and footwall gneisses.	Phyllonite, mylonite, planar gouges.	Extension with top-to-the-ENE/E movements focused along mylonite belt margins. Probably of late Silurian or Early Devonian age.
Phyllonite and mylonite. Greenschist-facies mineralogies (biotite).	Thrust zones with movement towards the WNW. Attributed to sinistral strike-slip movements by some authors. Late Silurian (Scandian) age.	Phyllonite and mylonite. Greenschist-facies mineralogies (biotite).	Thrust zones with movement towards the WNW and possibly south-west. Attributed to sinistral strike-slip movements (top-to-the-NE) by some authors. Late Silurian (Scandian) age.
Pseudotachylite breccia and 'Mashed Gneiss'. Cataclasite and ultracataclasite zones. Gneisses with marked cataclastic and protomylonitic fabric.	Main thrust zones and lensoid zones of fault rock. Formed in relatively dry gneisses but now commonly retrogressed. Reflect major top-to-the-WNW thrust movements with multiple seismic movements. Mainly of late Silurian age (Scandian Event).	Pseudotachylite breccia and 'Mashed Gneiss'. Gneiss with marked cataclastic and protomylonitic fabric.	Well-defined western bounding thrust to OHFZ showing top-to-the-WNW movement. Some defined thrusts and areas of pseudo-tachylite development west of OHFZ. Local movement sense more variable. Probably of Late Silurian age (Scandian Event), but parts may be considerably older.
None identified.	Meso/Neoproterozoic Torridon Group sedi-mentary rocks preserved at depth in Minch Basin. Sequence thickest in hangingwall of OHFZ implying extensional movement along the fault zone at *c.* 1000 Ma.	None identified.	Meso/Neoproterozoic Torridon Group sedi-mentary rocks preserved at depth in Minch Basin. Sequence thickest in the hangingwall of OHFZ implying extensional movement along the fault zone at *c.* 1000 Ma.
Mylonitic gneisses.	Dextral oblique shear zone postulated in the Langavat Belt offsetting earlier elements of the OHFZ. Biotite cooling ages imply movement at *c.* 1100 Ma (Grenvillian).	No equivalent fault rocks identified.	
Mylonite, ultramylonite pseudotachylite and cataclasite. Lower amphibolite-grade mineralogies.	Mainly small-scale shallow E-dipping thrust zones with top-to-the-WNW sense of movement. Focused in part on Laxfordian granite sheets. Age of between 1550 Ma and 1100 Ma postulated.	No equivalent fault rocks identified.	

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 (σ-type and δ-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, MacInnes *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 (Shìphoirt) and Loch Claidh in south-east 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 (Figures 2.1, 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.

ROINEABHAL, SOUTH HARRIS (NG 045 865–NG 055 845)

J.R. Mendum

Introduction

Roineabhal is the most prominent hill of South Harris, forming an 'elephant-grey'-weathering, rocky bulwark, some 460 m high that overlooks the Minch and the Sound of Harris. It is composed largely of anorthosite and forms part of the Palaeoproterozoic South Harris Igneous Complex. The intrusion has been folded into a large-scale, tight, sideways-closing fold with a near-vertical axis, thus providing a natural cross-section from marginal layered gabbros through to pure-white anorthosite in its central part. The Roineabhal Intrusion is unique in being the largest gabbro–anorthosite body in the British Isles and one of only two such bodies in the Lewisian Gneiss Complex. In addition to its invaluable scientific importance, in the 1990s the intrusion was investigated as to the possible establishment of a superquarry, mainly as a source of white reflective roadstone.

The South Harris Igneous Complex (SHIC) comprises major gabbro, norite, anorthosite and diorite bodies that dominate the geology of the south-western part of South Harris. The bodies were metamorphosed under high-pressure granulite-facies conditions after their emplacement into metasedimentary rocks, although they were later partially retrogressed to lower amphibolite-facies assemblages. Note that the prefix 'meta-', which should be appended to all these igneous members of the SHIC, is omitted for clarity in this account. Although the igneous bodies now all show metamorphic mineralogies, they still retain an igneous appearance and exhibit unmodified geochemical trends where relatively undeformed and containing granulite-facies assemblages. Metamorphic studies and isotopic ages for the intrusions and surrounding metasedimentary rocks imply that the SHIC was emplaced into the base of an island arc or continental-margin arc during the Palaeoproterozoic at around 1880–1875 Ma (Baba, 1998; Friend and Kinny, 2001; Whitehouse and Bridgwater, 2001). The metasedimentary rocks that now form the carapace to the SHIC were themselves probably deposited in a trench and forearc environment at around 1890–1880 Ma and then rapidly subducted (Baba, 1999b; Friend and Kinny, 2001). They consist of psammites, semipelites, quartzites, graphitic and aluminous pelites, metalimestones, and mafic metavolcanic rocks that now form two NW-trending metasedimentary belts, the Leverburgh and Langavat belts (Figure 2.4) (see **Na Buirgh** GCR site report, this chapter).

The Roineabhal Intrusion is the most south-easterly exposed member of the SHIC and together with its marginal gabbros forms an elongate triangular outcrop some 6 km long by 0.75–2.5 km wide, surrounded by Leverburgh Belt metasedimentary rocks. Granulite-facies mineralogies are preserved in its central part, but the marginal zones are more strongly deformed and have amphibolite-facies mineralogies. Shear zones have developed along the margins, with mylonitic fabrics developed locally. The south-eastern part of the Roineabhal Intrusion has been mylonitized, brecciated and cataclased in the Outer Hebrides Fault Zone. A zone of greenschist-facies hydrous retrogression that has resulted in extensive saussuritization of the anorthosite overlaps the OHFZ and also extends farther to the north-west (Figure 2.7).

The Roineabhal Intrusion and related gabbros can be divided into four distinct zones:

- a marginal zone of quartz-gabbros, banded ultramafic rocks and gabbros;
- a Lower Zone of banded mafic gabbros, gabbros and anorthosites;
- a Middle Zone of banded anorthosites and gabbros;
- an Upper Zone of banded anorthosites and leucogabbros.

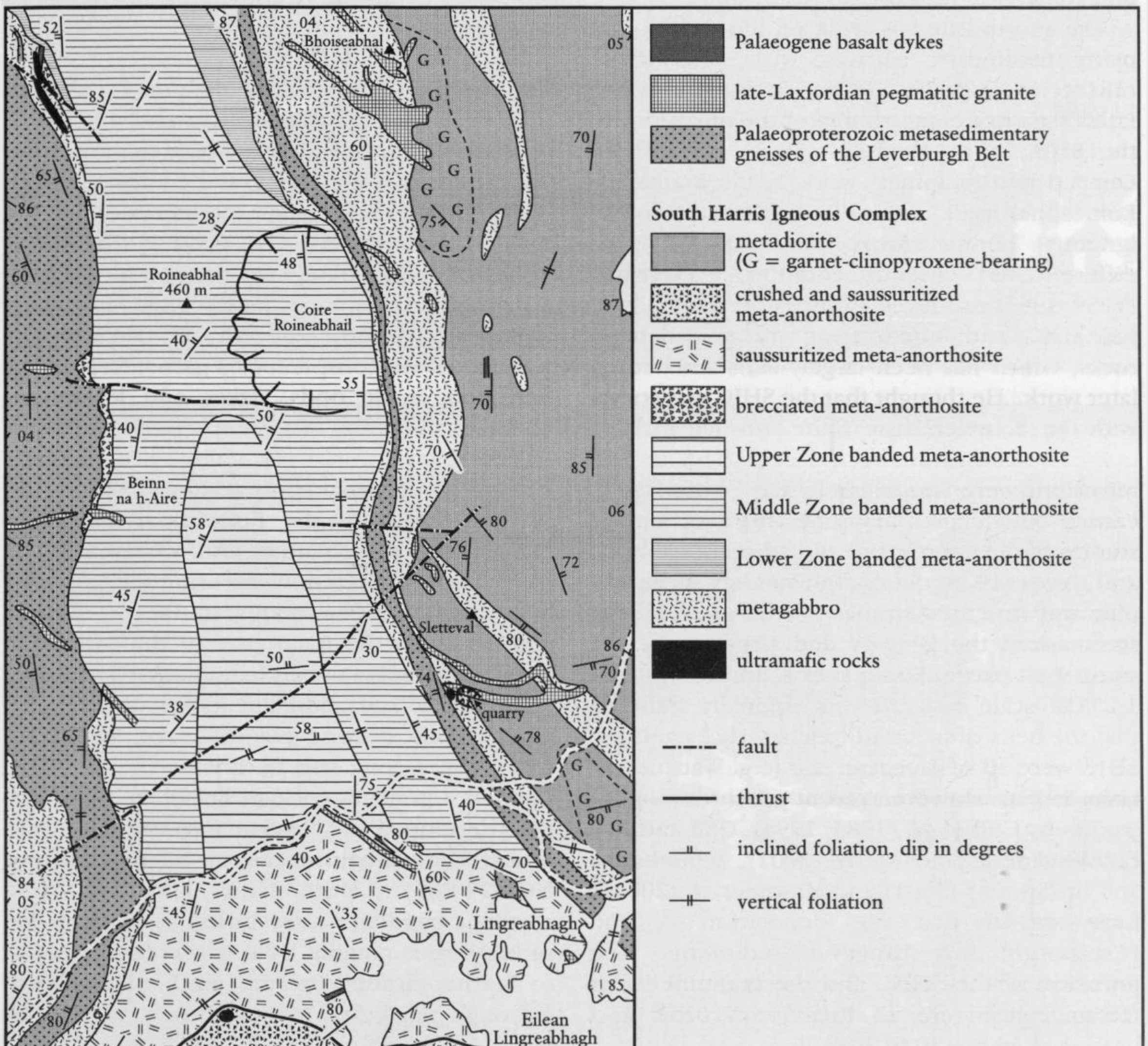


Figure 2.7 Simplified geological map of Roineabhal, South Harris. After Fettes *et al.* (1992).

These zones form an overall layered sequence with the gabbros at the base and the anorthosite at the top of the original sheet-like intrusion. Only a few later intrusions cut this zonal sequence. Gabbros form net-veins in the anorthosite and rarely mafic dykes are present (Fettes *et al.*, 1992). Late-Laxfordian pegmatitic granite veins are also present and some Palaeogene dolerite dykes occur around Lingarabay and in Coire Roineabhail.

The anorthosite has attracted the attention of many geologists, starting with MacCulloch (1819) and Heddle (1878). Jehu and Craig (1927) made a detailed map of the intrusions of the SHIC, and Davidson (1943) carried out detailed petrographical work in the Roghadal–Roineabhal area, recognizing that the meta-igneous bodies form part of a single differentiated igneous complex. Dearnley (1959, 1963) produced a further detailed map of the SHIC and surrounding metasedimentary rocks, which has been largely substantiated by later work. He thought that the SHIC was coeval with the 'Younger Basic' Suite and that the two main metamorphic events recorded in the intrusions were Laxfordian in age. Witty (1975) carried out detailed mapping and geochemical studies of the anorthosite and adjacent gabbros, and Heyes (1978) did complementary metamorphic and structural studies. Fettes *et al.* (1992) summarized the geology and structure of the south-west part of South Harris, and compiled a 1:25 000-scale map. It was originally assumed that the belts of metasedimentary rocks and the SHIC were all of Archaean age (e.g. Watson and Lisle, 1973). However, recent geochronological studies by Cliff *et al.* (1983, 1998), Cliff and Rex (1989), Friend and Kinny (2001), Whitehouse and Bridgwater (2001) and Mason *et al.* (2004a) have shown that the deposition of the Leverburgh and Langavat sediments, the intrusion of the SHIC, and the granulite-facies metamorphism are all Palaeoproterozoic and bracketed within 10 to 20 million years between 1890–1870 Ma. Overall models for rapid arc formation, deep subduction, collision, and high-pressure metamorphism in South Harris by Baba (1998, 1999a,b) accord well with this isotopic data (see 'Interpretation', below, for details).

Description

The Roineabhal GCR site covers the summit areas of Roineabhal (460 m) and Beinn na h-Aire (378 m), Coire Roineabhail, and the south-east slope of the mountain down to the Roghadal (Rodel)–Fionnsabhagh (Finsbay) road and the Lingreabhagh (Lingarabay) Quarry (Figure 2.8a). The summit area is exposed bedrock and block-field and the south-east flank consists of nearly 100% exposed, glacially scoured, pale-grey-weathered bedrock with numerous gullies and small crags.

Rock types

The Leverburgh Belt metasedimentary rocks that surround the anorthosite consist mainly of quartzites and psammites. Only a thin sliver, 20–100 m wide, is present on the north-east side of the intrusion, in which the metasedimentary rocks are interbanded with pods and lenticular bands of amphibolite. On the south-west side a thicker succession of metasedimentary rocks is present. Around Sgriosan (NG 034 857) the psammites are conspicuously garnetiferous, but here too, mafic pods, dykes and lenses are abundant (Fettes *et al.*, 1992).

The oldest intrusive rocks are the gabbros and ultramafic rocks that effectively form a basal unit at the margin of the Roineabhal Intrusion. Subsequent deformation and metamorphism has resulted in their now discontinuous, foliated and amphibolitized appearance. Quartz-gabbros form the main part of the mafic rim rocks, with lenses of banded ultramafic rock and melagabbro, and abundant lenses of gneissose garnet-biotite-bearing psammite and semipelite up to 270 m long and 18 m wide (Witty, 1975). Banded ultramafic-rock–melagabbro units are best developed on Hà-cleit (NG 032 873), and above the Abhainn Easean Chais (around NG 029 866). Here, large- and small-scale rhythmic banding was recorded by Witty (1975) in lithologies ranging from garnet-hornblendite to garnet-clinopyroxenite and melagabbro. Although plagioclase feldspar is present, ranging from An_{85} (bytownite) to An_{50} (labradorite/andesine), the granulite-facies metamorphism has resulted in its reaction with pyroxene to form amphibole and garnet, giving the rocks a more-mafic appearance. In contrast the quartz-gabbros are a product of assimilation of metasedimentary material and consist of plagioclase feldspar, clinopyroxene, hornblende, quartz, minor biotite and even microcline feldspar. The plagioclase ranges from An_{30} (andesine) to An_{14} (oligoclase) and forms

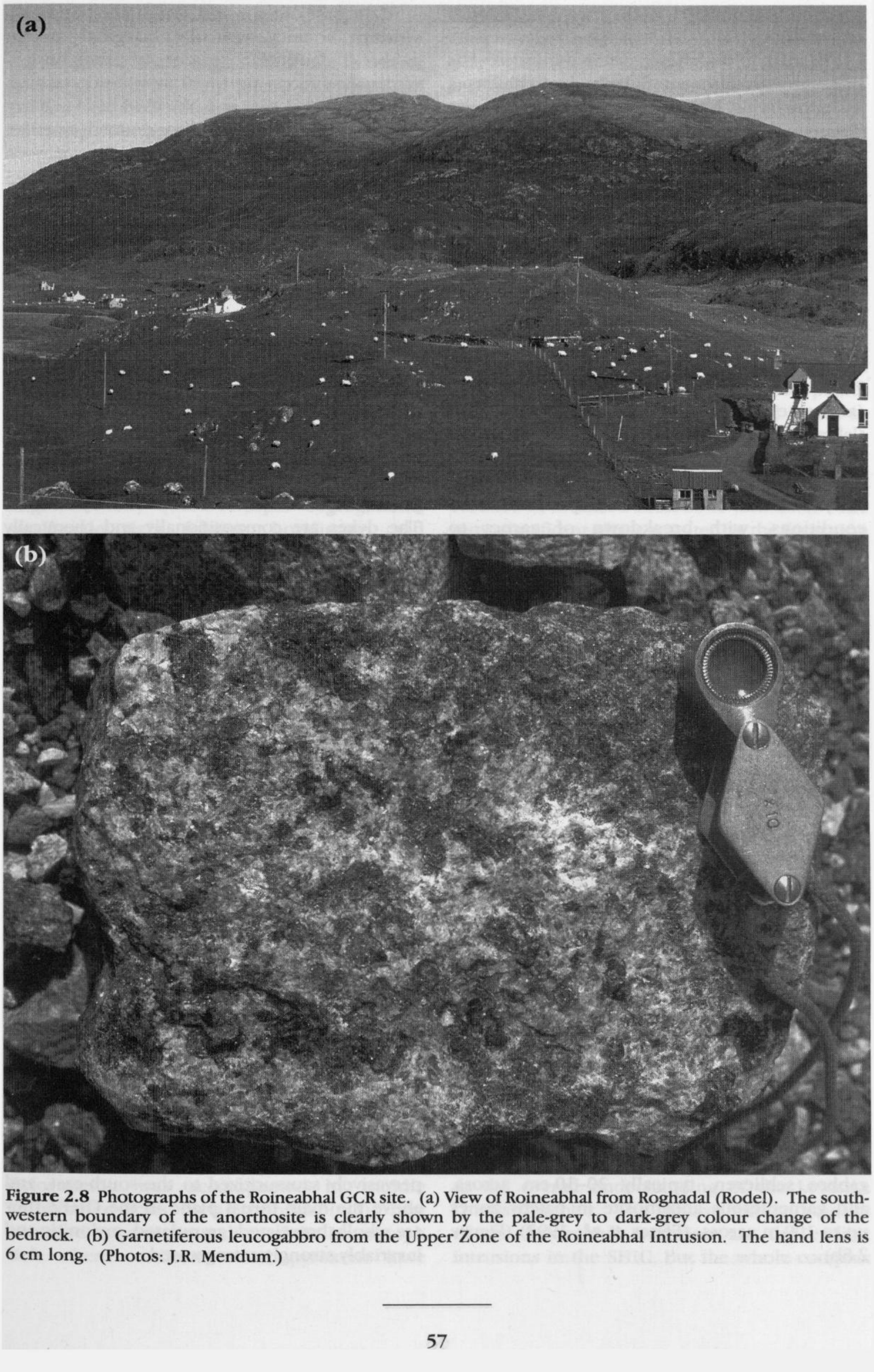


Figure 2.8 Photographs of the Roineabhal GCR site. (a) View of Roineabhal from Roghadal (Rodel). The south-western boundary of the anorthosite is clearly shown by the pale-grey to dark-grey colour change of the bedrock. (b) Garnetiferous leucogabbro from the Upper Zone of the Roineabhal Intrusion. The hand lens is 6 cm long. (Photos: J.R. Mendum.)

between 15% and 50% of the rock (see Fettes *et al.*, 1992).

The main fold of the Roineabhal Intrusion has thin, strongly attenuated limbs but exhibits a wide low-strain hinge zone. Hence, the Lower Zone is *c.* 70 m wide on the attenuated fold limbs but *c.* 600 m wide in the hinge area, some 2 km north-west of Roineabhal summit. It is made up of 14 gravity-stratified units, which range from melagabbro to gabbro and leucogabbro with minor anorthosite 'tops'. Note that leucogabbro was previously termed 'gabbro–anorthosite' by most authors – see Fettes *et al.* (1992). Hornblende and garnet are the common mafic minerals with clinopyroxene only found in gabbroic units in the upper part. Plagioclase compositions range from An_{37} (andesine) in the melagabbros to An_{68} (labradorite) in the anorthosite. In much of the Roineabhal GCR site area the Lower Zone rocks have been pervasively deformed and recrystallized under middle amphibolite-facies conditions, with breakdown of garnet to orthopyroxene + plagioclase symplectite and of clinopyroxene to hornblende. Scapolite is abundant in parts, and clinozoisite, zoisite, chlorite, biotite and calcite are developed locally in the more highly sheared zones.

The Middle Zone consists of banded anorthosite, leucogabbro and gabbro, with eight major gabbro bands (0.5–1.2 m thick) and numerous smaller ones (< 30 cm thick) recorded by Witty (1975). These rocks crop out over most of the summit area and on the north-west flank of Roineabhal, in Coire Roineabhail, and on Beinn na h-Aire. Clinopyroxene is abundant in the gabbros in this zone and plagioclase compositions mainly lie in the labradorite field (An_{70} to An_{50}). The gabbros have patchy garnetiferous zones, and circular to oval clots of gabbro up to 30 cm across are present in some anorthosite bands. On the fold limbs the Middle Zone rocks are attenuated and extensively recrystallized, but the degree of deformation is less strong than in the Lower Zone rocks or marginal gabbros.

The Upper Zone rocks are best seen on the south-east slopes of Roineabhal and consist of 65–70% leucogabbro with some pure white anorthosite bands. The zone contains abundant diffuse to well-defined spherical to ovoid gabbro schlieren, typically 20–30 cm across, and garnetiferous anorthosite in patchy zones up to 100 m across (Fettes *et al.*, 1992) (Figure 2.8b).

At the base of the Lower Zone, along its south-western contact with the marginal quartz-gabbros, lenticular masses of anorthosite–ultramafic breccia up to 50 m wide occur (e.g. around NG 043 855 and NG 0338 8644) (Witty, 1975). They consist of disorientated, angular, foliated and banded anorthosite blocks separated by thin veins consisting of pale-green clinopyroxene (augite), scapolite and plagioclase-hornblende symplectite. Garnet occurs as diffuse patches, streaks and locally abundant nodules. The breccias are commonly associated with small ultramafic intrusions. Melagabbro dykes and sheets, typically 1–2 m wide, but up to 7 m across, are common throughout the Roineabhal Intrusion. They form generally concordant bodies in the lower units but discordant dykes and sheets in the upper units, and locally occur as net-veins. The typical mineral assemblage is clinopyroxene-amphibole-plagioclase feldspar-ilmenite, with garnet locally present. Quartz is a common accessory mineral. The dykes are compositionally and chemically indistinguishable from the Lower Zone melagabbros, but also from the 'Younger Basic' intrusions. Leucogabbro dykes up to 25 cm wide also cut the marginal gabbros and ultramafic rocks and some of the Lower Zone units.

Late-Laxfordian pegmatitic granites occur as thick E-trending veins and pods in the Roineabhal Intrusion and the marginal gabbros with prominent examples at the south-east end of the GCR site. They consist of microcline, plagioclase feldspar (oligoclase–albite), quartz, biotite and magnetite with abundant minor components including zircon, monazite, garnet, and thorium- and uranium-bearing minerals. The Sletteval Pegmatite, which consists of two veins, 20 m and 6 m thick, joined by an irregular vein at their north-west end, lies immediately adjacent to the Roineabhal Intrusion and cross-cuts the metagabbros and the adjacent diorite (Figure 2.7).

The south-eastern parts of the intrusion that occur east of the Roghadal–Fionnsbhagh road, effectively the Middle Zone and Upper Zone rocks, are saussuritized, with plagioclase feldspar altered to zoisite, sericite, paragonite and quartz and the mafic minerals to epidote, clinozoisite, chlorite and locally tremolite. The rocks become more highly fractured and pervasively saussuritized to the south-east, and above the main thrust plane in the OHFZ they are wholly brecciated, granulated, mylonitic and invariably strongly retrogressed.

Structure and metamorphism

Aeromagnetic data suggest that the intrusive bodies of the SHIC only extend downwards to 5–7 km, and are lenticular, both along strike and down-dip (Westbrook, 1974; Fettes *et al.*, 1992). The Roineabhal Intrusion is unusual in that it lies in the core of a large sideward-closing fold, normally termed an antiform (e.g. Dearnley, 1963; Witty, 1975). Limb dips generally range from *c.* 30° to *c.* 60° to both the north-east and south-west, but are commonly steeper and even subvertical (Figure 2.7). The fold has a subvertical to very steeply NW-plunging axis, and closes sideways and faces to the south-east. Dips in the hinge zone are variable, ranging from 30° to the north-west to subvertical. An early foliation ($S1_L$) is developed sub-parallel to the compositional banding in areas with upper amphibolite-facies metamorphic assemblages. Associated with foliation development are migmatization, quartz-feldspar segregations, small-scale tight folding, boudinage, and formation of small shear-zones. This deformation overlapped with the emplacement of the ultramafic rock–anorthosite breccias and intrusion of the melagabbro dykes and sheets. The relationship of folding and metamorphic grade suggests that this $D1_L$ deformation was accompanied by granulite- to upper-amphibolite-facies metamorphism. The granulite-facies areas show virtually no early deformation features. The assemblage garnet-clinopyroxene-plagioclase feldspar (An_{44})-(quartz)-(hornblende) is common in the gabbros and orthopyroxene occurs rarely. Clinopyroxene composition varies from calcic augite–salite in the Middle Zone units to diopside–salite in the Upper Zone. These mineralogies are indicative of hornblende granulite-facies conditions (see O'Brien and Rötzler, 2003).

The main penetrative deformation, $D2_L$, has folded the banded anorthosite into the large-scale 'antiform'. Attenuation and extensive shear-zone formation on the limbs of the main fold are focused along the margin of the Roineabhal Intrusion and in the adjacent gabbros. A strong biotite fabric has developed related to the shear zones but it is weak in the main fold hinge zone where spindle-shaped mafic clusters define a steeply plunging lineation. $D2_L$ deformation was accompanied by middle amphibolite-facies metamorphism (m3), best recorded in gneissose pelites of the Leverburgh Belt where cordierite + orthopyroxene have developed from garnet + quartz (Baba, 1998). Coronas or symplectites of orthopyroxene + plagioclase have formed between garnet and quartz in the more-psammitic rocks, and between garnet and clinopyroxene in the mafic rocks.

$D3_L$ represents a later phase of compression and pervasive shearing in the intrusion and adjacent gabbros. The main fold was undoubtedly tightened, and steep NNW-trending, dextral shear-zones up to 22 m wide and 500 m long were formed (Witty, 1975). Shearing was again focused in the marginal parts of the intrusion and it is difficult to separate $D3_L$ effects from earlier-formed fabrics. Deformation was accompanied by lower amphibolite-facies metamorphism (m4) with sillimanite, biotite and muscovite developed in the gneissose pelites and psammites, and hornblende and biotite in the mafic rocks (Baba, 1998).

Subsequently there were several further discrete Laxfordian deformation phases that resulted in localized shear-zone formation. The most significant phase resulted in the formation of E-trending, subvertical, sinistral shear-zones in the Roineabhal Intrusion. Lateral displacements of up to 140 m have been recorded (Witty, 1975). A later set of NE- to ENE-trending minor shear-zones cross-cuts the earlier structures and although they form prominent lineaments, visible on aerial photographs, they show only minor sinistral and dextral displacements. Some of the late-Laxfordian pegmatites show peripheral granulation suggesting that movements continued to the very end of the Laxfordian event. These later deformation episodes were accompanied by greenschist-facies metamorphism, although retrograde effects are only patchy in the Roineabhal Intrusion. The deformation and associated pervasive low-grade hydrous retrogression linked to the Outer Hebrides Fault Zone, probably occurred during the Silurian-age Scandian Event, as noted above.

Interpretation

The SHIC has long been recognized as a major element of the geology of the Outer Hebrides, and hence its origin, age and deformational and metamorphic history are particularly important to the overall understanding of the Lewisian Gneiss Complex. The gabbros and anorthosite of the Roineabhal Intrusion are the earliest intrusions in the SHIC, but the whole complex is compatible with differentiation from one or more tholeiitic basaltic magmas (see Fettes *et al.*, 1992). Igneous trends have been well documented in the granulite-facies parts of the anorthosite, gabbro and diorite intrusions, implying no re-distribution of elements during the granulite-facies metamorphism (Witty, 1975; Horsley, 1978). Such patterns are not preserved in the amphibolite-facies parts of these bodies. The SHIC shows an overall change from tholeiitic to calc-alkaline to alkaline magmatism with time, compatible with island-arc volcanism. The SHIC was interpreted as having been intruded at crustal levels of 25–30 km with the granulite-facies metamorphism reflecting its equilibration at these deep levels.

The correlation and absolute ages of main structural phases within the SHIC, the metasedimentary belts, and the gneisses farther afield, is not simple. The intrusive igneous bodies have acted as relatively competent elements of the geology particularly where they have retained their granulite-facies mineralogy. Witty (1975) suggested that the main 'antiform' in the anorthosite was partly a $D1_L$ structure, tightened and accentuated during the later $D2_L$ deformation and shearing. He also attributed some of the early boudinage and shearing of the gabbros and Lower Zone rocks to $D1_L$. The main $D1_L$ deformation and coeval granulite-facies metamorphism (m1 and m2) appear to overlap with intrusion of the SHIC. This interpretation fits well with the metamorphic evidence from adjacent parts of the Leverburgh Belt (see below). In the SHIC the $D2_L$ and $D3_L$ deformation events are confined mainly to shear zones and were accompanied by amphibolite-facies metamorphism (m3 and m4 respectively). In the Leverburgh and Langavat belts the deformation phases are better developed and are represented by fold phases and related fabrics. The Leverburgh Belt rocks lie in a steeply plunging synform that can be paired with the Roineabhal Antiform. The deformation events are labelled here as Laxfordian (e.g. $D1_L$), but recent isotopic age data suggests that the events may be partly local in extent and that they cannot necessarily be regionally correlated with the structural phases in the Laxfordianized Archaean gneisses of the Uists and North Harris (Coward *et al.*, 1970; Fettes *et al.*, 1992; Kinny and Friend, 1997; Mason *et al.*, 2004a).

Geochronological work on the anorthosite and in other parts of the SHIC and the metasedimentary belts has been used to constrain the time frame for the intrusive, deformational and metamorphic events. The early Sm-Nd work of Cliff *et al.* (1983) showed that the SHIC is Palaeoproterozoic in age rather than Archaean as had been assumed previously. They interpreted the age of intrusion of the SHIC as *c.* 2000 Ma, with the granulite-facies metamorphism in the anorthosite dated at 1870 ± 40 Ma. Subsequently, Cliff *et al.* (1998) obtained a Sm-Nd age of 1827 ± 16 Ma from the net-veined gabbros in the Roinabhal Intrusion, again interpreted as dating the granulite-facies metamorphic event. Whitehouse and Bridgwater (2001) recently revised this age to 1876 ± 5 Ma, based on more-precise ion-microprobe U-Pb zircon dating. They also obtained a U-Pb zircon age of 1876 ± 5 Ma from a small tonalite body that intrudes the diorite at Bàgh Steinigidh. On the basis of the zircon morphologies and zoning, they interpreted the date as representing the age of intrusion. This tonalite is taken to be the youngest member of the SHIC, except for the minor shoshonite dykes (see **Na Buirgh** GCR site report, this chapter; and Fettes *et al.*, 1992). Friend and Kinny (2001) showed that zircon overgrowths in adjacent aluminous pelitic rocks of the Leverburgh Belt have concordant SHRIMP U-Pb ages of 1874 ± 29 Ma, which they interpreted as the age of metamorphism. Mason *et al.* (2004a) obtained U-Pb TIMS data from zircons from a gabbro in the anorthosite body at NG 0275 8740. The data are discordant but give an upper intercept of 2491 ± 30 Ma, interpreted as the age of emplacement, and a lower intercept of 1877 ± 50 Ma, interpreted as the date of metamorphism. U-Pb zircon ages from the diorite and norite bodies gave ages of 1888 ± 2 Ma and 1883 ± 3 Ma respectively, both interpreted as emplacement ages. Thus, Mason *et al.* (2004a) argue that the anorthosite is some 600 million years older than the other elements of the SHIC.

The metasedimentary rocks of the adjacent Leverburgh and Langavat belts have also been shown to be of Palaeoproterozoic age by Friend and Kinny (2001). They obtained a spread of ages between 2780 Ma and 1880 Ma on detrital zircon cores from two metasedimentary samples, implying that their deposition pre-dated intrusion of the SHIC and granulite-facies metamorphism by only a few million years.

Baba (1997, 1998, 1999a,b) carried out detailed field, petrological and geochemical studies of the metasedimentary rocks, focused in the Roghadal–Leverburgh area. He showed that the Leverburgh Belt sedimentary protoliths were compatible with deposition in a trench environment linked to an island arc or continental-margin arc. He also reported sapphirine, orthopyroxene-kyanite, and orthopyroxene-sillimanite assemblages in pelitic and semipelitic rocks. These mineral assemblages are indicative of ultra high-temperature, high-pressure granulite-facies peak metamorphic conditions with temperatures of *c*. 930°–950° C and pressures of > 12 kbar (see O'Brien and Rötzler, 2003). Baba (1999a,b) pointed out that the main deformation and peak metamorphism in the anorthosite could not be explained merely by intrusion of SHIC into lower crustal levels (i.e. 25–30 km; see above) at the base of an arc, but required a subsequent definite pressure increase. He postulated that subduction must have continued downwards for a further 10–15 km following intrusion of the SHIC, possibly as a result of continental collision. Hence, two separate granulite-facies events were recognized (m1 and m2), followed by a static development of corona textures under middle amphibolite-facies conditions (Baba, 1998; see also Dickinson and Watson, 1976). Fettes *et al*. (1992) noted that this last 'm_{2a}' metamorphic event reflects a pressure decrease of 4 kbar, relating to rapid uplift. The D3 and later deformation and metamorphic features were considered to be compatible with localized strain and punctuated uplift during the Laxfordian, as documented previously by Dickinson and Watson (1976). Ar-Ar studies by Cliff *et al*. (1998) and Rb-Sr biotite ages obtained by Cliff and Rex (1989) document the later uplift history of the SHIC and metasedimentary belts of South Harris relative to the migmatitic Archaean gneisses and later granites in the adjacent terrain to the north-east.

Thus, the current interpretation is that the metasedimentary rocks of South Harris were deposited in a trench environment adjacent to an active island-arc or possible continental arc. They were subducted beneath the arc to crustal depths of *c*. 27 km where the SHIC was intruded. Then both elements were further subducted to 35–45 km depth, and were folded and metamorphosed under upper granulite-facies conditions (Baba, 1999b). Temperatures of 800° C to over 900° C and pressures of > 12 kbar were attained during the peak metamorphism (Baba, 1999a). All these events are currently interpreted to have occurred between 1890 Ma and 1870 Ma (Friend and Kinny, 2001), except by Mason *et al*. (2004a) who postulated that intrusion of the Roineabhal Intrusion occurred much earlier at *c*. 2490 Ma. It is significant that similar localized arc activity is recorded in other parts of the Laurentian and Fennoscandian shield at about 1850–1900 Ma (Park, 1994; Whitehouse and Bridgwater, 2001).

Conclusions

The Roineabhal GCR site covers a major part of the largest gabbro–anorthosite body found in the UK. The anorthosite (a white, almost pure plagioclase feldspar rock) occurs in the upper parts of the Roineabhal Intrusion, part of the Palaeoproterozoic-age South Harris Igneous Complex (SHIC) that comprises various metamorphosed intrusions of anorthosite, gabbro, norite, diorite and tonalite. The Roineabhal Intrusion contains distinct igneous layering on both large- and small-scales and can be readily divided into Lower, Middle and Upper zones that become younger to the south-east. It is tightly folded into a large-scale antiform with a subvertical to steeply NW-plunging fold axis. Anorthosite–ultramafic rock breccias occur in lenticular zones along its south-west margin, and late-stage melagabbro dykes and net-veins cut the compositional banding. The SHIC intrusions show geochemical trends typical of calc-alkaline rocks derived from differentiation of basaltic magma at deep crustal levels.

These igneous rocks were intruded into metasedimentary rocks of the adjacent Leverburgh and Langavat belts. Geochronological work suggests that both the metasedimentary rocks and the intrusions were formed between about 1890 Ma and 1870 Ma. The metasedimentary rocks are compatible with deposition in a trench environment adjacent to an island arc and must have been subducted to lower crustal levels where the SHIC intrusions were emplaced. The earliest deformation and metamorphism were coeval with emplacement of the intrusions. Subduction continued until the SHIC and metasedimentary rocks reached crustal depths of *c*. 35–45 km where the rocks were metamorphosed further under high-pressure granulite-facies conditions. Rapid uplift followed, with renewed metamorphism under lower-pressure amphibolite-facies and finally under greenschist-facies conditions. Deformation during this phase was mainly confined to generation and reworking of shear zones marginal to the anorthosite. The main deformation and metamorphism spanned the period of Laxfordian reworking and progressive uplift between *c*. 1875 Ma and *c*. 1500 Ma. However, the south-east part of the anorthosite was later affected by considerably hydrous retrogression and associated shearing and cataclasis, linked to movements on the Outer Hebrides Fault Zone, probably during the Silurian-age Scandian Event.

The Roineabhal Intrusion is unique in the Lewisian Gneiss Complex and provides compelling evidence of Palaeoproterozoic igneous and tectonic events. It has been the subject of innumerable geological studies and is likely to remain a prime research and teaching locality. It is undoubtedly of international importance.

NA BUIRGH (BORVE), SOUTH HARRIS (NG 009 937–NG 038 964)

J.R. Mendum

Introduction

The Na Buirgh (Borve) GCR site covers a 4 km-long coastal section in South Harris stretching from Sgeir Liath to Rubha Romaighidh. It provides an across-strike traverse from the South Harris Igneous Complex, north-east through Palaeoproterozoic metasedimentary rocks of the Langavat Belt, to the migmatitic Archaean gneisses and Laxfordian granites of the Uig Hills–Harris Granite Vein-Complex. Recent work has shown that these three elements have distinct and disparate geological histories although their boundaries have been the subject of debate.

The metamorphosed diorite and tonalite found at the south-west end of the section belong to the South Harris Igneous Complex (SHIC) (see 'Introduction', **Roineabhal** GCR site report, this chapter). The diorite is volumetrically the largest member of the complex. Here, it is locally gabbroic and is cross-cut by thin orthoclase feldspar-bearing basaltic dykes termed 'shoshonites' (potassic variety of basaltic trachyandesite). At Bàgh Steinigidh (Bay Steinigie) (NG 019 939) the diorite is in contact with a metasedimentary succession 60–70 m thick, composed of thinly banded amphibolite and subsidiary metalimestone, calc-silicate rock and gneissose pelite (Figure 2.9). Immediately north-east of these rocks, lies a thin strip of tonalite, which together with the metasedimentary rocks, forms a *c*. 4 km-long and 100–300 m-wide septum, included within the diorite body. The foliation and shear zones in the diorite increase in intensity towards its north-eastern boundary. The deformation is accompanied by amphibolite-facies retrogression of the earlier granulite-facies mineralogy.

The Langavat Belt metasedimentary rocks and intercalated gneisses to the north-east form a *c*. 1.35 km-wide outcrop between Borvemore and Borve Lodge (Taigh Buirgh). They consist of generally thinly banded quartzofeldspathic gneisses with abundant amphibolite pods and bands. The metasedimentary belts range from quartzitic to semipelitic with abundant biotite, but metalimestone is present locally. Zoned ultramafic pods and strongly foliated, thinly banded amphibolite units are present. Deformation is high and the majority of elements dip steeply to the south-west. The south-western contact zone between the belt and the foliated diorite lies concealed beneath the sands of Tràigh Mhòr, but the north-eastern contact zone is exposed in places.

The Langavat Belt rocks pass rapidly north-east into Archaean, migmatitic, banded felsic gneisses with subsidiary pods and thin bands of amphibolite. Sheets of granite and pods and veins of granitic pegmatite are common. These late-Laxfordian intrusive elements become very abundant within 100–200 m of the contact. Farther to the NNE along the coastal section, granitic sheets and veins continue to dominate, and thick unfoliated granite sheets are present in parts, for example on Rubha Romaighidh.

Some younger dykes are also present in the section. Thin ENE-trending camptonite dykes of Late Carboniferous to Permian age are found just east of Sgeir Liath, and NNW-trending basalt and dolerite dykes of the Palaeogene Skye swarm are present in several places (Fettes *et al*., 1992).

The Langavat Belt rocks were recognized and defined by Jehu and Craig (1927), but were mapped in more detail and divided further by Dearnley (1959, 1963), Myers (1968) and Palmer (1971). Fettes *et al*. (1992) considered the various interpretations put forward by

Na Buirgh (Borve)

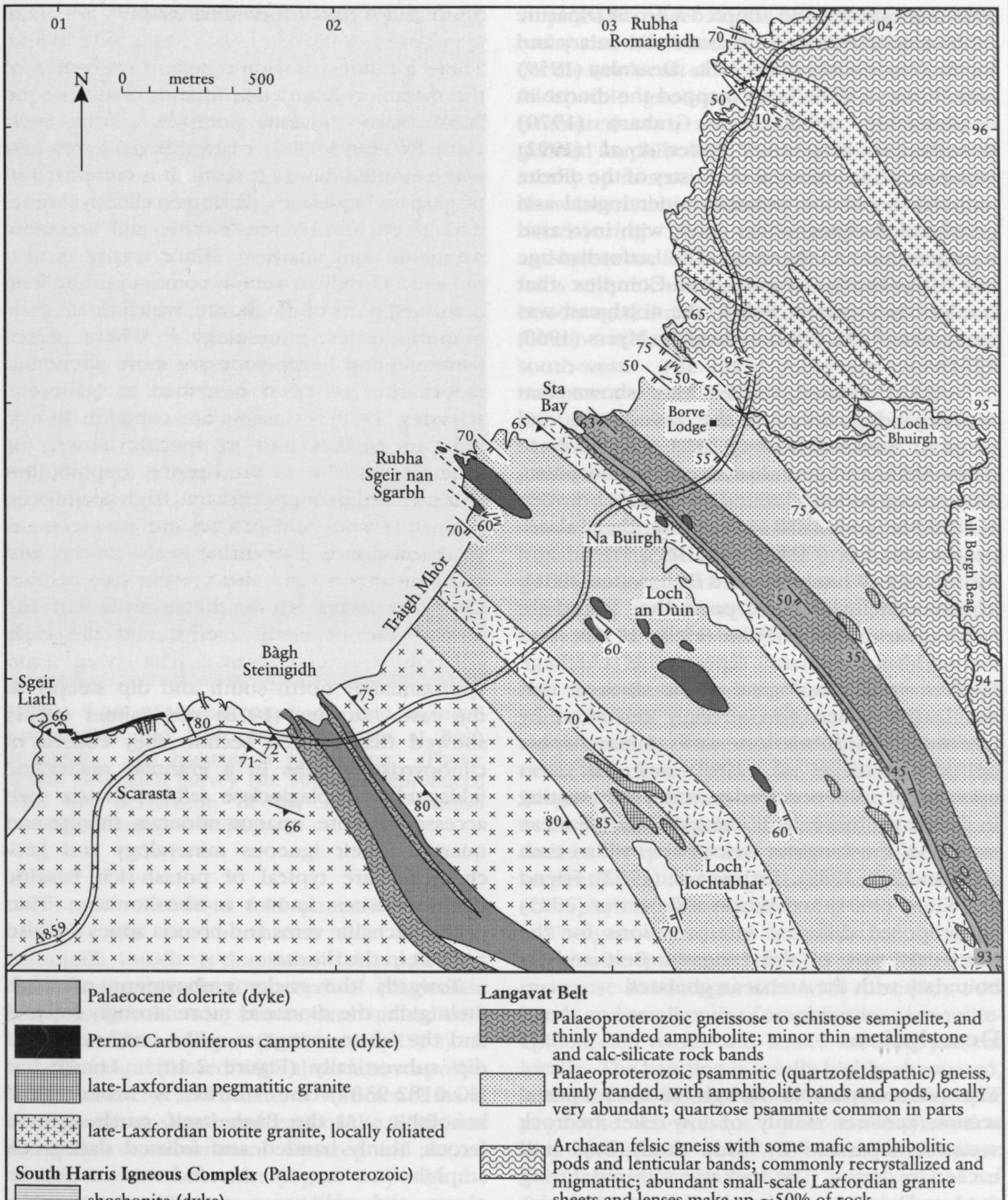


Figure 2.9 Simplified geological map of Na Buirgh (Borve), South Harris.

previous authors, and adopted a broad tripartite lithological division of the metasedimentary and metavolcanic rocks of the belt. Dearnley (1959) and Horsley (1978) both mapped the diorite in considerable detail, and Graham (1970) described its structure. Fettes *et al.* (1992) summarized the mineral chemistry of the diorite and also noted the textural, mineralogical and geochemical changes that occur with increased retrogression and shearing. The Laxfordian-age Uig Hills–Harris Granite Vein-Complex that borders the Langavat Belt to the north-east was mapped and described in detail by Myers (1968, 1971).

Geochronological studies have shown that sediment deposition in the Leverburgh and Langavat metasedimentary belts, emplacement of the SHIC, and granulite-facies metamorphism all occurred within a limited time-frame between *c.* 1890 Ma and 1870 Ma, during the Palaeoproterozoic Era (Cliff *et al.*, 1983; Friend and Kinny, 2001; Whitehouse and Bridgwater, 2001). These conclusions support the island-arc subduction model of Baba (1998, 1999b) (see **Roineabhal** GCR site report, this chapter). Further geochronological work showed that the Langavat Belt was strongly reworked by Laxfordian deformation and metamorphic episodes (Cliff *et al.*, 1998) and that later episodes of uplift occurred, possibly culminating in shear-zone movements along the north-eastern margin of the Langavat Belt in Grenvillian time (Cliff and Rex, 1989). Fettes *et al.* (1992), Friend and Kinny (2001) and Mason and Brewer (2005) all proposed different interpretations for the north-east part of the Langavat Belt and its boundary with the Archaean gneisses.

Description

The picturesque Na Buirgh (Borve) coastal section consists mainly of low-relief bedrock sections, separated by wide sandy bays and backed by dunes. The rock was scoured during the Late Devensian and earlier glaciations by ice moving south-east and shell sand commonly blows onshore resulting in clean, etched exposures. In the northern part of the section steeper cliffs up to 10 m high occur around Geòdha Martainn (NG 036 961). Access is relatively easy from the nearby A859 Tarbert–Leverburgh road. The geological description below traverses from south-west to north-east.

Sgeir Liath and Bàgh Steinigidh

These localities provide excellent exposures of the metamorphosed diorite and tonalite of the South Harris Igneous Complex. From Sgeir Liath (NG 0095 9390) eastwards dark-grey and white mottled diorite is seen. It is composed of plagioclase (andesine), pale-green clinopyroxene, dark-green hornblende, biotite, and accessory magnetite and apatite. Minor quartz is also present. Orthopyroxene is common in the less-deformed parts of the diorite, which retain their granulite-facies mineralogy. Where clinopyroxene and hornblende are more abundant, the diorite has been described as 'gabbroic' (Horsley, 1978). Garnets are common locally, both in patches and in specific zones, for example adjacent to the banded amphibolites and metasedimentary rocks at Bàgh Steinigidh. Pegmatitic veins and patches are also seen. A weak foliation is discernable in the diorite, and small shear-zones are also present (see below). Dark-grey dykes up to 50 cm wide cut the diorite, the pegmatitic veins, and the early foliation at several places. The dykes trend approximately north–south and dip steeply to the east. Horsley (1978) and Palmer (1971) showed that in thin section they consist of clinopyroxene laths in a granular microcline feldspar-biotite-plagioclase (albite) matrix with accessory apatite, opaque minerals, titanite and quartz. Their igneous mineralogy and geochemistry are typical of potash-rich basaltic trachyandesites, known as shoshonites. Thin pseudotachylite veins and breccia zones are also present in the diorite.

Towards the rocky embayment of Bàgh Steinigidh, the diorite is more strongly foliated and the fabric swings to strike north-west and dip subvertically (Figure 2.10). Locally (at NG 0182 9387) the diorite is broken and xenolithic. At the Bàgh itself, partly garnetiferous, thinly banded and foliated dark-green amphibolites are interbanded with white to cream and pale-green metalimestones, calc-silicate rocks, and fawn and purplish-grey psammites and semipelites. Four separate metalimestone bands can be distinguished with the largest reaching 2.2 m wide. Locally, veins of grey tonalite cut discordantly across the amphibolites and metasedimentary rocks. The rocks are tightly folded with fold axes varying in plunge from gently to the south-east to subvertical. Fold axial planes dip very steeply to the

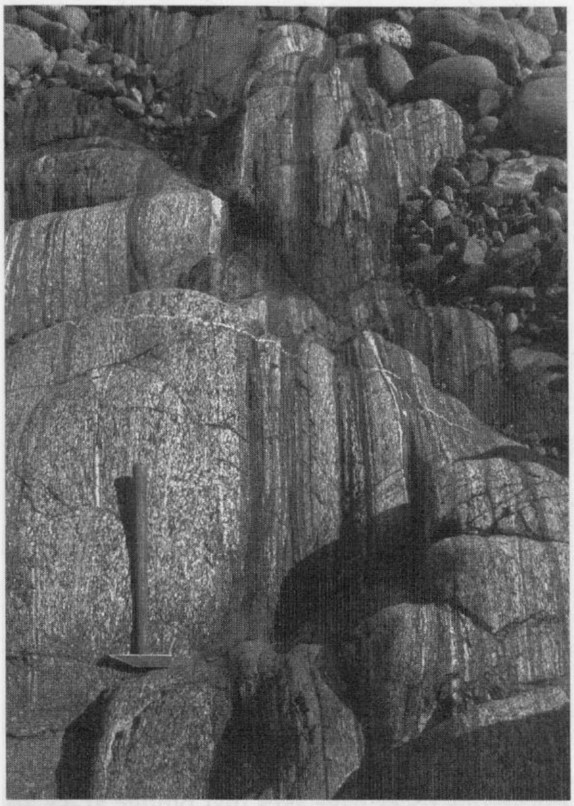


Figure 2.10 Foliated metadiorite and included amphibolitic and felsic gneiss enclaves at Bàgh Steinigidh. The hammer is 42 cm long. (Photo: British Geological Survey, No. P008366, reproduced with the permission of the Director, British Geological Survey, © NERC.)

north-east. Refolded fold patterns are seen locally. On the north-east side of Bàgh Steinigidh, tonalite is dominant. It is a pale-grey, coarse-grained rock composed of plagioclase feldspar, hornblende, biotite and quartz with rare microcline feldspar (Fettes *et al.*, 1992). It is foliated and altered with abundant scapolite, epidote, sericite and calcite. Ovoid xenoliths of amphibolite are common east of the Bàgh and shear zones are common. Sheared and altered diorite occurs to the east (Figure 2.9) with the main foliation dipping some 75° to the north-east.

Tràigh Mhòr–Sta Bay–Allt Borgh Beag (Borvebeg Burn)

The diorite–Langavat Belt boundary is not exposed on the coast section, but its position can be interpolated from inland outcrops just north of Loch Iochtabhat (Eachkavat). A thick amphibolite sheet within the metasedimentary rocks also lies beneath the sands (Figure 2.9). On the north-east side of Tràigh Mhòr are quartzo-feldspathic gneisses, interbanded and inter-laminated with abundant fine- to medium-grained amphibolite. The amphibolite units are locally up to several metres thick and commonly show internal hornblende-, biotite- and feldspar-rich layering. Some of the amphibolite layers and lenses are folded into tight to isoclinal minor folds with thick hinge zones and attenuated and boudinaged limbs. The dominant banding and foliation in these gneisses dips at 65°–70° to the south-west. The mafic rocks are more sub-ordinate towards Rubha Sgeir nan Sgarbh. At NG 0253 9469 a 25 m-wide pod of dark-green to black serpentinized ultramafic rock occurs in the gneisses. It has weathered to a prominent buff colour with a pitted surface. Its marginal zones show alteration to tremolite-actinolite and talc schist. Some 50 m of felsic and mafic striped gneisses, locally rich in biotite, separate this ultramafic pod from the larger, *c.* 80 m-wide, body that forms the headland of Rubha Sgeir nan Sgarbh. The marginal alteration zones that are rich in actinolite and talc are correspondingly wider in this main intrusion. It is the most north-westerly of a series of ultramafic pods that occur at intervals down the central part of the Langavat Belt (Fettes *et al.*, 1992). Except for Scara Ruadh, which shows banding, they are dunites or peridotites with olivine-tremolite-serpentine centres and altered shells containing anthophyllite, chlorite, actinolite and talc.

The gneisses to the north-east of the main ultramafic pod are dominantly felsic and quartzose banded gneisses with subsidiary thin bands and small pods of amphibolite. Actinolite-epidote-rich bands and lenses are also present locally. The banding is locally highly attenuated, and veins and pods of quartz and quartz-feldspar pegmatite are present. The banding/foliation dips consistently at 65°–70° to the south-west. The promontory immediately south-west of Sta Bay (NG 0292 9494) is composed of some 35 m of finely banded amphibolite with diopside lenses up to 30 cm across containing abundant pyrite and epidote. This amphibolite sheet can be traced south-eastwards along the length of the Langavat Belt to Finsbay. A thin metalime-stone band containing the assemblage forsterite (mainly serpentinized)-calcite-dolomite occurs adjacent to the amphibolite on the south-west side of Sta Bay. The bay itself has formed by preferential erosion of a large Palaeogene dolerite dyke. On the north-east side of Sta Bay some 20 m of thinly banded to laminated, semi-pelitic to psammitic gneisses with minor amphibolite bands occur. A single metalimestone band is also present. The typical violet-tinged biotite-rich felsic gneisses consist of quartz, plagioclase feldspar (oligoclase) and biotite (foxy brown), with subsidiary potash feldspar and locally abundant pyrite. Epidote and garnet are also present in parts (Dearnley, 1963). Relict clinopyroxene has been recorded in some of the laminated amphibolites (Fettes *et al.*, 1992).

North-east from Sta Bay numerous laminated amphibolite units up to 25 m thick are inter-banded with finely banded quartzofeldspathic gneisses. Epidote-, biotite- and pyrite-rich bands are present in the sequence. The bulk of the rocks farther to the north-east as far as the Allt Borgh Beag are finely banded quartzofeldspathic and amphibolitic gneisses with a dominant banding and foliation that dips at 50°–70° to the south-west. Quartz and quartz-feldspar pegmatite veins are abundant locally, but are strongly deformed or attenuated. The boundary of the Langavat Belt is placed at the Allt Borgh Beag, where the proportion of amphibolite falls significantly, and to the north-east the gneisses are dominantly felsic. Small amphibolite pods and bands do occur to the north-east but the fine-scale banding and interlamination of quartzo-feldspathic gneisses and amphibolite is absent. This change, although difficult to pinpoint exactly (see discussion below), also corresponds to the incoming of thicker less-deformed pegmatitic granite and granite veins of Laxfordian age.

Allt Borgh Beag–Rubha Romaighidh

The gneisses in the northernmost section of the GCR site range from thin- to medium-banded pale-grey felsic gneisses with subsidiary pods and thin bands of amphibolite, to more-nebulous granitoid gneisses with only a weakly developed biotite fabric. The gneisses are strongly recrystallized and partly migmatitic and contain abundant pale-grey to pink, medium-grained biotite granite sheets and veins, in part pegmatitic (Myers, 1971). These granites are weakly to moderately foliated in the southern part of this section but their late-Laxfordian origin is shown by their locally discordant and unfoliated nature. The proportion of granite increases rapidly to the north-east from the Allt Borgh Beag to constitute up to 50% of the bedrock. On Rubha Romaighidh, the felsic gneisses occur as xenoliths in a particularly thick massive, unfoliated granite sheet. Pegmatitic bodies up to 10 m wide are present marginal to the larger gneiss xenoliths. The regional banding and foliation in the gneisses dips to the south-west at between 50° and 70°.

Structure and metamorphism

The foliation in the diorite on Sgeir Liath is weak, strikes north-east, and dips some 60° to the north-west. It becomes more intense and finer grained where it curves into the small shear-zones, which trend *c.* 140°–150° and *c.* north–south, and show both sinistral and dextral movement geometries. The trend of the foliation changes eastwards and it becomes steep and NW-trending as Bàgh Steinigidh is approached. There is also a marked increase in the fabric intensity, matched by the incoming of amphibolite-facies assemblages. At Bàgh Steinigidh, tight folding of the metasedimentary rocks and tonalite veins on several scales is seen. Minor folds in the calcareous rocks have axes that plunge at 85° to 305° and appear to refold earlier structures. A larger-scale synformal structure has axes that plunge at 26° to 138°. The related axial-plane fabric dips very steeply to the north-east and corresponds to the main foliation and general banding. To the north-east of Bàgh Steinigidh dextral shear-zones are abundant and the sub-vertical NW-trending foliation is dominant.

The overall structure of the Langavat Belt appears to be simple. It is dominated by an attenuated, steeply SW-dipping, lithological banding and sub-parallel foliation. Tight minor folding is present but no large-scale structures can be recognized convincingly. Between Tràigh Mhòr and Rubha Sgeir nan Sgarbh, tight to isoclinal minor folding of the amphibolite bands and compositional banding is common. A locally prominent quartz lineation plunges at 16° to 305°, but fold axes plunge at 60° to the WSW. Fold axial planes dip steeply to the south-west and Z-profile (northwards verging) folds are most abundant, as noted by Myers (1968). Farther to the north-east, towards Sta Bay, minor folding is best developed immediately south-west of the banded amphibolite. Here tight to isoclinal minor folds of the compositional banding have axes that plunge at 55°–65° to the south-west and WSW. The remaining part of the

Langavat Belt shows only sporadic folding but here too axes plunge at 50° to the south-west. However, these are later, open to tight folds that fold the main foliation.

In the migmatitic, dominantly felsic gneisses north-east of the Langavat Belt, minor folding is not abundant but both tight to isoclinal early folds and related lineations plunge gently to moderately to the WNW and north-west.

Although granulite-facies assemblages are preserved in the diorite, amphibolite-facies assemblages are dominant in the Langavat Belt rocks and are ubiquitous in the migmatitic gneisses north-east of the Langavat Belt. The diorite assemblage is plagioclase feldspar (andesine)-hornblende-clinopyroxene-magnetite-quartz. Garnet is locally abundant and pink-grey orthopyroxene is present in the most westerly part of the exposed section. Mineral compositions reflect the granulite- and upper-amphibolite-facies metamorphism rather than the original igneous mineralogy (Dearnley, 1963; Horsley, 1978). Thus, the clinopyroxene lies in the calcic augite field, and the orthopyroxene is hypersthene with low Fe/Mg ratios.

At Bàgh Steinigidh the calcareous rocks contain forsterite, diopside and humite group minerals. This mineralogy is typical of upper amphibolite-facies conditions, although alteration products are abundant, such as serpentine (from forsterite) and actinolitic hornblende (from diopside). In the adjacent tonalite and diorite the typical assemblage is hornblende-biotite-plagioclase-quartz, with large poikiloblastic hornblendes common. Farther east the retrogression is more penetrative and the assemblage hornblende-biotite-epidote-plagioclase feldspar (oligoclase)-quartz-titanite is typically developed (Dearnley, 1963).

In the Langavat Belt the rocks are strongly recrystallized and the dominant mineral assemblages lie within the amphibolite facies. The typical assemblage in the quartzofeldspathic gneisses is quartz-plagioclase feldspar (oligoclase)-biotite-potash feldspar (orthoclase)-magnetite with accessory pyrite. However, remnants of higher-grade assemblages are preserved in parts, for example near Sta Bay relict clinopyroxene has been recorded in foliated amphibolite (Fettes *et al.*, 1992). Myers (1968) recorded grunerite/cummingtonite and anthophyllite from the mafic and ultramafic rocks and staurolite, garnet and sillimanite from the pelitic rocks. The presence of forsterite in the calc-silicate rocks, albeit strongly serpentinized, also suggests that the metasedimentary and metavolcanic rocks experienced upper-amphibolite- or even granulite-facies conditions prior to their extensive deformation, recrystallization and metamorphism under lower-amphibolite conditions during Laxfordian and possibly Grenvillian reworking.

Interpretation

Jehu and Craig (1927) recognized the rocks of the Langavat Belt as possible metasedimentary and metavolcanic rocks on account of their finely interbanded felsic and mafic nature, and the presence of pelitic and quartzitic lithologies, metalimestones and calc-silicate rocks. Subsequent workers have generally agreed with this basic interpretation, but the detailed disposition, number and extent of metasedimentary and metavolcanic units, and structural pattern, have all been interpreted somewhat differently (see Fettes *et al.*, 1992; Mason and Brewer, 2005 for summaries). The Langavat Belt lithologies contrast with those of the Leverburgh Belt, where granulite-facies mineralogies are still present, the rocks are less thoroughly reworked, and their sedimentary protoliths are more readily recognized. The mineralogy and composition of the finely interbanded amphibolite and quartzofeldspathic gneisses that dominate the north-eastern part of the Langavat Belt are compatible with being derived from basic volcanic or volcaniclastic rocks, at least in part, but they may also represent highly deformed Archaean orthogneisses with abundant mafic intrusions as preferred by Mason and Brewer (2005). Individual metasedimentary and possible metavolcanic units can apparently be traced along the length of the exposed belt. Dearnley (1963) postulated that the beds in the central part of the Langavat Belt were disposed in a near-isoclinal antiformal fold and that minor fold vergence changed across the belt. Myers (1968), Palmer (1971), Fettes *et al.* (1992) and Mason *et al.* (2004b) all rejected this interpretation as they failed to find any duplication of lithological units and could not confirm any systematic variation in minor fold vergence.

High strain, the presence of shear zones and mylonitic rocks, and lack of observed contact relationships all mask the relationships between the Langavat Belt and the adjacent intrusions of the SHIC to the south-west. However, Fettes *et al.* (1992) noted a divergence of regional strike between the diorite boundary and individual metasedimentary units, such that mapped quartzitic units became progressively cut out to the south-east. Hence, they interpreted the diorite as being intrusive into the metasedimentary rocks, an interpretation rejected by Mason *et al.* (2004b) (see below). The relationship between the major amphibolite bodies and metasedimentary rock units within the belt is also unclear. The main south-western sheet, some 125–150 m thick, is concealed beneath Tràigh Mhòr on the coast section. Inland, it is a consistently foliated amphibolite with flattened feldspar aggregates and lacks quartzofeldspathic gneiss interbeds. It is interpreted as a highly deformed metagabbro sheet, linked to the SHIC, as regionally it appears to cut across the Langavat Belt stratigraphy (Fettes *et al.*, 1992). However, the thinner laminated amphibolite unit on the south-west side of Sta Bay appears to bound the Sta Bay metasedimentary succession and may not relate to the SHIC. It may represent an earlier basic intrusion or mafic lavas.

The north-eastern boundary of the Langavat Belt has been defined as a transition from interbanded quartzofeldspathic gneiss and amphibolite north-eastwards over *c.* 100 m into coarser-grained, recrystallized and migmatitic, grey, biotitic felsic gneisses and more-leucocratic granitoid gneisses (Dearnley, 1963; Fettes *et al.*, 1992). This coincides with the incoming of Laxfordian medium- to coarse-grained granite sheets, pods and dykes and pegmatitic granite pods and veins, part of the Uig Hills–Harris Granite Vein-Complex. When both the Langavat Belt rocks and the adjacent felsic gneisses in the vein-complex were assumed to have Archaean protoliths, it was relatively easy to envisage that the extensive Scourian and Laxfordian deformation would have erased any trace of the sediment–gneiss unconformity, or conversely any intrusive relationship. However, Friend and Kinny (2001) postulated that, although the felsic gneisses do have Archaean granodioritic protoliths, the metasedimentary rocks are Palaeoproterozoic in age. The resultant boundary should represent a major crustal suture, as well as an early-Laxfordian and possible Grenvillian deformation front. This is not in accord with its transitional appearance in the field. As a result Friend and Kinny (2001) have suggested that the boundary be placed at Rubha Sgeir nan Sgarbh, coincident with the ultramafic pods. They interpreted the rocks north-east from here to NG 031 950 as mylonites derived from felsic gneisses and granite sheets, and the rocks to the south-west as being non-mylonitic with granite sheets absent. However, the purported mylonites include the calcareous and semipelitic rocks of Sta Bay, and the amphibolite-rich gneisses to the north-east, both of which are placed within the Langavat Belt by all other authors. Dearnley (1963), Myers (1968) and Fettes *et al.* (1992) also failed to recognize any significant differences in the gneisses to the north-east and south-west of Rubha Sgeir nan Sgarbh.

Mason *et al.* (2004b) and Mason and Brewer (2005) suggested an alternative interpretation. Firstly, they postulated that the metasedimentary component of the Langavat Belt had been over-estimated by earlier workers and suggested that the bulk of the rocks, some 70%, were derived from Archaean tonalitic gneisses and subsidiary mafic intrusive bodies. They explained the inter-relationships of metasedimentary rocks and the orthogneisses by early structural imbrication, the pattern being obscured by the subsequent high Laxfordian strain and shear-related deformation. They suggested that the more finely banded units adjacent to the diorite were composed of blastomylonitic rocks, locally highly quartz-rich, and that two ages of mylonites and ultramylonites could be recognized (cf. Friend and Kinny, 2001). The earlier-formed (Laxfordian) amphibolite-facies mylonites (type-1 tectonites) were intruded by late-Laxfordian pegmatitic granite pods and veins, which show only slight deformation, whereas the later-formed greenschist-facies mylonites (type-2 tectonites) contain strongly deformed pegmatitic bodies. Zircons from a representative pegmatitic granite pod from near Finsbay were dated by U-Pb TIMS methods at 1657 ± 2 Ma (Mason *et al.*, 2004b). Hence, Mason *et al.* (2004b) suggested that the Langavat rocks are not part of the Roineabhal Terrane of Kinny and Friend (2001) and that the Bàgh Steinigidh septum belongs to the Leverburgh Belt, not the Langavat Belt. They postulated that the main suture lay adjacent to the diorite where the gneisses are very highly sheared. Recent SIMS zircon age dates obtained by Kelly *et al.* (2008) show that the felsic gneisses from the north-east boundary of the Langavat Belt formed from tonalitic protoliths between *c.* 2850 Ma and

2830 Ma. High-grade metamorphism followed rapidly at *c.* 2830 Ma with evidence for a later Archaean event at *c.* 2730 Ma. Kelly *et al.* (2008) also confirmed the age of emplacement of the late-Laxfordian granite sheets at between 1704 Ma and *c.* 1670 Ma, noting that their intrusion overlapped shearing. The age of the metasedimentary units thus remains open to speculation.

As noted in the **Roineabhal** GCR site report, the geological history of South Harris has been significantly revised in recent years in the light of radiometric dating results. Friend and Kinny (2001) and Whitehouse and Bridgwater (2001) presented U-Pb zircon geochronological evidence that the SHIC and the host Langavat and Leverburgh metasedimentary and metavolcanic belts are Palaeoproterozoic in age and were formed between *c.* 1890 Ma and 1870 Ma. These conclusions support the island-arc subduction model of Baba (1998, 1999b), based on studies of lithologies and metamorphic assemblages in the Roghadal–Leverburgh area. The preferred model suggests that the sedimentary and volcanic rocks were deposited in a trench environment adjacent to an island arc, and then subducted to crustal depths of *c.* 27 km where they were intruded by the SHIC. Further subduction to 35–45 km depth resulted in deformation and granulite-facies metamorphism, followed by rapid uplift. Injection of the shoshonite dykes probably occurred during this later subduction phase. The Palaeoproterozoic terrain was then reworked by later Laxfordian deformation and metamorphic episodes. These later reworking events were more penetrative in the Langavat Belt than in the SHIC and the Leverburgh Belt.

The timing of uplift can be constrained by studies of various mineral isotopic systems that have different theoretical closure temperatures. Cliff *et al.* (1998) obtained ^{40}Ar-^{39}Ar ages from hornblendes in mafic rocks across South and North Harris. These gave consistent values between 1780 Ma and 1630 Ma implying that uplift had occurred following the main Laxfordian event at around 1800 Ma. Cliff and Rex (1989) obtained 20 Rb-Sr biotite ages from South and North Harris concentrating on the SHIC and the Langavat Belt. The Rb-Sr biotite age pattern is more sensitive to times of uplift than the hornblende ^{40}Ar-^{39}Ar isotopic systems and shows a distinct step across the Langavat Belt. Ages to the south-west, in the granulite-facies SHIC and Leverburgh Belt, range from *c.* 1630 Ma to 1340 Ma, whereas those to the north-east of the belt range from *c.* 1300 Ma to 950 Ma. Ages from North Harris and Lewis are generally in the range 1115 Ma to 1020 Ma. The youngest ages were obtained from the north-eastern margin of the Langavat Belt, suggesting that Grenvillian-age shearing may have occurred along this boundary.

Conclusions

The Na Buirgh (Borve) GCR site is of international importance, as it provides a coastal section across the complex Langavat Belt, a much debated and significant part of the Lewisian Gneiss Complex in South Harris. The 1.4 km-wide belt is composed of Archaean gneisses, and metasedimentary and metavolcanic rocks of possible Palaeoproterozoic age. It is sandwiched between the diorite of the Palaeoproterozoic South Harris Igneous Complex (SHIC) to the south-west and Archaean migmatitic, dominantly felsic gneisses, and late-Laxfordian granites to the north-east.

The Langavat Belt consists of thinly banded and laminated felsic and subsidiary amphibolitic gneisses with thin semipelitic, metalimestone and calc-silicate rock-units. Amphibolites that are finely interbanded with the felsic gneisses are interpreted as being derived from basic volcanic rocks, possibly volcaniclastic. In contrast, the more-prominent and coherent amphibolite units are interpreted as highly deformed metagabbro or metadolerite sheets belonging to the SHIC. Serpentinized ultramafic pods appear to represent original Palaeoproterozoic intrusions, now boudinaged, sheared and fragmented by Laxfordian deformation and shearing.

The rocks of the Langavat Belt now retain little evidence of their earliest deformation and higher-grade metamorphic history at deeper crustal levels (see **Roineabhal** GCR site report, this chapter). Both early- and late-Laxfordian tectonometamorphic events have reworked the units extensively under amphibolite-facies conditions, giving rise to the fine-scale compositional banding and generally parallel foliation or schistosity. The belt has been a locus for shearing and differential uplift movements from *c.* 1870 Ma to *c.* 1000 Ma and hence it has provided vital radiometric dates that help to elucidate the later history of the Lewisian Gneiss Complex in the Outer Hebrides.

The diorite of the SHIC is less affected by the Laxfordian events and retains relict granulite-facies metamorphic assemblages except in its marginal zone where it becomes progressively more sheared, foliated and recrystallized to amphibolite-facies assemblages as the contact with the Langavat Belt is approached. Within the marginal part of the diorite at Bàgh Steinigidh, a 30–100 m-wide septum consists of interbanded semipelitic and calcareous gneisses with prominent metalimestones, calc-silicate rocks and laminated amphibolites, all intruded by a sheet of pale-grey tonalite, some 125 m wide. The tonalite is the youngest member of the SHIC, except for minor late-stage dykes of shoshonite (potassic basaltic trachyandesite). Different authors attribute the Bàgh Steinigidh metasedimentary rocks to either the Leverburgh or Langavat belts.

To the north-east of the Langavat Belt are dominantly grey, biotitic felsic gneisses of undoubted Archaean age. These gneisses are coarsely recrystallized, partly migmatitic and contain weakly banded granitoid rocks that may represent later Scourian (Archaean) granite sheets. The contact is transitional over *c.* 100 m, and has been interpreted very differently by the various workers. Various sheets and pods of grey to pink, weakly foliated, Laxfordian granite have intruded the Archaean gneisses. These granites, some of which are pegmatitic, form part of the Uig Hills–Harris Granite Vein-Complex.

NORTH PABBAY, SOUND OF HARRIS (NF 875 885–NF 904 887)

D.J. Fettes

Introduction

This coastal site provides an excellent cross-section across an area of Laxfordian reworking of Scourian metasedimentary and meta-igneous gneisses and 'Younger Basic' Suite mafic intrusions in the Lewisian Gneiss Complex of North Pabbay. The Laxfordian reworking varies from very low to high and is manifest as progressive changes in the degree of strain and the style and intensity of folding, fabric development and recrystallization. In North Pabbay these structural and metamorphic effects can readily be related to the regional Laxfordian structures and strain patterns (Figure 2.11).

The North Pabbay GCR site also crosses the junction between the two major lithological groups present on Pabbay; the typical grey to white and cream, banded, Archaean-age, granodioritic to tonalitic felsic gneisses with subsidiary amphibolitic mafic sheets and pods of the north-eastern part of Pabbay; and the dominantly metasedimentary succession in the remainder of the island. The metasedimentary rocks are mainly flaggy biotite-rich quartzo-feldspathic gneisses, but in parts contain pink homogeneous granitic gneisses and locally abundant quartz-feldspar and pegmatitic granite veins. Graham (1970) termed these rocks the 'pink and blue' gneisses, and found that they were useful for determining the degree of Laxfordian strain. Around Bàgh Alairip (Alarip Bay) impure quartzite and minor semipelite are present (Figure 2.12). The metasedimentary rocks show similarities to both the Langavat Belt of South Harris and the zone of metasedimentary rocks mapped in North Uist (Institute of Geological Sciences, 1981; Fettes *et al.*, 1992). A notably thick amphibolitic mafic sheet forms the main part of the ridge of Greanan. To the south-east of this body in the central part of Pabbay is a thick sheet-like ultramafic body. The lithologies of North Pabbay can be readily traced south-east along strike into Berneray (Graham, 1970).

The Sound of Harris Antiform and the Berneray Synform dominate the regional structure (Figure 2.11). The axial planes of these major Laxfordian ($D3_L$) folds trend approximately north-west, and their axes plunge at low to moderate angles to the north-west. The steeply dipping common limb of this fold pair runs through the islands of Berneray and Pabbay and is marked by high degrees of Laxfordian reworking. Laxfordian strain falls off north-eastwards towards the axial zone of the Sound of Harris Antiform.

The area received little attention from the early surveyors (for example, Jehu and Craig, 1926). It was first mapped in detail and described comprehensively by Graham (1970) and the following account draws heavily from his work.

Description

The island of Pabbay lies at the western entrance to the Sound of Harris. The north coast is marked by a rocky cliff-line 5–30 m high, and the GCR site between Cisinis (Kishinish) and Rubha

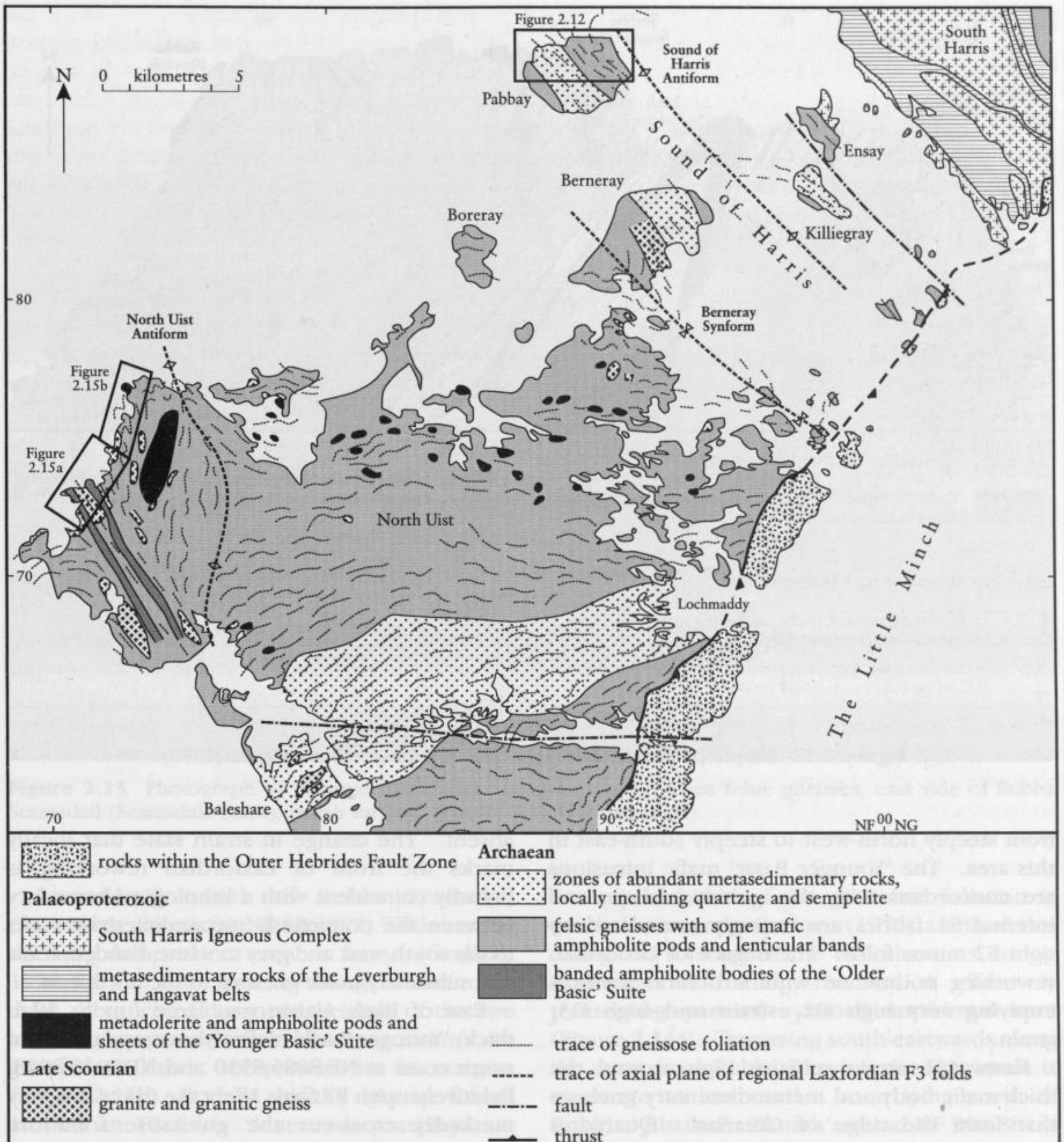


Figure 2.11 Map showing the regional lithologies and structure of North Uist and the Sound of Harris. The positions of the North Pabbay (Figure 2.12) and **North Uist Coast** (Figure 2.15) GCR sites are indicated. After Fettes *et al.* (1992).

Bhreinis (Brenish Point) provides a near-continuous exposed coastal section and hinterland area some 3 km long. The clean rocky outcrops extend inland to the high point of Beinn a' Chàrnain at 196 m above OD.

The western end of the section around Cisinis (NF 875 888) is marked by fine-grained, typically planar-banded and foliated, grey biotitic felsic gneiss with locally abundant pink granitic and felsic veins. These are the typical 'pink and blue' gneisses of Graham (1970). The banding and foliation dip steeply north-east. Tight F2 folds are common with a well-developed planar biotite fabric parallel to the axial planes. The L2 lineations show variable orientations in the plane of the foliation with their plunge varying

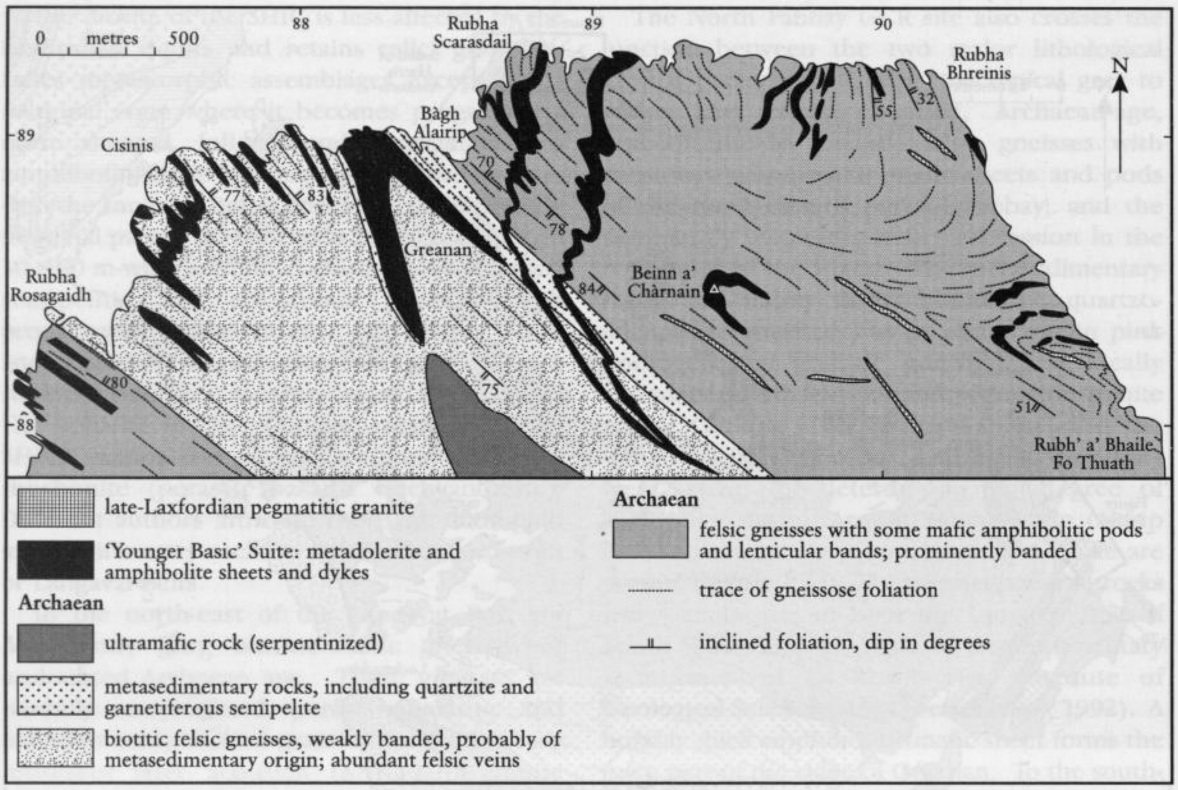


Figure 2.12 Simplified geological map of North Pabbay. After Graham (1970).

from steeply north-west to steeply south-east in this area. The 'Younger Basic' mafic intrusions are concordant with this gneissic fabric, and internal S1 fabrics are strongly crenulated by tight F2 minor folds. The degree of Laxfordian reworking is intense with structural features implying very high $D2_L$ strain and high $D3_L$ strain.

Eastwards, strain remains high around the thick mafic body and metasedimentary gneisses that form the ridge of Greanan. Quartzites and gneissose garnetiferous semipelite occur immediately adjacent to the mafic amphibolite body and also extend farther east, forming the western side of Bàgh Alairip (NF 885 890). Inland to the south-east of Greanan is a thick ultramafic body, some 250–300 m thick that extends for at least 1.3 km. It is probably a peridotite or harzburgite, by analogy with a similar sheet-like body along strike on Berneray.

Across Bàgh Alairip, the degree of Laxfordian strain decreases markedly. To the east F2 folds are typically open monoclines and S2 fabric development becomes weaker and eventually absent. The change in strain state that locally marks the front of Laxfordian reworking is broadly coincident with a lithological boundary between the dominantly metasedimentary rocks to the south-west and grey to white, banded, felsic and subsidiary mafic gneisses to the north-east.

East of Bàgh Alairip two large (up to 50 m thick) 'Younger Basic' mafic dykes crop out on the north coast at NF 8885 8930 and NF 8912 8928. Relatively open F2 folds affect the dykes but they markedly cross-cut the gneissose foliation, which therefore must be dominantly Scourian (Figure 2.13). The fold axial planes and related S2 fabric trend north-west, here regionally parallel to the gneissose foliation. Traced inland to the south and east the two dykes become thinner and their angular discordance to the gneissose foliation decreases as the $D2_L$ strain increases. At around NF 892 879 the mafic dykes are effectively concordant with the gneissose foliation. This zone of high $D2_L$ strain is the south-eastward extension of that seen between Cisinis and Bàgh Alairip in the western part of the section.

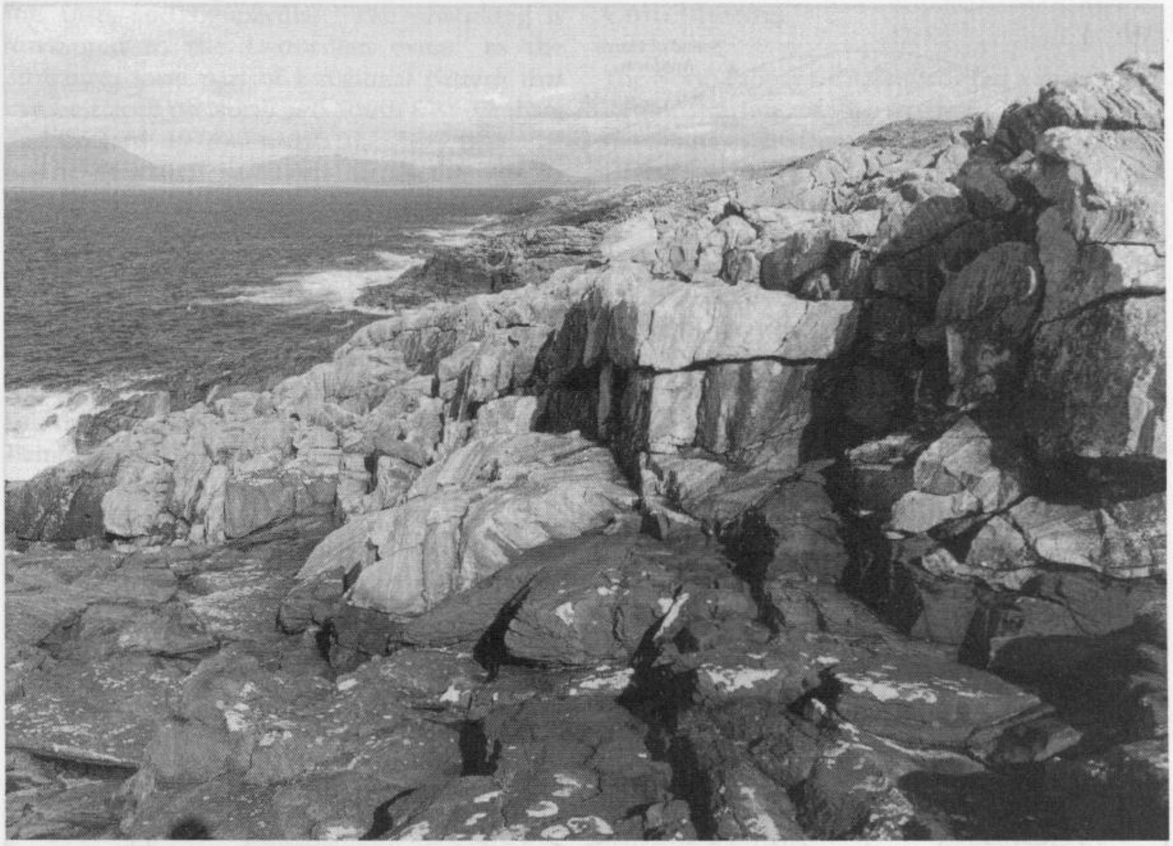


Figure 2.13 Photograph of 'Younger Basic' dyke cross-cutting Scourian felsic gneisses, east side of Rubha Scarasdail (Scarasdale Point), North Pabbay. (Photo: K.M. Goodenough.)

Immediately south of Rubha Scarasdail (Scarasdale Point) (at NF 886 891) evidence for the $D1_L$ deformation event is found (Graham, 1970, fig. 5, p. 70). Here, a 'Younger Basic' mafic dyke, a branch of the more westerly of the two large dykes mentioned above, contains an internal S1 fabric sub-parallel to its margins (Figure 2.14b). Both S1 and the dyke are folded around an F2 fold. A secondary axial-planar fabric (S2) has developed in the dyke. East of Rubha Scarasdail F2 folds are absent and the 'Younger Basic' dykes are highly oblique to the gneiss foliation. However, the mafic dykes still retain an internal S1 fabric, although $D1_L$ structures are not demonstrable in the host gneisses whose foliation is essentially of Scourian age (Figure 2.14).

Around NF 891 893 the 'Younger Basic' intrusions dip only gently, whereas the gneissose foliation has a steep attitude. Eastwards, these relationships change until at Rubha Bhreinis (NF 901 892) the dip of the 'Younger Basic' dykes is steep and that of the gneissose foliation is nearly horizontal. Graham (1970) ascribed this change to rotation of the two elements during Laxfordian F3 folding, the section effectively transecting part of a broad antiformal core (Figure 2.14a). Traversing south-eastwards along the coast from Rubha Bhreinis the $D2_L$ strain is moderate to low until a zone lying north of Rubh' a' Bhaile Fo Thuath around NF 908 881 is reached, where it increases rapidly. Here, 'Younger Basic' dykes and sheets show tight F2 folds, analogous to those seen on the east side of Bàgh Alairip.

Farther south the transition into the $D2_L$–$D3_L$ high-strain zone, which can be traced across the island from the north coast, is poorly exposed. Graham (1970) carried out a detailed analysis of the deformed lineations on Pabbay and was able to show that the degree of $D3_L$ strain mimics that of $D2_L$, increasingly markedly south-westwards across the transition zone.

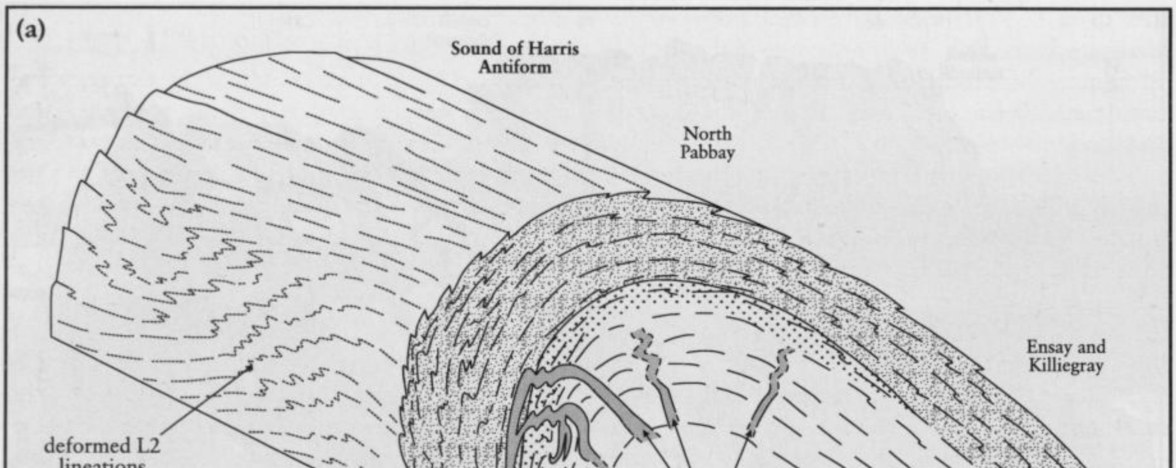


Figure 2.14 (a) Sketch diagram of the Sound of Harris Antiform and the nature of Laxfordian strain (after Graham, 1970). (b) Detailed diagram of weakly deformed 'Younger Basic' dyke.

Interpretation

The grey felsic orthogneisses and the metasedimentary gneisses on Pabbay have not been dated, and hence the ages of their protoliths or their reworking are not known. However, Whitehouse and Bridgwater (2001) have obtained ion-microprobe U-Pb zircon ages from tonalitic felsic gneisses at Loch a Bhàigh in Berneray, which lie along strike from the felsic gneisses of north-east Pabbay. The ages were discordant, and ranged from 2860 Ma to 2740 Ma. The most concordant age, from a finely banded zircon phase, gave a Pb-Pb age of 2834 ± 9 Ma, interpreted as the age of the igneous protolith. Surprisingly, these gneisses show no sign of disturbance to the U-Pb system during Laxfordian times. It is unclear as to whether the metasedimentary rocks link to the Palaeoproterozoic rocks of the Leverburgh and Langavat belts of South Harris (see **Na Buirgh** GCR site report, this chapter), or whether they too are of Archaean age. Lithologically, they lack the more-exotic metalimestones, calc-silicate rocks and graphitic pelites of the Leverburgh Belt, and resemble the metasedimentary rocks of the Uists and Benbecula. The reworking is attributed to the Laxfordian event, as the structures form part of a regional pattern that can be traced on North and South Uist (Graham and Coward, 1973).

The structural variations across the site, as described above, clearly demonstrate that the north-east area of Pabbay is an area of low Laxfordian strain (Figure 2.14). South-westwards there is a rapid transition over some 500 m through a zone of moderate strain into one of high strain that encompasses the remainder of the island. Graham (1970) argued that throughout the island the Laxfordian $D1_L$ strain was low, being largely confined to the development of an internal foliation in the 'Younger Basic' mafic dykes and other bodies. The main agent of reworking was $D2_L$, and it is this episode that effectively superimposed the current strain pattern. $D3_L$ strain, as evidenced by the gentle F3 structures on the north coast, generally mimics the $D2_L$ pattern, increasing markedly to the south-west into the $D2_L$ high-strain zone. Indeed Graham (1970) argued that the distribution of $D3_L$ strain was determined by the $D2_L$ pattern. This is reflected in the regional-scale F3 folds, namely the Sound of Harris Antiform and Berneray Synform (as depicted in Figure 2.11). The former has a wide hinge zone marked by a low degree of Laxfordian reworking; the latter is a tight structure characterized by high degrees of reworking, particularly on its limbs (Graham, 1970; Fettes *et al.*, 1992). The common limb of the fold pair corresponds to the zone of very high strain on Pabbay. Graham has documented a complex pattern of folded L2 lineations in this steep zone, and attributed the geometry to the effects of the $D3_L$ deformation. The more-competent low $D2_L$ strain area of north-east Pabbay controlled the open nature of the F3 antiformal closure and the very high $D2_L$ strain zone formed the locus for high $D3_L$ strain, resulting in the development of the tight synformal closure.

Graham (1970) noted that the change from very high- to very low-strain is near-coincident with the change from the flaggy metasedimentary succession to the felsic orthogneisses. He suggested that it was this competence variation between the two lithologies that controlled the pattern of Laxfordian $D2_L$ strain and ultimately the pattern of $D3_L$ reworking in the region.

Conclusions

The North Pabbay GCR site provides a spectacular demonstration of the nature of Laxfordian reworking in the Outer Hebrides. The reworking affects Scourian orthogneisses, metasedimentary rocks and mafic intrusive rocks of the Palaeoproterozoic 'Younger Basic' Suite.

In the western part of the GCR site the Laxfordian reworking effects and strain are high and the 'Younger Basic' sheets and gneissose foliation are typically sub-parallel. In contrast in the north-eastern corner of Pabbay the Laxfordian effects are weak and 'Younger Basic' dykes markedly cross-cut the Scourian gneissose foliation. Individual 'Younger Basic' dykes can be traced along the section for over 1 km from areas where they are markedly discordant to where they are more strongly foliated, strained and only slightly discordant to the gneissose banding. This transition takes place over a *c.* 500 m-wide zone, coincident with the lithological change from banded Archaean felsic and mafic orthogneisses in the north-east to dominantly metasedimentary rocks in the south-west. The metasedimentary succession has acted in a less-competent manner compared to the orthogneisses and forms a locus for both the $D2_L$ and the subsequent $D3_L$ Laxfordian deformation episodes and related metamorphic effects. This illustrates the way in which an inherent weakness and lithological boundary within a gneissose basement terrain can become a focus for subsequent tectonothermal reworking.

The site is one of national importance and provides a coherent section where Laxfordian processes and structures can be demonstrated and further studied.

NORTH UIST COAST (NF 738 767–NF 729 756, NF 727 755–NF 717 731, NF 714 729–NF 706 713)

J.R. Mendum

Introduction

The *c.* 6.5 km-long coast section in the north-west part of North Uist between Hogha Gearraidh (Hougharry) in the south and Caisteal Odair in the north provides a well-exposed oblique transect through folded Scourian felsic gneisses and 'Older Basic' and 'Younger Basic' mafic dykes, sheets and irregular bodies. Minor occurrences of metasedimentary rocks also occur. The rocks have been reworked during Laxfordian tectonometamorphic events. A complex pattern of folds and strain variation has resulted, dependent largely on the nature and geometry of the pre-existing elements of the Lewisian gneisses. The 'Younger Basic' bodies are now mainly amphibolites, but in rare instances the larger mafic bodies retain granulite-facies mineralogies. In these mafic bodies, shear zones are developed that have been the subject of analysis to determine amounts of strain and relative movement involved (Ramsay and Graham, 1970).

The area contains two main types of felsic gneiss: the typical white to grey, banded tonalitic to granodioritic orthogneiss, and a pink to pale-grey granitic orthogneiss. Graham (1970) referred to them as 'Rough' and 'Smooth' gneisses respectively, reflecting their coastal weathering characteristics. Their distribution and that of the mafic rocks is shown on Figure 2.15. The abundant mafic rocks are mostly members of the Palaeoproterozoic 'Younger Basic' Suite, originally metadolerites and metagabbros. As Laxfordian strains are commonly high, most mafic bodies are parallel or sub-parallel to the gneissose banding. They range from a few centimetres up to 100 m wide, and now are generally amphibolites. However, the two thickest units, the Hoglan and Hosta amphibolites that occur north-west of Tigh a' Ghearraidh, are both finely striped, partly garnetiferous, planar subvertical bodies that are interpreted as part of the Archaean 'Older Basic' Suite. Between the two bodies are granitic gneisses and metasedimentary schists and gneisses, with interbanded mafic and ultramafic bodies and layers. The metasedimentary rocks include quartzites, semipelites and iron-rich cherts. Metasedimentary rocks also crop out at Bàgh Scolpaig where anthophyllite-bearing quartzose gneiss is recorded.

The low cliffs and intervening sandy bays provide clean and accessible exposures of variable orientation, which facilitate detailed analysis of the structural pattern. The area lies on the complex western limb of a large NW-plunging Laxfordian F3 asymmetrical antiform that encompasses the whole of North Uist and whose hinge zone lies at the northern end of the coast section (Figure 2.11). The hinge of the complementary synform lies at the south-western end of the section. The fold axial planes trend north-west and dip subvertically.

Jehu and Craig (1926) briefly described the geological aspects of the area, noting the presence of pink 'acid' gneisses and the abundant hornblende 'gneiss' bodies. R.H. Graham carried out a detailed structural analysis of the coast section as a major part of his PhD studies (Graham, 1970), and subsequently the hinterland area was mapped by the Geological Survey as part of the regional coverage of the Outer Hebrides (Fettes *et al.*, 1992). The information in this account is taken mostly from these last two sources.

Description

The indented coast section consists of low cliffed headlands and rocky foreshores separated by small shell-sand beaches. The cliffs rise to some 25 m high north of Scolpaig. At Rubha Ghriminis (Griminish Point) natural arches and geos have developed as a result of enhanced marine erosion along broken fault-zones, and a large blowhole, Sloc Rubha, is present. The normally prevailing westerly wind and salt spray naturally clean the section and also etch the various lithologies to different degrees. Wide areas of clean glaciated bedrock are common in the immediate coastal hinterland, but are covered by windblown shell sands and limited machair in the southern part of the section.

Lithologies

The typical felsic gneiss is a white- to pale-grey and fawn-weathering, thin- to medium-banded, coarse-grained quartzofeldspathic rock composed of essential quartz, plagioclase feldspar and biotite, commonly with subsidiary hornblende. Subsidiary interbanded mafic amphibolite layers, pods and lenses are very common in the gneisses. Early-formed, mainly concordant, thin quartz-feldspar pegmatite veins and pods are also present. In places the pegmatite veins exhibit folds that pre-date the Laxfordian deformation. This typically banded felsic and mafic gneiss (the 'Rough' gneiss of Graham, 1970) is interspersed with zones of more-homogeneous, pink-weathering, foliated, medium-grained, but only weakly banded gneiss (the 'Smooth' gneiss of Graham, 1970). This pale-grey to pink granitic gneiss is composed of

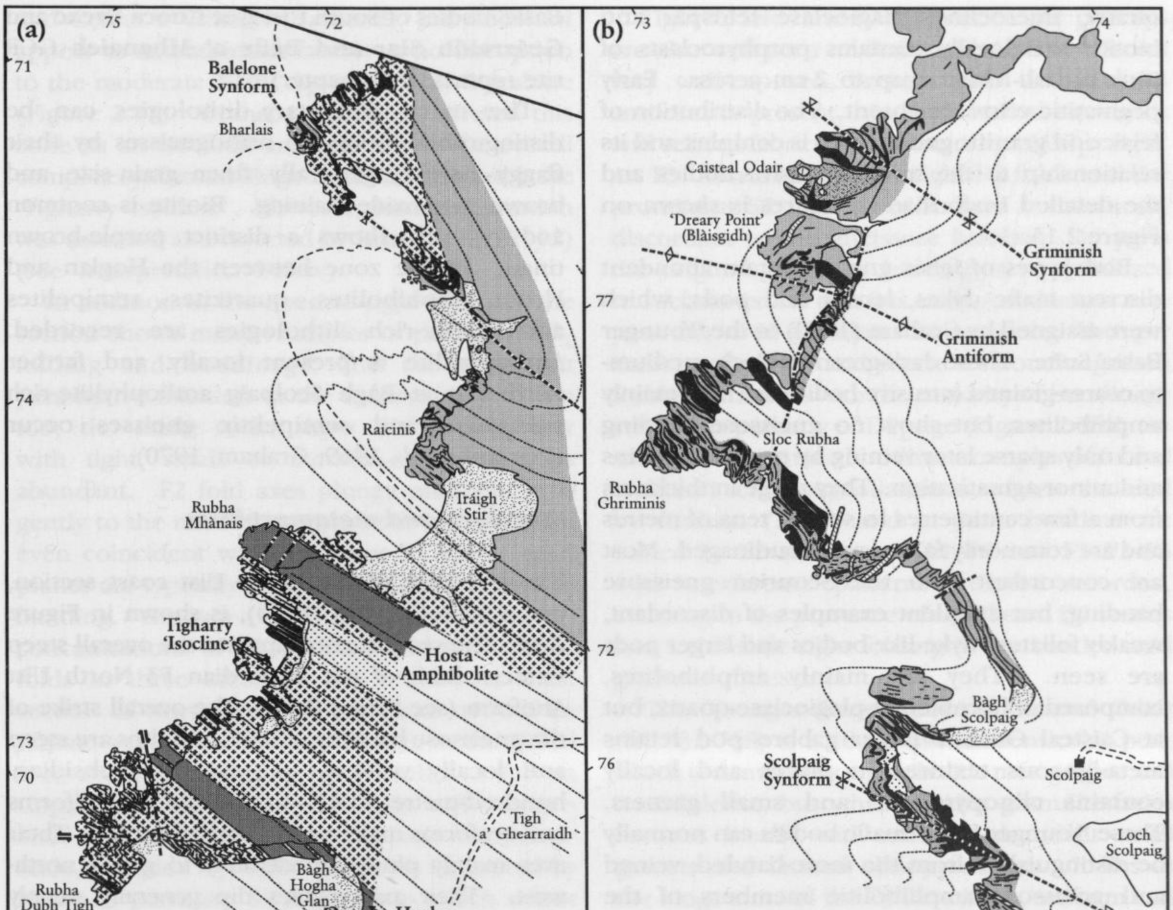


Figure 2.15 Geological map of the North Uist Coast GCR site showing the detailed lithology and structure. After Graham (1970).

quartz, microcline, plagioclase feldspar and biotite and locally contains porphyroclasts of pink potash-feldspar up to 2 cm across. Early pegmatitic veins are absent. The distribution of felsic and granitic gneiss types is complex and its relationship to the mafic intrusive bodies and the detailed Laxfordian structures is shown on Figure 2.15.

Both types of felsic gneiss contain abundant discrete mafic dykes, lenses and pods, which were assigned by Graham (1970) to the 'Younger Basic' Suite. These dark-green to black, medium- to coarse-grained intrusive bodies are now mainly amphibolites, but show no gneissose banding and only sparse later veining by pegmatitic veins and minor agmatization. They range in thickness from a few centimetres to several tens of metres and are commonly folded and boudinaged. Most are concordant with the Scourian gneissose banding, but excellent examples of discordant, weakly foliated, dyke-like bodies and larger pods are seen. They are mainly amphibolites, composed of hornblende-plagioclase-quartz, but at Caisteal Odair a larger gabbro pod retains meta-igneous textures in places and locally contains clinopyroxene and small garnets. These 'Younger Basic' mafic bodies can normally be distinguished from the more-banded, veined and gneissose amphibolitic members of the Archaean 'Older Basic' Suite except where Laxfordian deformation and recrystallization are very strongly developed. Figure 2.15 shows the distribution of the main mafic units on the coastal section.

Near the south end of the coast section in Bàgh Hogha Glan (Hoglan Bay) (NF 7070 7234) and on Rubha Mhànais (NF 7115 7311) two *c.* 140 m-wide amphibolitic metabasic bodies, the Hoglan and Hosta amphibolites, crop out (Graham, 1970). They are both subvertical, exhibit strong planar and linear fabrics, and include quartzofeldspathic and granitic gneiss layers and some metasedimentary lithologies. In parts they show a fine-scale but marked compositional banding, which is defined locally by garnetiferous layers. Pyrite- and chalcopyrite-rich bands are common in the amphibolites. They lie within a zone of high Laxfordian strain and both the mafic bodies and their internal banding and fabrics are parallel to banding and foliation in the adjacent felsic gneisses. The two bodies can be traced along strike to the SSE for some 6 km, and here too mineralogical banding is seen. They are similar to the banded 'Older Basic' bodies of South Uist (see **Cnoca Breac** and **Gearraidh Siar and Baile a' Mhanaich** GCR site reports, this chapter).

The metasedimentary lithologies can be distinguished from the orthogneisses by their flaggy nature, generally finer grain-size and brown iron-oxide staining. Biotite is common and typically shows a distinct purple-brown tinge. In the zone between the Hoglan and Hosta amphibolites, quartzites, semipelites and pyrite-rich lithologies are recorded. Anthophyllite is present locally, and farther north-east at Bàgh Scolpaig anthophyllite-rich psammitic and semipelitic gneisses occur (Coward *et al.*, 1969; Graham, 1970).

Structure and metamorphism

The structure of the North Uist coast section, taken from Graham (1970), is shown in Figure 2.15. The section encompasses the overall steep western limb of the Laxfordian F3 North Uist Antiform (see Figure 2.11). The overall strike of the gneissose banding is NNE, and dips are steep and locally vertical. A series of subsidiary hundred-metre- to kilometre-scale F3 antiforms and synforms make up the overall profile. Their axes mainly plunge moderately to gently north-west. Their axial planes dip generally steeply (commonly at > 75°), with the dip direction variable from ENE and north-east through the vertical to WSW and south-west. Graham (1970) named the major structures, from south to north, the 'Hougharry Synform and Antiform', the 'Hoglan Synform', the 'Tigharry 'Isocline'', the 'Balelone Synform', the 'Cliffs Antiform', the 'Scolpaig Synform', and the 'Griminish Antiform and Synform'. Generally, the nature, geometry and thickness of the mafic bodies define the F3 fold profiles. The medium- and large-scale F3 folds are commonly spectacularly displayed in the coastal cliff-sections, for example in the vertical cliffs immediately west of Loch Sgileabhat at NF 7225 7481. At the southern end of the section by Hogha Gearraidh (Hougharry) the regional strike turns from NNE to ENE and overall dips are moderate to the north and north-west as they are over much of North Uist.

The subvertical zone around Tigh a' Ghearraidh (Tighgarry), defined by the lineated, foliated and highly strained Hoglan and Hosta amphibolites, is unusual in that it does not fit easily into the overall structural profile. The zone can be traced south-eastwards to Balranald and Ceann a' Bhàigh (Bayhead), but does not appear to extend much farther as no disruption to the moderate NNW dip is seen on Baleshare (Figure 2.11). Graham (1970) interpreted this zone as an isoclinal antiform within an overall complex synformal hinge zone, and termed it the 'Tigharry 'Isocline''. However, this interpretation was assessed and rejected by Fettes *et al.* (1992) (see 'Interpretation' below).

In addition to the open to tight F3 folds, the section shows many examples of pervasive $D2_L$ folding and boudinage, and the dominant penetrative foliation in the section is S2. Here too, the mafic rocks show the folding best with tight, small- to medium-scale examples abundant. F2 fold axes plunge moderately to gently to the north-west, generally close to, and even coincident with, the later F3 axes. Axial planes are typically sub-parallel to the gneissose banding. Graham (1970) noted that there are concentrations of F2 medium- and minor-scale folds in three areas on the north-west coast section of North Uist. These occur at Aird an Rùnair, south-west of the GCR site, in the cliffed area west of Loch Sgileabhat (Bharlais to Port na Copa), and on Rubha Ghriminis. The larger-scale $D2_L$ pattern is one of mainly kilometre-scale, complex S-profile tight folds separated by zones of pervasive S2 foliation in which minor F2 folds are only present in parts.

Good examples of F2 folds defined by mafic sheets and dykes were recorded by Graham (1970) from the 10–15 m-high cliffs around Geodha nan Colman (NF 7213 7458). These F2 folds occur in the simple open hinge zone of the F3 Cliffs Antiform. Farther north around NF 7235 7506 F2 folds are locally refolded by small- to medium-scale F3 open to close folds giving rise to complex interference patterns. On the west side of the Raicinis peninsula at NF 7173 7330 an F2–F3 interference pattern defined by amphibolitic 'Younger Basic' sheets can be mapped out over some 60 m on the foreshore. These structures lie on the south-western limb of the F3 Balelone Synform close to the fold hinge. Metabasic sheets define tight F2 folds with axial planes orientated sub-parallel to the gneissose banding. These are refolded by moderately N-plunging, open F3 folds with sub-vertical N-trending axial planes. In parts of this area minor F2 structures fold a pre-existing foliation/schistosity in the amphibolitic metabasic sheets. Graham (1970) assigned this fabric to a Laxfordian $D1_L$ event.

Tight F2 folds and F2–F3 interference patterns are also well seen on Rubha Ghriminis. Here a very well-exposed, broad, open 'box-like' F3 antiform is present, but the detailed structures and related fabrics are all basically of $D2_L$ origin. An F3 monocline refolds tight F2 folds and the prominent S2 fabric, which here is commonly discordant to the gneissose banding. In parts the original gneissose banding is recrystallized to such an extent that it is transposed into a new penetrative S2 foliation. Many of the 'Younger Basic' mafic dykes and sheets are boudinaged on Rubha Ghriminis with the majority of boudinage structures patently of $D2_L$ age (Figure 2.16a). In some of these mafic boudins, examples of folded earlier S1 schistosity/foliation have been recorded by Graham (1970) and in parts boudins are folded by F2 structures. F1–F2 and F1–F2–F3 fold interference patterns are also recorded, attesting to the presence of significant D1 strains and small-scale tight folding in the banded acid gneisses of this area.

The 'Younger Basic' body on Caisteal Odair (NF 732 768) is a 40–50 m-wide lenticular pod, which is dominantly amphibolitic metagabbro and metadolerite, but which retains granulite-facies textures locally and contains abundant small garnets and limited clinopyroxenes. It lies in the hinge zone of the F3 Griminish Antiform and is a region of low $D2_L$ strain. Its margins are moderate to strongly foliated and amphibolitic and it is traversed by a series of small shear-zones (Ramsay and Graham, 1970) (Figure 2.16b). Other examples of relict granulite-facies mineralogies are found within the larger 'Younger Basic' body that underlies the hills of Beinn Riabhach (NF 740 744) and Carra-crom (NF 734 735) (Fettes *et al.*, 1992).

Interpretation

The main protolith of the grey and white, banded felsic gneisses was a complex sequence of granodiorite and tonalite sheets intruded at moderate to deep crustal levels. Although now strongly reworked by the Laxfordian deformational and metamorphic episodes, isotopic data suggest that the igneous protoliths to the felsic gneisses are Archaean in age (Moorbath *et al.*, 1975; Whitehouse, 1990b; Friend and Kinny, 2001; Mason *et al.*, 2004a; Kelly *et al.*, 2008). Within these gneisses are several early mafic bodies, termed the 'Older Basics' by Fettes *et al.* (1992). Some of the

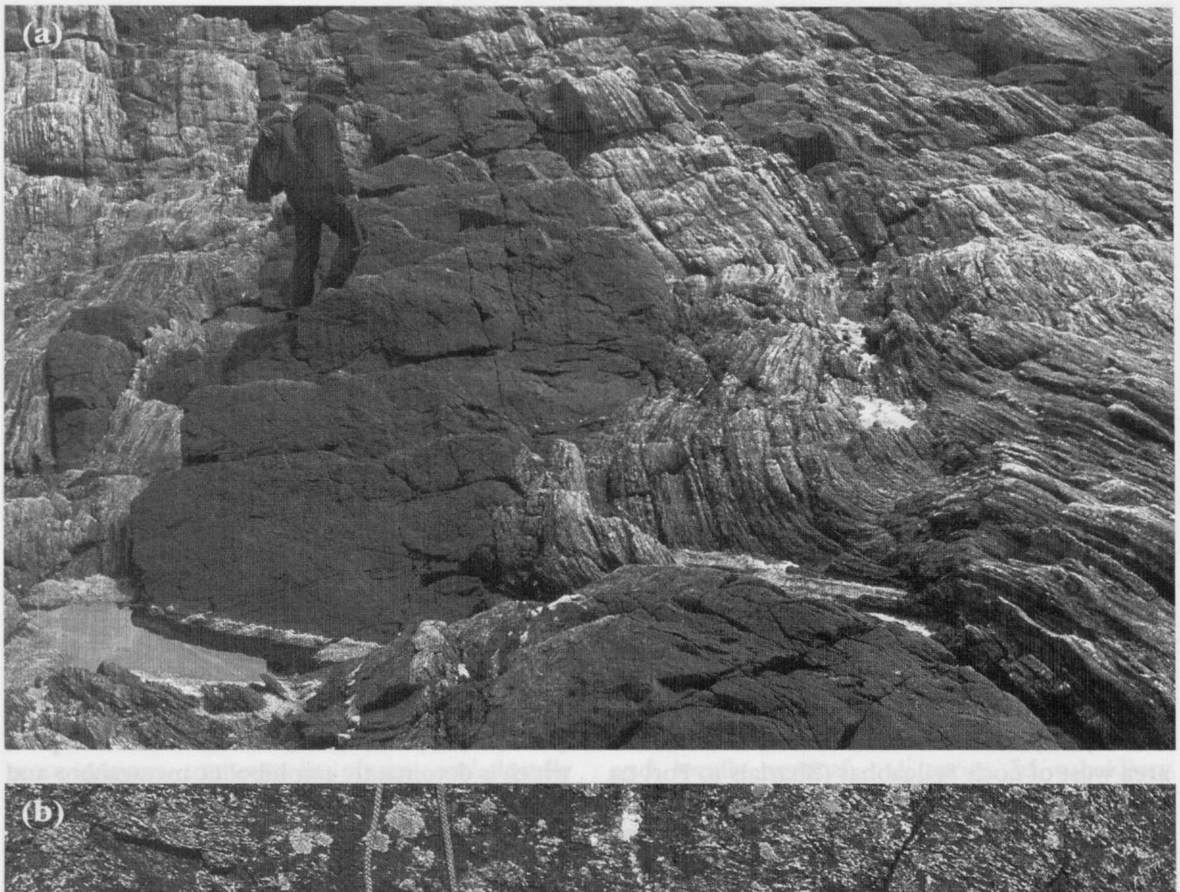


Figure 2.16 (a) 'Younger Basic' dykes and pods at Rubha Ghriminis (Griminish Point). Note that although the dykes are boudinaged, foliated and now amphibolites, they cross-cut the prominently banded Archaean felsic and mafic gneisses. (b) Small shear-zone in granulite-facies 'Younger Basic' body at Caisteal Odair. Relative dextral movement across the shear zone can be inferred from the foliation traces. The hand lens is 6 cm long. (Photos: J.R. Mendum.)

larger bodies were originally mineralogically and compositionally banded (cumulate banding), with the geochemical variations, notably in Fe and Al, later reflected in the relative abundance of metamorphic plagioclase, garnet, hornblende and more rarely pyroxene. Although now strongly deformed and pervasively metamorphosed under amphibolite-facies conditions during Laxfordian reworking, the Hoglan and Hosta amphibolites still show well-developed fine-scale mineralogical banding and are attributed to the 'Older Basic' Suite. Early mafic rocks also occur as thinner amphibolite pods or bands within the acid gneisses. They represent Archaean basic sheets, dykes and irregular pods, which were either intruded into the tonalite and granodiorite protolith or, by analogy with rocks in west Greenland, were incorporated as xenoliths or screens (see Fettes *et al.*, 1992). Although some of the mafic bodies were probably intruded into the felsic intrusions, the bulk of the 'Older Basic' bodies are interpreted as included screens and hence as pre-existing older mafic material.

Metasedimentary lithologies are spatially associated with the larger 'Older Basic' bodies, and Fettes *et al.* (1992) have discussed the nature and wider significance of this relationship. Metasedimentary rocks are not abundant in the North Uist coast section and here they may represent xenolithic or hornfelsed material, preserved adjacent to the 'Older Basic' intrusions as suggested by Coward *et al.* (1969). They are problematic in that they were undoubtedly originally deposited at the Earth's surface, yet are interleaved with meta-igneous rocks that appear to have been emplaced at deep crustal levels (> 15 km). They are assigned to the Archaean, in contrast to the wider, more-coherent belts of metasedimentary rocks in the Outer Hebrides, for example the Leverburgh and Langavat belts of South Harris, which have been shown to have a younger Palaeoproterozoic age. These thicker Palaeoproterozoic belts have been juxtaposed against the older Archaean gneisses by later Proterozoic orogenic events (Friend and Kinny, 2001).

The granitic or 'Smooth' gneisses of Graham (1970) represent late-Scourian granite bodies that intruded the earlier gneissose complex, probably at around 2600 Ma (Fettes *et al.*, 1992). They contain few included mafic lenses or pegmatitic veins and pods, in contrast to the earlier banded felsic 'Rough' gneisses, which are coarser grained, lithologically well banded, contain abundant thin mafic bands and lenses, and are cross-cut by numerous pegmatitic veins and lenses. The granitic 'Smooth' gneisses are foliated medium-grained sheets that range from *c.* 1 m up to several tens of metres wide. Porphyritic examples are not common in this coastal section, but are found within a 2–4 km-wide zone that roughly 'tracks' the north and west coasts and hinterland of North Uist (Institute of Geological Sciences, 1981). Within this zone and farther south around Balranald and Ceann a' Bhàigh (Bayhead), foliated, coarser-grained, porphyritic granites form larger ovoid intrusive bodies, typically 600 m to 1 km long, but exceptionally up to 3.5 km long and 500 m wide (Fettes *et al.*, 1992).

The bulk of the mafic rocks in the GCR site belong to the 'Younger Basic' Suite, a series of irregular sheets and dykes that post-date the late Archaean granites and related pegmatites. They are thought to be equivalent to the Scourie dykes of the mainland, which were mostly emplaced around 2420 Ma and 2000 Ma (Heaman and Tarney, 1989). They were intruded into the gneisses at crustal depths of some 20 km and equilibrated to the ambient metamorphic conditions. Hence they contain mineral assemblages typical of middle- to upper-amphibolite- and, locally, even granulite-facies conditions. Laxfordian reworking has largely retrograded these assemblages to lower- and middle-amphibolite facies but at Caisteal Odair relict granulite-facies assemblages still remain.

Laxfordian deformation is generally pervasive in this part of the Outer Hebrides, although the section does show excellent examples of local strain variation and different structural styles. The coast section is situated on the highly folded short limb of a major F3 asymmetrical fold, the North Uist Antiform. F3 axial planes mainly trend north-west and dip steeply, and the fold axes and attendant lineations plunge consistently to the north-west at moderate to low angles. Graham (1970) produced a structural synthesis of the fold geometry along the coastal section and distinguished elements of three major fold/deformation phases. He also noted the way in which competence differences in the gneisses were reflected in the style and tightness of the Laxfordian structures. During deformation the metabasic rocks acted as more-competent sheets or dykes, and as a result were folded and boudinaged. Coward *et al.* (1970) showed how the large-scale Laxfordian structures relate to the variable regional strain pattern and that most F3 folds have broad open antiformal zones but restricted and tight 'pinched-in' synforms.

Graham (1970) showed that F1 fold structures are rare and confined to minor tight folds of felsic veins and thin metabasic units in the hinge zones of F2 folds such as the Griminish and Cliffs antiforms. However, F2 folds locally refold a penetrative planar S1 fabric in amphibolitic 'Younger Basic' sheets and pre-$D2_L$ boudinage is also seen. $D2_L$ structures and fabrics are more abundant and pervasive, and S2 is the main gneissose fabric in most parts of the section. Graham (1970) deduced that prior to the F3 folding the F2 structures consisted of a few large-scale asymmetrical S-profile folds with near-planar long limbs and tightly folded short limbs. They are coaxial with the later F3 folds, but their axial planes originally trended north-east and dipped moderately to the north-west.

The F3 fold geometry is represented on Figure 2.15. On a large scale it is controlled by the gross Archaean structural and lithological variations in the Lewisian gneisses of North Uist and by the pre-existing F1 and particularly F2 fold pattern. On a smaller scale (metres to kilometres) Graham (1970) documented numerous examples mainly showing how the abundance and thickness of amphibolites (mainly 'Younger Basics') control the amplitude and tightness of the F3 fold pattern. In parts the $D2_L + D3_L$ strain is very high and the Archaean elements are highly attenuated. Graham (1970) obtained minimum $D3_L$ strain values from the measurements on deformed thin quartz-feldspar pegmatite veins that cut amphibolite from the Tigharry 'Isocline'. The veins cross-cut the earlier Laxfordian S2 fabric. Strain ellipse X: Y: Z values of 18: 6: 1 were obtained in the more-deformed parts, implying Laxfordian shortening of the succession here to *c.* 21% of its pre-deformation thickness.

In the hinge zones of the Hougharry and Hoglan synforms Graham (1970) recorded outcrop-scale examples of quartzofeldspathic gneiss lamellae that breach the amphibolitic mafic sheets which define the folds, resulting in geological 'hernias', which he termed 'shoot-through' structures. In effect the mafic sheet or dyke is boudinaged and gneissose material has flowed into the neck. In some examples quartz-feldspar pegmatite pods are also present. Graham interpreted the Hoglan and Hosta amphibolites as the two limbs of a much larger-scale isoclinal 'shoot-through' structure (F2 + F3). However, later mapping showed that the two amphibolites extend for at least 7 km to the south-east, no F2 or F3 hinge zone could be recognized, and the purported change in F3 minor fold vergence across the structure could not be substantiated (Fettes *et al.*, 1992). More probably, this zone represents an attenuated, highly sheared part of the large-scale F3 fold limb, possibly focused along an earlier Archaean and Laxfordian $D2_L$ lineament.

The shear zones in the large metabasic body at Caisteal Odair illustrate the inhomogeneous nature of the Laxfordian strain in this more-anhydrous lithology. D3 strain is very low in this fold hinge zone and the more-penetrative D2 strain has focused along certain zones giving rise to a three-dimensional pattern of anastomosing shear-zones. In the shear zones a new, lower amphibolite-facies, hornblende-plagioclase-quartz foliation is developed. Measurement of the variable angle between the internal fabric and the shear-zone margin can be used to assess the amount of simple shear (non-coaxial plane strain) across the shear zone, to give an estimate of the total amount of translation. Ramsay and Graham (1970) used this locality in their studies of strain variations in shear belts and it is cited as a 'classic' example in structural textbooks (e.g. Ramsay and Huber, 1983).

Conclusions

The North Uist Coast GCR site is one of national importance and provides a readily accessible, clean, etched and coherent section through large- and small-scale Laxfordian folds. The strain variations are already portrayed in various structural textbooks and the area remains an excellent site for teaching and for further detailed structural and metamorphic studies.

The site exposes a two- and locally three-dimensional oblique section through dominantly felsic and mafic orthogneisses formed from igneous intrusions during the Scourian event (*c.* 2850–2650 Ma). The gneisses here include the older metasedimentary units, and 'Older Basic' banded mafic bodies, which were intruded by late-Scourian granites (*c.* 2550 Ma), and abundant 'Younger Basic' mafic sheets, dykes and pods (*c.* 2420 Ma). All these elements that make up the Lewisian Gneiss Complex in North Uist were strongly folded and metamorphosed during the later multi-phase Laxfordian event (*c.* 1850–1600 Ma). The heterogeneity has resulted in the different Laxfordian fold patterns and strain variations seen in the section.

The 'Younger Basic' intrusive bodies, now dominantly amphibolites, generally lie subparallel to the gneissose banding. They have acted as more-competent units than the surrounding dominantly felsic gneisses under the amphibolite-facies metamorphic conditions prevailing at the time of Laxfordian deformation. It is the size and abundance of these mafic bodies that mainly control the resultant fold geometry and strain variations now seen along the section.

The coastal profile lies on the western short limb of a large Laxfordian third phase ($D3_L$), S-profile fold structure, the North Uist Antiform, and extends south-west to the complementary synformal hinge zone. The axes of these major F3 folds, and the related smaller kilometre- and metre-scale structures, all plunge moderately to gently to the north-west. Their axial planes trend north-west or NNW and dip steeply. The effects of earlier penetrative second phase ($D2_L$) deformation are apparent in a regionally developed fabric, minor folds and boudinage. Earlier D1 effects are limited to a locally developed planar fabric in some amphibolitic bodies, some tight minor folding, and boudinage.

GEARRAIDH SIAR (GARRY-A-SIAR) AND BAILE A' MHANAICH (BALIVANICH), BENBECULA (NF 759 526–NF 760 535, NF 761 542–NF 767 555)

D.J. Fettes

Introduction

The two coastal sections of Gearraidh Siar (Garry-a-siar) and Baile a' Mhanaich (Balivanich) on the west coast of Benbecula together comprise one of the best-documented and important geological sites in the Outer Hebrides. These low-lying rocky coastal exposures of Lewisian gneisses contain many members of the 'Younger Basic' Suite, mainly metadolerite dykes, which exhibit a wide variety of Laxfordian reworking effects. In the Gearraidh Siar section and the southern half of the Baile a' Mhanaich section the 'Younger Basic' dykes are little deformed and generally show a high degree of discordance reflecting relatively low levels of Laxfordian reworking. In contrast, in the northern half of the Baile a' Mhanaich section the dykes are thoroughly deformed and are generally concordant, reflecting high levels of Laxfordian strain. The change from the area of low strain to that of high strain occurs over about 1 m and can be observed on the ground.

The area of low Laxfordian reworking corresponds approximately to the broad antiformal hinge area in an anticline–syncline pair of some 4 km wavelength. These Laxfordian F3 structures fold the regional gneissose banding (Coward, 1973a,b). The folds are open to tight with upright axial planes and moderately NW-plunging axes. At the northern end of the Baile a' Mhanaich section an area of high strain lies in the core of the tight synform. The fold pair lies west of the main antiformal structure that governs the overall structural pattern on Benbecula (Coward, 1973b; Fettes *et al.*, 1992). The structural detail provided by the Gearraidh Siar and Baile a' Mhanaich sections, both on a regional scale, and along individual dykes, has allowed researchers to document the nature and variety of the Laxfordian event and of its component phases as well as pointing to the factors that control the pattern of deformation. These studies have provided an important basis for interpreting the regional patterns of Laxfordian reworking.

The sections also provide excellent examples of late-Laxfordian pegmatitic granite veins, which cut across the variously deformed 'Younger Basic' dykes and main Laxfordian structures and thus mark the end of the main Laxfordian events. Also present in the area are rare examples of the late-Scourian microdiorite sheets, and the only documented occurrence of a post-Laxfordian microdiorite dyke.

Although Jehu and Craig (1926) mapped the west coast of Benbecula, the first detailed work on the Gearraidh Siar and Baile a' Mhanaich coast sections was carried out by Dearnley and Dunning (1968). They studied the Laxfordian effects on the 'Younger Basic' dykes, and documented the variety of structural complexity and the associated metamorphism. Subsequently, Coward (1973a) carried out a detailed structural analysis of the sections, and Coward *et al.* (1970), Coward (1973b) and Fettes *et al.* (1992) have all discussed the regional context. The present account draws on these references and also on unpublished data held by the British Geological Survey in Edinburgh.

Description

The two coastal sections lie mostly in the intertidal zone on the westernmost part of Benbecula (Figure 2.17). The southern section runs from NF 760 535 around the headland of Gearraidh Siar to NF 760 526 and is separated from the Baile a' Mhanaich section to the north by the small sandy bay of Culla. The northern section extends from Quirnish (NF 757 544), north and then east for some 2 km to the fringes of the small town of Baile a' Mhanaich (NF 770 555). Both sections are backed by storm beaches and sandy machair, and consist of low rocky outcrops, which provide almost continuous exposure except where interrupted by small inlets of shingle and sand. The exposure may extend west for up to 100 m from the shoreline at low tide. Because of its low-lying nature the sand and shingle banks do shift over time and alter the detailed pattern of exposed bedrock.

Gearraidh Siar (Garry-a-siar) section

The Gearraidh Siar section consists predominantly of grey to white granodioritic and tonalitic Lewisian gneisses. These are banded, but relatively homogeneous, coarse- to medium-grained rocks, with the gneissose banding defined by the quartzofeldspathic and biotite- and hornblende-rich layers. The banding and concordant Scourian fabrics vary in strike from

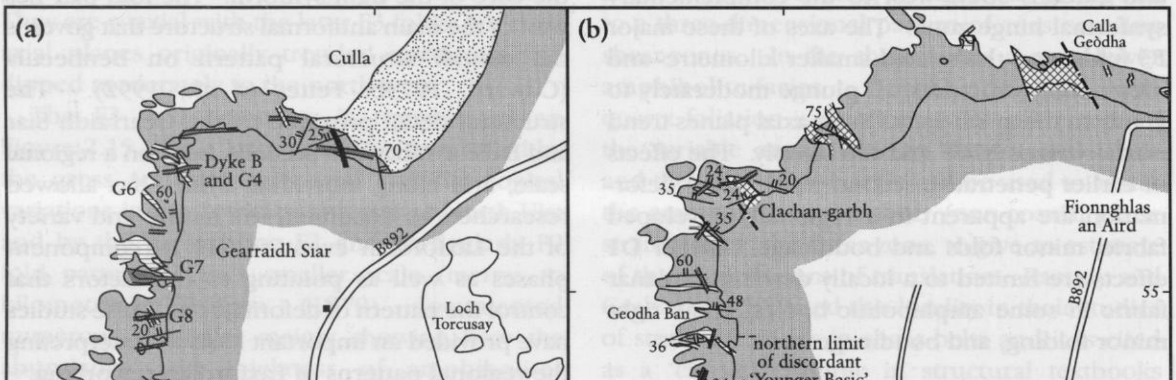


Figure 2.17 Simplified geological maps of Gearraidh Siar (Garry-a-siar) and Baile a' Mhanaich (Balivanich), Benbecula. Based on Dearnley and Dunning (1968), Coward (1973a) and BGS mapping. (G4, etc. – locality numbers from Coward (1973a); Dyke A, etc. – locality from Dearnley and Dunning (1968); see text for details.)

NNW to north and north-east and dip generally at 50°–60° towards the west. Only minor 'Older Basic' bodies occur in the section. However, the gneisses contain many mafic dykes of the 'Younger Basic' Suite, mainly metadolerite, which are cut by a suite of late-Laxfordian pegmatitic granites. The original orientation of the dykes was predominantly north-west but a few lay at high angles to this trend. They vary in width from a few centimetres up to *c.* 25 m and can be traced for up to 100 m across the exposed section. Many of the dykes have small offshoots and apophyses that may lie at high angles to the trend of their parent dyke. The degree of reworking shown by the dykes varies considerably (Figure 2.18). Dearnley and Dunning (1968) erected four categories to define the deformational state, namely:

- type-1, dykes and small apophyses completely undisturbed and cutting sharply across the gneissose foliation;
- type-2, dykes showing signs of deformation but with the main contacts and apophyses still cross-cutting;
- type-3, dykes and offshoots locally parallel to the gneissose foliation with some folding and boudinage;
- type-4, dykes strongly deformed, commonly boudinaged and migmatized, and almost wholly concordant to the gneissose foliation.

Dearnley and Dunning (1968) also examined the mineralogy of the dykes. They showed that the cores of the bigger dykes exhibit granulite-facies assemblages characterized by garnet + clinopyroxene, whereas the margins and smaller dykes contain amphibolite-facies assemblages of hornblende + plagioclase. The former they attributed to an early-Laxfordian granulite-facies metamorphism; the latter to a later Laxfordian retrogressive phase.

Coward (1973a) related the Laxfordian reworking to four phases, $D1_L$–$D4_L$. He documented many examples of multi-phase deformation and demonstrated that the degree of reworking can vary from virtually absent to very high across transitional zones as narrow as 0.5 m. He showed that the deformation associated with his first and third phases is relatively intense but confined to narrow zones whereas the second phase also resulted in a more-widespread but moderate style of reworking. He regarded the amphibolite-facies assemblages as syntectonic and closely related to the deformational phases.

Throughout the section the many members of the 'Younger Basic' Suite illustrate this variation in the degree of reworking. Although regionally the degree of Laxfordian reworking is low, some narrow zones of high strain do occur. Strongly discordant and largely undeformed mafic dykes may exist within metres of concordant and deformed dykes. In some cases large dykes may be boudinaged although their apophyses are largely undeformed; in other cases the reverse occurs. The following localities illustrate these points, although many other examples also occur along the section (Figures 2.17, 2.18).

At NF 756 535 a 2 m-wide vein of bright-red pegmatitic granite cuts two mafic dykes. This is locality G4 of Coward (1973a, fig. 6) and Dyke B of Dearnley and Dunning (1968, fig. 6). The two dykes are sub-parallel and trend roughly north-west; they are boudinaged and weakly folded with a locally prominent lineation that plunges 20°–40° to the north and NNW. The dykes are discordant to the general trend of the gneissose foliation, but locally the foliation has been rotated into concordance with their margins. There are a number of small apophyses, which show a range of fold styles. The cores of the dykes have garnet + pyroxene-bearing assemblages, but the margins are amphibolitized. These dykes have been subject to a moderate degree of reworking and were classified as type-3 by Dearnley and Dunning (1968).

At NF 756 535 an undeformed, markedly cross-cutting mafic dyke with numerous unmodified apophyses is exposed. Some 50 m to the west of this locality a weakly folded mafic dyke still shows narrow, largely undeformed, cross-cutting apophyses (G6 of Coward, 1973a). At NF 756 533 a 1–1.5 m-thick Laxfordian pegmatitic granite vein cuts refolded isoclinal folds of apophyses on the north-east side of a large mafic dyke (G7 of Coward, 1973a, fig. 5). At NF 756 532 a late-Laxfordian pegmatitic granite vein cuts a narrow zone of intensely deformed dykes where the dykes and their apophyses have been pulled into conformity with the gneissose foliation (G8 of Coward, 1973a, fig. 7).

At NF 756 530 a 2 m-thick vein of pink pegmatitic granite with a core of white quartz cuts a strongly discordant 3 m-wide mafic dyke. This is locality G12 of Coward (1973a) and Dyke A of Dearnley and Dunning (1968, fig. 4). The mafic dyke is *c.* 10 m wide and can be traced for

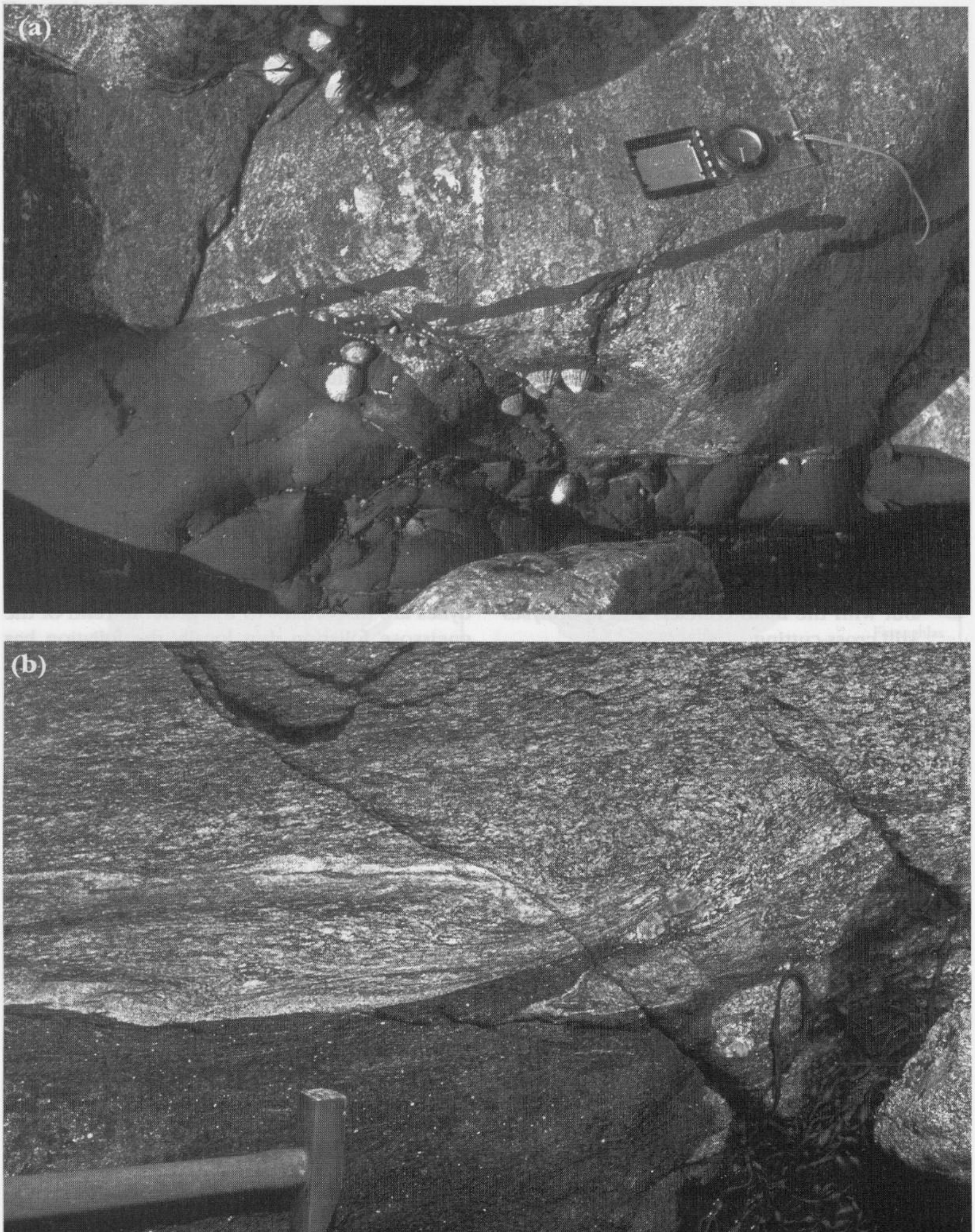


Figure 2.18 Gearraidh Siar. (a) Discordant 'Younger Basic' dyke apophyses unaffected by Laxfordian strain. The compass is 18 cm long. (b) Foliated 'Younger Basic' dyke apophyses in an area of moderately strong Laxfordian strain. The hammer head is 14 cm long. (Photos: J.R. Mendum.)

nearly 100 m. It lies at a high angle to the gneissose foliation and shows virtually no trace of Laxfordian deformation as evidenced by a lack of internal planar fabrics and small undeformed and cross-cutting apophyses. The dyke is largely composed of garnet + clinopyroxene-bearing assemblages with amphibolite-facies assemblages confined to narrow marginal zones. Dearnley and Dunning classified this dyke as type-1. Some 80 m to the SSW, near the low-tide mark at NF 7557 5291, a concordant to slightly discordant thin microdiorite sheet is tightly folded and locally podded. It lies adjacent to thin, folded but markedly discordant mafic dykes (G13 of Coward, 1973a). The microdiorite sheet is thought to be late-Scourian in age.

At NF 758 526 an irregular *c.* 1.5 m-wide pegmatitic granite vein with a quartz core cuts a 5 m-wide mafic dyke. This is locality G15 of Coward (1973a) and Dyke C of Dearnley and Dunning (1968, fig. 5). The dyke trends north-east but is highly discordant to the gneissose foliation. Several apophyses also cut the foliation in the adjacent gneisses. Dearnley and Dunning classified the dyke as type-2, partly on the presence of a marginal lineation, which, they argued, signified weak Laxfordian deformation.

At NF 758 535 a 3 m-wide foliated microdiorite dyke cuts across the gneissose banding and across a 1 m-wide late-Laxfordian pegmatitic vein. Some 12 m to the east the same pegmatitic vein cuts a 0.5 m-wide 'Younger Basic' mafic dyke. Two biotites from the microdiorite dyke have given a K-Ar minimum age of intrusion of 1421 ± 25 Ma (Fettes *et al.*, 1992).

NNW-trending Palaeogene dolerite dykes occur sparsely in the section, for example at NF 7593 5350 where a 2 m-wide dyke cuts a 20 m-wide pegmatitic vein. These are easily recognized as sharp-edged, undeformed, partly vesicular, dark-grey dolerites with igneous textures. Inland, they weather to a mid-grey and rusty-brown colour.

Baile a' Mhanaich (Balivanich) section

The Baile a' Mhanaich section has similar lithological elements to that at Gearraidh Siar, except for the additional presence of large 'Older Basic' masses in its northern part (Figure 2.17). The Scourian felsic and subsidiary mafic gneisses generally trend north-east to east and dip at 35°–45° to the north-west and north. A prominent complex synformal zone occurs in the northern part of the section, adjacent to the 'Older Basic' bodies (Coward, 1973a). These bodies are generally strongly banded, defined by variations in the amounts of hornblende, plagioclase feldspar, garnet, and more rarely by quartz or clinopyroxene. They are pervasively metamorphosed and recrystallized. Normally, quartz-feldspar pegmatite veins cross-cut the 'Older Basic' bodies, and lenticular and irregular pegmatitic concentrations occur at their margins. This reflects the considerable competency contrast between the felsic gneisses and the mafic bodies. The smaller 'Older Basic' bodies occur as boudinaged sheets and disaggregated masses, typically heavily veined, either by the host gneisses or by pegmatitic felsic material. In places agmatitic textures are common. Ultramafic pods, now coarse hornblendite, also occur sparsely in the gneisses. Metadolerite dykes of the 'Younger Basic' Suite occur throughout the section; in the northern part they exhibit high degrees of Laxfordian reworking, but in the southern part the degree of reworking falls dramatically. The 'Younger Basic' dykes are cut by late-Laxfordian granite veins, which themselves are locally cross-cut by pegmatitic granite veins (e.g. at NF 7582 5493). A few NNW-trending Palaeogene dolerite dykes also occur (e.g. at NF 7562 5435).

At the eastern end of the section around Calligeo (NF 769 556) there are many scattered small exposures of felsic gneiss with both concordant and tightly folded 'Younger Basic' amphibolitic sheets. West from here, as far as Clachan-garbh (NF 760 553), the gneisses contain some large mafic bodies of the 'Older Basic' Suite. Members of the 'Younger Basic' Suite are also common, again concordant with the gneissose foliation (type-4 deformation *sensu* Dearnley and Dunning, 1968). A good example of a 12 m-wide mafic dyke cut by a late-Laxfordian pegmatitic granite is exposed at NF 7580 5515. Here, the host quartzofeldspathic gneiss is fine- to medium-grained, biotite-rich and locally garnetiferous, and may be a metasedimentary enclave. About 100 m to the south a 7 m-thick concordant mafic sheet exhibits a flattened fabric marked by bands of retrogressed garnet. Southwards, on the headland immediately south of Geodha Ban, there is a dramatic reduction in the degree of Laxfordian strain. At NF 7575 5488, a thin basic dyke may be followed across this transition. South of the transition, the dyke, which is *c.* 30 cm thick, trends roughly north-west to WNW and is markedly discordant to the gneissose foliation, which strikes roughly ENE and dips to the north. Traced northwards the dyke suddenly swings into concordance and develops a strong planar fabric. Coward (1973a) recorded the transition zone as merely 0.5 m wide. South from this point discordant contacts between the mafic dykes and gneissose foliation are common, for example at NF 7580 5478, where an 80 cm-wide discordant dyke is cut by two granite veins; at NF 7563 5435, just south of Eilean Chrossain, where there are 2–10 cm-thick discordant mafic dykelets; and at NF 7568 5430, where a 13 m-wide 'Younger Basic' dyke is demonstrably discordant. The deformational state of the southern part of the section is broadly comparable with that present in the Gearraidh Siar section to the south. The Baile a' Mhanaich section thus contains a regional-scale boundary between an area of high Laxfordian strain (and degree of reworking) and one of low strain.

Interpretation

Dearnley and Dunning (1968) documented the variable Laxfordian reworking within the Gearraidh Siar and Baile a' Mhanaich sections but suggested that overall the two areas lay in a regional zone of low finite Laxfordian strain. They noted that the Laxfordian reworking within the two areas is concentrated in relatively narrow zones. They also interpreted the granulite-facies assemblages present in the cores of the larger dykes as a product of an early-Laxfordian granulite-facies metamorphism, subsequently partially retrograded by the later pervasive Laxfordian amphibolite-facies metamorphic event, which broadly accompanied the main deformation. Although it was subsequently shown that the granulite-facies mineralogy related to post-consolidation recrystallization in hot country rocks at mid-crustal levels (see Fettes *et al.*, 1992), the main observations of Dearnley and Dunning (1968) laid the grounds for the currently accepted interpretation of the nature of Laxfordian reworking.

Coward *et al.* (1970) noted that, on the regional scale, the areas of low Laxfordian strain, such as Gearraidh Siar and the southern part of the Baile a' Mhanaich section, occupy broad regional F3 antiformal cores that close to the west; the fold axes plunging to the north-west at moderate angles. In contrast, the regional high-strain zones, such as at the northern end of the Baile a' Mhanaich section, are coincident with the axial zones of pinched-in F3 synforms. Coward (1973a) showed that the broad antiformal F3 hinge zones are relatively rich in basic rock-types and suggested that these areas may have acted as more highly competent blocks compared to those with fewer mafic bodies. He concluded that such a contrast might well have influenced the development of the regional $D3_L$ fold pattern.

Coward (1973a,b) recognized four Laxfordian deformational phases ($D1_L$–$D4_L$), which affected the rocks of the site area and postulated that the first three phases were coaxial. Coward (1973a) argued that the effects of the first deformation phase were relatively minor and the main reworking was accomplished during the $D2_L$ and $D3_L$ phases. He also argued that the pattern of reworking established during $D2_L$ effectively controlled the nature of $D3_L$, with the later strain concentrated in the areas of high $D2_L$ deformation, thus reinforcing the areas of maximum reworking. The majority of the 'Younger Basic' dykes originally trended north-west, an orientation normal to the maximum compression direction during $D1_L$ and $D3_L$. As a result, the deformation during $D1_L$ largely resulted in boudinage of the dykes and the development of flattening fabrics and zones of intense strain parallel to the dyke margins. Only those dykes and apophyses lying at high angles to the maximum compression direction were folded. However, during $D2_L$, the maximum compression direction lay at a low angle to the majority of dykes. This resulted in a broader more-uniform deformational style with relatively open folds whose axial planes trend between north-east and north. A prominent gently to moderately NNW-plunging lineation is widely developed. F2 folds of $D1_L$ boudinaged dykes dominate the outcrop at locality G4 of Coward (1973a, fig. 6, see above). During $D3_L$, as in $D1_L$, the strain was concentrated in localized strongly deformed zones. Coward (1973a) argued that the $D3_L$ strain was focused in $D1_L$ deformation zones, increasing the intensity of deformation in these areas. The $D4_L$ event resulted in open to tight and even isoclinal folds, generally with east–west subvertical axial planes. The folds affected zones already strongly reworked by the Laxfordian $D1_L$–$D3_L$ events as well as previously little-deformed areas.

Coward (1973a) also noted cuspate structures at the margins of the basic dykes and dykelets and the host gneisses. He interpreted them as reflecting the ductility contrast between the rock types during deformation, the pinched-in areas between the cusps pointing to the lithology with the lower ductility. He noted that the relative ductility of the dykes and gneisses changed during Laxfordian reworking, particularly where the rocks suffered amphibolitization or deformation-induced recrystallization. This resulted in a considerable variation in the ductility contrast between the gneisses, the large dykes and the small dykelets and, in consequence, in the style of the accompanying deformation. Coward cited, for example, virtually undeformed dykes hosted by strongly deformed and more-ductile gneisses, but with amphibolitized apophyses behaving as more-ductile elements within the gneisses. He noted that the concentration of $D1_L$ and $D3_L$ strain in specific zones promoted recrystallization and hence increased ductility in these zones, thus predisposing them to act as the focus of further strain. Hence, the ductility contrasts and the variety of orientations of the 'Younger Basic' dykes were major factors determining the heterogeneous nature of the overall Laxfordian deformation and varied pattern of Laxfordian strain across the section.

Conclusions

The coastal sections of the Gearraidh Siar to Baile a' Mhanaich GCR site illustrate the detailed nature of Laxfordian reworking of the earlier Archaean-age Scourian gneisses and the meta-dolerite dykes of the Palaeoproterozoic 'Younger Basic' Suite in one of the best-studied areas in the Outer Hebrides. The rocks form an upright antiform–synform fold pair some 4 km in wave-length that lies on the western limb of a larger-scale antiform that covers most of Benbecula. In simple terms, the southern part of the section exhibits a low degree of Laxfordian reworking where the mafic dykes strongly cross-cut the gneissose foliation and largely preserve their early-formed metamorphic fabrics. However, in the north, Laxfordian strains are high and the dykes have been strongly deformed and rotated into concordance with the gneissose foliation. The accompanying recrystallization has also modified their original mineralogy and fabrics in the mafic dykes so that they are now amphibo-lites. The boundary between the two zones is very sharp, locally occurring over less than a metre. However, internally, local strain varia-tions and detailed deformation patterns have been studied based on the nature of the 'Younger Basic' dykes.

Variations along the section in the style and geometry of deformation allow conclusions to be drawn about the amount of strain, mechanisms of deformation, the ductility contrasts between the different rock-types, and the original orientation of the 'Younger Basic' dykes. The distribution and intensity of the early-Laxfordian deformation was controlled by the relative abundance of the mafic dykes of the 'Younger Basic' Suite. Where the dykes are abundant the overall competence of the rocks was high, and hence structural and metamorphic reworking was concentrated in areas of relatively few basic intrusions. Successive deformational phases were then focused in zones of already highly deformed rocks, thus reinforcing the structural pattern and emphasizing the boundaries between the zones.

This GCR site is of international importance as one of the keys to unlocking the history of the Laxfordian event in the Outer Hebrides. It is an excellent and readily accessible teaching site, both for Hebridean and Lewisian geology, and it demonstrates features commonly found in other ancient crystalline basement rocks.

RHUGHASINISH, SOUTH UIST (NF 821 447)

D.J. Fettes

Introduction

At Creag Loisgte, in the Rhughasinish area of South Uist, a metadolerite pod is enclosed within an ultramafic body. Both rock-types are assigned to the 'Younger Basic' Suite and the contact between the two is exposed. Their juxtaposition is unusual in the Lewisian gneisses of the Outer Hebrides and shows that the metadolerites post-date the ultramafic members of the suite. Internally the bodies are little deformed and retain granulite- and upper-amphibolite-facies assemblages, but the margins of the ultramafic body show evidence of amphibolite-facies retrogression. Ultramafic bodies are relatively uncommon in the Uists so the Rhughasinish GCR site is also important in furnishing an example.

The ultramafic body forms a roughly rectangular pod some 600 m long by 400 m across, whereas the metadolerite body is ovoid, measures some 150 m by 100 m, and forms the small hill of Creag Loisgte itself (Figure 2.19). Both bodies are elongated with their long axes orientated north-west. The host rocks are the grey to white and cream, biotitic and hornblendic felsic orthogneisses typical of the Lewisian Gneiss Complex.

Jehu and Craig (1925) were the first to describe the locality and it has been mapped subsequently by Coward (1969) and by the Geological Survey (Fettes *et al.*, 1992).

Description

The area of interest is centred on a small area at the head of the small inlet of Bàgh na Creige Loisgte on the north coast of South Uist. Rock is

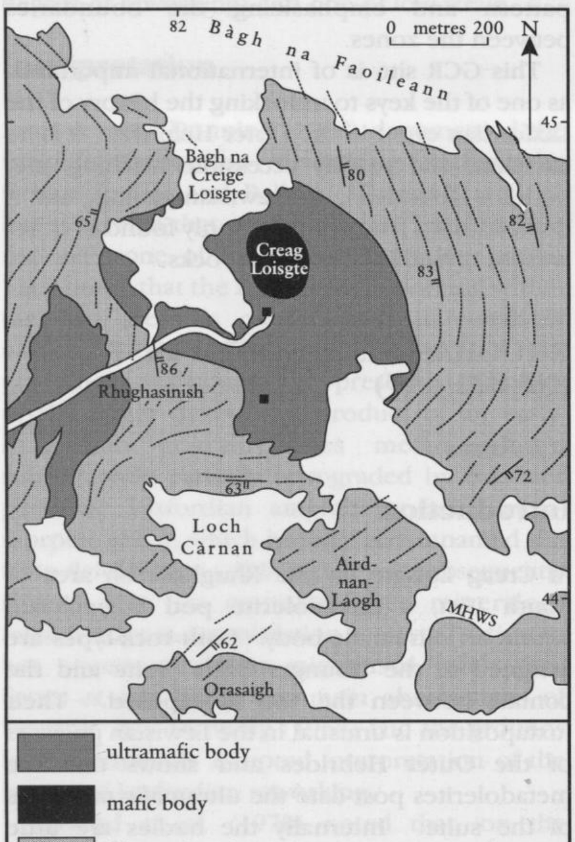


Figure 2.19 Simplified geological map of Rhughasinish, South Uist. After Coward (1969).

exposed on the foreshore near the mouth of the inlet and on the adjacent low rocky knolls. Creag Loisgte is a small rocky hill, about 15 m in height, which lies on the east side of the inlet. Its western side provides a short section through the metadolerite body and its steep contact with the ultramafic mass.

The metadolerite body is typical of the mafic rocks of the 'Younger Basic' Suite in the area. It is a dark grey-green, medium-grained rock with small reddish garnets visible in hand specimen. In thin section it consists of an equigranular assemblage of clinopyroxene, garnet, amphibole and feldspar. In parts the feldspar has been altered to a cloudy, fine-grained, sericite-rich aggregate. The metadolerite does show a variation in feldspar content on the scale of about 0.5 m, which probably reflects original igneous layering. Although pervasively recrystallized, the rock retains some relict igneous features with mafic aggregates and larger pyroxene plates probably reflecting a primary igneous texture. In contrast, the ultramafic body has a relatively uniform texture. It has a characteristic yellowish-brown weathered crust but is dominated by coarse-grained black clinopyroxene crystals on fresh surfaces. In thin section it consists of large clinopyroxene plates and finer-grained equigranular aggregates of hornblende and pyroxene; minor flakes of biotite are also present. The original rock was a pyroxenite, probably of cumulate origin, which has undergone considerable recrystallization. The contact between the two rock-types is sharp. Thin-section studies show that in the metadolerite there is no variation in overall grain-size or mineralogy towards the contact. In the pyroxenite there is merely a thin (*c.* 1 mm) selvage of equigranular amphibole at the contact. The contact of the ultramafic mass with the gneisses has not been recorded, but it is likely to be marked by a sheared or altered rim of retrogressed actinolitic and talcose material.

Interpretation

Mafic and ultramafic rocks of the 'Younger Basic' Suite occur throughout the Outer Hebrides. Mafic rocks, notably dyke-like bodies, are particularly abundant and they exhibit a great variety of structural states and varied amphibolite- and granulite-facies metamorphic assemblages (Fettes *et al.*, 1992). The ultramafic bodies are far less abundant. They occur characteristically as isolated lensoid pods, normally several tens of metres long, and only rarely up to several hundred metres long. Their greatest development is in central Lewis where they are relatively abundant and define a broadly east–west belt some 10 km long and 3 km wide. In the Uists they are sparse, being confined mainly to a few bodies in the eastern half of South Uist. Both mafic and ultramafic bodies post-date the Scourian deformation and metamorphism, but have been modified by deformation and recrystallization during the Laxfordian event. The majority of the ultramafic bodies are dunites and peridotites with minor pyroxenites. They exhibit cumulate textures and mineralogical banding, but are normally dissociated from the mafic intrusions. Both mafic and ultramafic bodies can be correlated with the Scourie Dyke Suite of the mainland, which shows a similar range of compositions. However, the ultramafic members in the mainland Lewisian gneisses occur mainly as dykes rather than as pods (Tarney, 1973).

Most members of the 'Younger Basic' Suite were intruded as dykes and would not be expected to exhibit igneous layering. However, a few of the larger bodies, probably originally thick sheets or laccoliths, do show crude layering, even where their mineralogy and texture have been largely recrystallized (Fettes *et al.*, 1992). The layering is generally evidenced by variations in the plagioclase feldspar content but may also be indicated by the abundance of garnet or indeed by the partial retrogression of garnet to plagioclase. A large layered ultramafic cumulate body of 'Younger Basic' Suite age has been documented at Maaruig in North Harris (Soldin, 1978). There, no felsic units are present and the mafic elements are subsidiary. A layered igneous body ranging from ultramafic cumulates to leucogabbro has been described also from East Gerinish, some 5.5 km SSE of Rhughasinish in South Uist (Fettes *et al.*, 1992). That body is unique in that its chemistry shows a strong calc-alkaline trend, in contrast with the normal tholeiitic trends shown by both the 'Younger Basic' and the pre-Scourian banded 'Older Basic' suites (see **Cnoca Breac** GCR site report, this chapter). Hence, it is difficult to be definitive on the age and affinities of the East Gerinish body (Coward, 1969; Fettes *et al.*, 1992). In general, 'Younger Basic' layered complexes are rare, and hence the petrogenetic relationship of the ultramafic cumulate bodies to the more-uniform metadolerites of the 'Younger Basic' Suite is generally unclear.

Although the Rhughasinish site is one of the few localities where a contact between the 'Younger Basic' ultramafic and mafic rock-types may be examined, unfortunately definitive evidence of their relative age and petrogenetic relationship is absent. Internally the intrusions show little evidence of Laxfordian deformation, but the two rock-types have clearly been recrystallized during or after emplacement. The mafic dykes and sheets are interpreted as having been intruded at mid-crustal levels into relatively hot rocks. As a result they have either crystallized directly from the basic magma to a garnet-pyroxene-bearing, granulite-facies mineralogy, or have recrystallized in the relatively anhydrous metamorphic environment subsequent to solidification and cooling (see Fettes *et al.*, 1992). Similarly, in the pyroxenite the large early-formed clinopyroxene crystals have recrystallized to equigranular pyroxene-amphibole aggregates.

There are three possible models for the relationship between the two rock-types at Rhughasinish. First, the contact is tectonic; second, the metadolerite pod has intruded the pyroxenite body; and third, the contact is an example of primary igneous layering. The first possibility is unlikely because there is no evidence of shearing or alteration at the margin. Even though the rocks are pervasively recrystallized, relict primary igneous textures are still found up to the contact. There is no evidence of 'chilling' in either body to support intrusion of one into the other. However, their probable intrusion into already 'hot' gneisses would inhibit the development of such marginal 'chill' textures. Nevertheless, it is difficult to imagine that basic magma would have intruded an existing ultramafic body when the regional evidence suggests that they have behaved as rigid coherent masses. It is also improbable that an ultrabasic cumulate mush could have picked up a lump of unrelated basic material, particularly given the absence of any other xenoliths. The third possibility of a partial layered sequence is compatible with the evidence. Although there is no evidence elsewhere in 'Younger Basic' intrusions of massive ultramafic cumulate layers in association with discrete layered mafic sequences, the balance of the evidence does point towards the Rhughasinish rocks as forming part of a disrupted layered mafic–ultramafic sequence of the 'Younger Basic' Suite.

Conclusions

At Rhughasinish an ovoid metadolerite pod, some 130 m across, lies enclosed within a larger pyroxenite body. This mafic–ultramafic body of the 'Younger Basic' Suite has been intruded into typical quartzofeldspathic Lewisian gneisses, which in this region show moderate degrees of Laxfordian tectonic and metamorphic reworking. The mafic and ultramafic rocks are largely undeformed but show equigranular metamorphic textures and granulite- or sub-granulite-facies metamorphic assemblages. The contact between the mafic and ultramafic rocks is sharp with no evidence of chilling or marginal alteration. This relationship is interpreted as most consistent with primary igneous layering, with the ultramafic fraction representing a cumulate layer.

The mafic and ultramafic rocks of the 'Younger Basic' Suite are interpreted as analogous to the Scourie Dyke Suite of the mainland Lewisian. Although such mafic intrusions are very abundant throughout the Outer Hebrides and ultramafic pods are common in parts, the two rock-types are rarely in contact. Hence, the exposed section through the contact at Rhughasinish is of regional importance and merits further detailed work. The easy accessibility of the site makes it a useful teaching locality.

LOCH SGIOPORT (SKIPPORT), SOUTH UIST (NF 812 384)

D.J. Fettes

Introduction

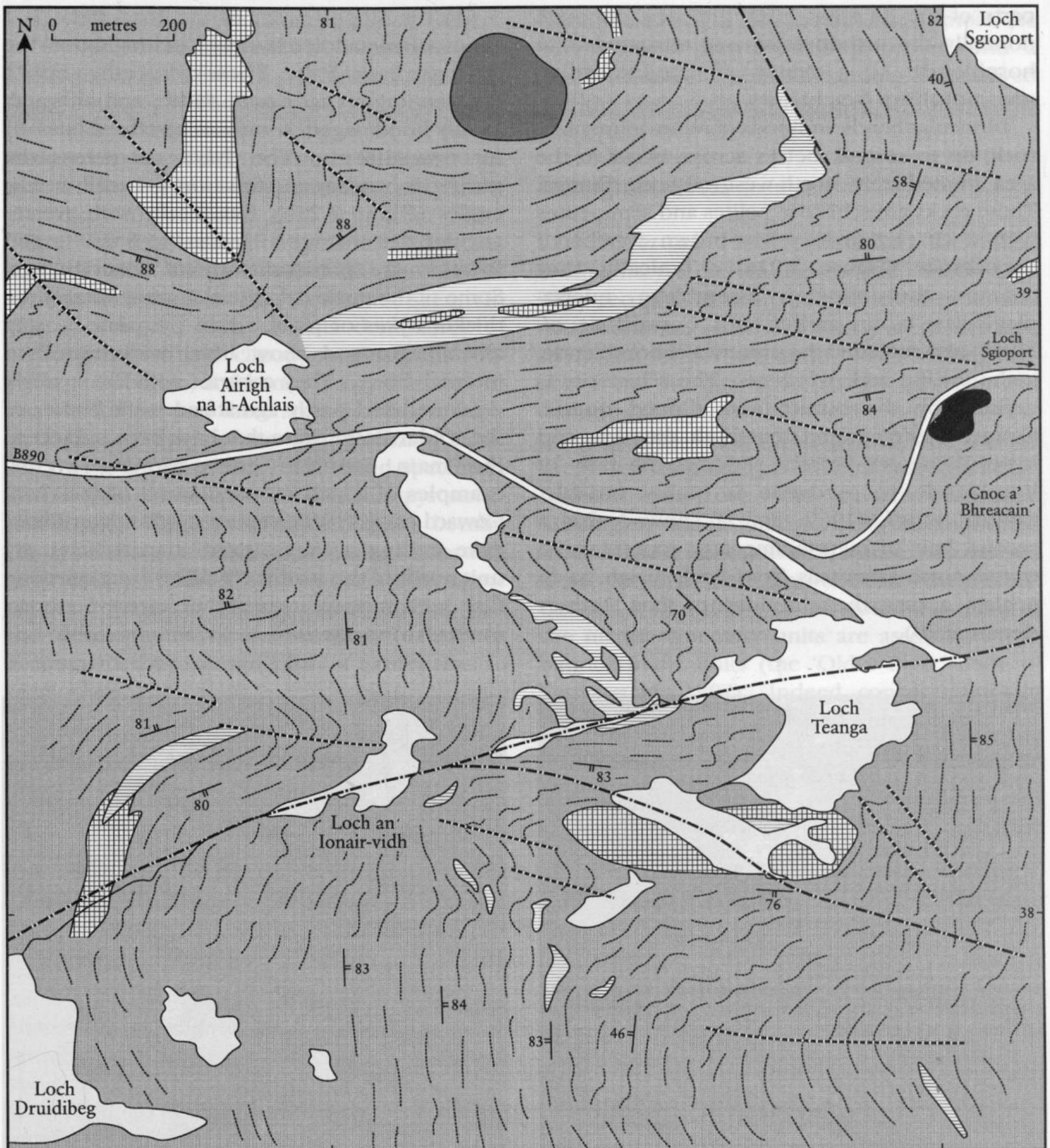
The Loch Sgioport GCR site (formerly termed 'Loch Skipport') shows several features and relationships that are critical to the overall interpretation of the Lewisian Gneiss Complex in South Uist. Firstly, it is one of the few areas west of the Outer Hebrides Fault Zone to contain relict granulite-facies pyroxene-bearing felsic gneisses. Secondly, metasedimentary rocks are present and their relationships to the Scourian-age migmatization and to the mafic dykes and sheets of the 'Younger Basic' Suite can be seen. Thirdly, although the overall Laxfordian deformational effects are low to moderate, local late-stage Laxfordian folding and remobilization of the gneisses are both well developed in the area.

The area of interest spans the southern slopes of Ben Tarbert, the Loch Sgioport road (B890), and the area immediately west of Loch Teanga (Figure 2.20). The dominant rocks are felsic gneisses, with subsidiary amphibolitic mafic units. In parts the gneisses are migmatitic, and contain numerous veins of leucogranite and veins and pods of pegmatitic granite. Belts of pelitic metasedimentary rocks occur immediately west of Loch Teanga and on the south-eastern slopes of Ben Tarbert. Amphibolite dykes of the 'Younger Basic' Suite are abundant, particularly on the north side of the road. Coward (1969) first mapped the area in detail and described its varied features (Coward *et al.*, 1969; Coward, 1973b). The overall geology is also summarized in Fettes *et al.* (1992).

Description

Within the GCR site area, south of the Loch Sgioport road and west of Loch Teanga, there are numerous low-relief rocky exposures and a scattering of small lochs. North of the road the ground rises towards Ben Tarbert, and here the exposure is generally good with progressive tiers of low crags. Glaciation has scoured most of the area and has left many clean rock slabs and rounded outcrops. Glacial striae and roche moutonnée bedforms show clearly that the ice flow moved eastwards across the site area, at least during the Late Devensian.

The area is dominated by white to grey, massive to blocky, thinly banded, biotite- and hornblende-bearing quartzofeldspathic gneisses, with thin bands and larger pods and lenses of mafic gneiss, up to 2–3 m across. The banding in the felsic gneisses is commonly migmatitic, and veins and pods of quartz-feldspar pegmatite and pegmatitic granite are abundant in places. In rare instances these features are seen to be cross-cut by mafic dykes of the 'Younger Basic' Suite. The gneissose foliation is disposed around late-Laxfordian folds (see below) and its strike varies from north-west to north and north-east, with dips of 50°–80° to the west. Coward (1969) recorded relict clinopyroxene-orthopyroxene and clinopyroxene-garnet assemblages in some of the agmatitic 'Older Basic' bodies, particularly around Loch Teanga. He also noted the presence of orthopyroxene in



Palaeoproterozoic

- metadolerite and amphibolite sheets and dykes of the 'Younger Basic' Suite
- ultramafic rock (mostly pyroxenite)

Archaean

- mafic amphibolite bodies of the 'Older Basic' Suite
- metasedimentary rocks, including garnetiferous semipelite
- felsic gneisses with some mafic amphibolitic pods and lenticular bands

- generalized trend of gneissose foliation
- inclined foliation, dip in degrees
- axial trace of F4 folds
- fault, lineament

Figure 2.20 Simplified geological map of Loch Sgioport (Skipport), South Uist. After Coward (1969).

parts of the adjacent felsic gneisses, although normally the orthopyroxene is retrograded to hornblende as a result of late-Laxfordian metamorphism (see below).

Lenticular bands and pods of metasedimentary rock, up to several metres across, occur in the area immediately north-west of Loch Teanga. These rocks are schistose pelites and semipelites with a characteristic yellow-brown weathered appearance (Figure 2.21a). Typically, they contain the mineral assemblage quartz-plagioclase-biotite-garnet, but Coward *et al.* (1969) also recorded the presence of hornblende, anthophyllite and pyroxene. The schistosity is defined by the biotite and aligned quartz. Coward (1969) noted that both diopside and hypersthene are present and that the ratio of hornblende to pyroxene is highly variable. Coward *et al.* (1969, fig. 2) showed that a second belt of metasedimentary rocks can be traced north-eastwards from Loch Airigh na h-Achlais across the shoulder of Ben Tarbert (Figure 2.20).

On the slopes north of the road there is a series of metadolerite dykes belonging to the 'Younger Basic' Suite. These dykes range from a few centimetres to 1 m in width, and although locally boudinaged, some can be traced laterally for over 100 m. The dykes cut across the gneissose banding and foliation, generally at low angles (Figure 2.21b), but locally with greater angular discordance. Hence the banding and foliation are predominantly of Scourian age. Some of the mafic dykes in this area, notably the thicker dykes or pods, retain pyroxene-bearing assemblages and show little evidence of an internal fabric. They contrast with the strongly deformed and partly agmatized mafic bodies of the 'Older Basic' Suite that have been subject to the main Scourian gneiss-forming events, examples of which are seen south of the road. Coward *et al.* (1969) reported a 'Younger Basic' dyke cutting a 'migmatized' metasedimentary unit north of the road at NF 389 814, confirming that such metasedimentary units are Scourian (Archaean) in age.

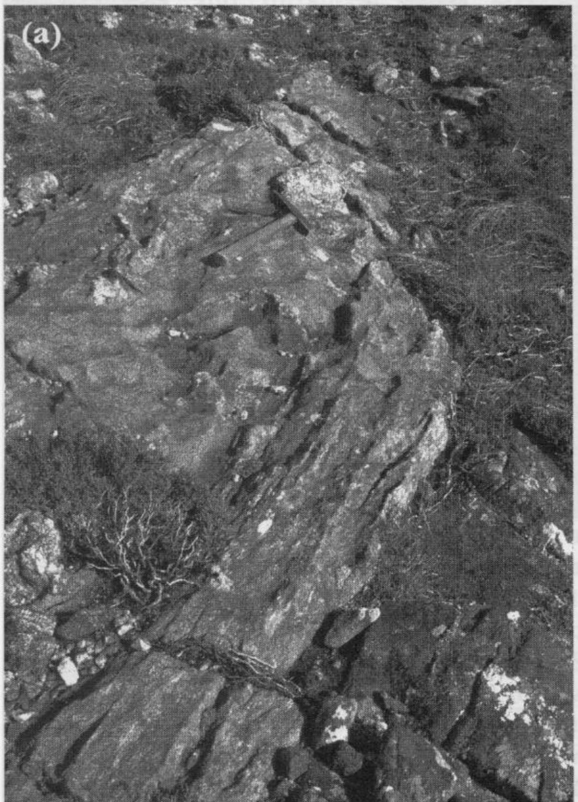


Figure 2.21 Loch Sgioport. (a) Schistose and gneissose semipelitic rocks by Loch Teanga. (b) Deformed thin planar 'Younger Basic' dykes cutting Scourian felsic gneisses at NF 812 389. The hammer is 37 cm long. (Photos: J.R. Mendum.)

Farther north on the shoulder of Ben Tarbert, at NF 813 393, an ultramafic pod approximately 150 m in diameter forms a prominent upstanding craggy outcrop. The rock has a characteristic brownish-yellow weathered appearance, but is dark green to black on fresh surfaces. In places the rock shows evidence of patchy alteration to tremolite and actinolite. The degree of recrystallization generally increases towards the margins although the actual contact with the host gneisses is not seen. In thin section the rock consists dominantly of orthopyroxenes and clinopyroxenes with subsidiary amphibole, and hence is a pyroxenite. To the west of this pod there are a number of fairly thick (3–4 m) dykes of the 'Younger Basic' Suite. They have granular textures in hand specimen, and in thin section they exhibit clinopyroxene-garnet-plagioclase-quartz assemblages. Locally, the dykes show evidence of increasing Laxfordian strain relative to those seen to the south. Some of the thinner dykes are tightly folded and the development of deformational fabrics is accompanied by retrogression of garnet rims to plagioclase.

Coward *et al.* (1969) noted that the metasedimentary units could be used as lithological markers to trace out the regional trend of the gneissose foliation. The foliation is basically of Scourian age, but has been enhanced by moderate Laxfordian $D2_L$ deformation and weak $D3_L$ deformation. Coward (1973b) noted that the F2 fold axes and L2 lineations are generally indistinguishable from the equivalent D3 structures. In the Loch Teanga area these linear elements plunge at 30°–40° to the south-west. However, the foliation traces define a series of folds with subvertical axial planes trending roughly east–west. Related minor folds range from open to tight with generally disharmonic profiles. Coward (1973b) ascribed these folds to the regional Laxfordian $D4_L$ event. He also noted that there is a progressive eastward development in the intensity of $D4_L$ deformation, which reaches its acme in the eastern part of the Loch Sgioport area. He also noted that as the F4 folding became more intense there is a concomitant increase in the degree of remobilization and recrystallization of the Scourian gneisses. This recrystallization was syn- to post-tectonic, such that it overprinted the new $D4_L$ fabrics. This phenomenon reaches its greatest development in an area north of Hecla, about 4 km to the SSE of the GCR site area. Here, Coward (1973b) noted that 'almost the whole gneiss has been transformed into a granitic mass, the gneissic banding is destroyed and the basic rocks remain only as hornblende- and biotite-rich schlieren'.

Interpretation

Coward *et al.* (1969) described the metasedimentary units in North and South Uist. They recognized two types, which they termed metasediments *sensu stricto* (*ss*) and *sensu lato* (*sl*). The former are more readily distinguishable from the quartzofeldspathic gneisses and include the brownish-weathering schistose garnetiferous biotite semipelites and pelites seen near Loch Teanga. The 'metasediments *sl*' include quartzose and quartzofeldspathic lithologies, which are less easily distinguished from the host felsic gneisses, which were derived from tonalite and granodiorite intrusions. Coward *et al.* (1969) further noted that many of the metasedimentary units are associated with banded mafic units (the 'Older Basic' Suite of Fettes *et al.*, 1992). Indeed, concentrations of associated mafic–metasedimentary units appear to define linear belts, traceable for several kilometres, even though the individual units are normally lenticular and only a few tens of metres wide.

The relationships at Loch Sgioport, particularly the undeformed 'Younger Basic' dykes cutting already foliated and migmatized metasedimentary rocks and the host felsic and mafic gneisses, allowed Coward *et al.* (1969) to argue that the metasedimentary rocks had been subjected to the Scourian gneiss-forming events. They further postulated that the 'metasediments *sl*' grade into the quartzofeldspathic gneisses and that the felsic gneiss complex is effectively a migmatized supracrustal sequence. The currently observed metasedimentary units thus represented unmigmatized more-exotic relics. Such circumstances seem unlikely, as normally semipelitic rocks are preferentially migmatized and quartzites or mafic lithologies tend to be preserved as relics. The interpretation of Coward *et al.* (1969) was overturned by Moorbath *et al.* (1975) who, on the basis of Pb-Pb and Rb-Sr isotopic systematics, showed that the protoliths of the felsic gneisses were upper-mantle-derived igneous rocks emplaced *c.* 100–200 Ma before the main Scourian events, that is at *c.* 2900 Ma. This conclusion together with correlations with analogous rocks in Greenland suggests that the metasedimentary and spatially associated banded mafic units are distinctly older than the bulk of the felsic gneisses (see Fettes and Mendum, 1987, for discussion). Hence they represent preserved xenolithic rafts or screens within the igneous protoliths.

Coward (1973b) described pyroxene-bearing felsic gneisses and metasedimentary units from the Loch Sgioport area. This is the only part of the Outer Hebrides, outwith eastern Barra, where such high-grade felsic gneisses are found. Their granulite-facies mineralogy and the cross-cutting nature of the 'Younger Basic' mafic dykes all indicate low degrees of Laxfordian reworking. Coward (1969) argued from textural evidence that pyroxene recrystallized (or remained stable) in the gneisses during and immediately after the regional Laxfordian $D2_L$ event but became almost completely retrograded in the felsic gneisses during the $D4_L$ event. Drawing parallels with the geological history inferred from Leinis in Barra (see **Leinis** GCR site report, this chapter), it seems probable that the gneisses were subject to granulite-facies metamorphism during the main Scourian tectonometamorphic events. Their resulting relatively anhydrous nature allowed recrystallization of the pyroxene during the early Laxfordian. In contrast, the granulite-facies mineralogies found widely in the mafic dykes and larger pods of the 'Younger Basic' Suite are deemed to be a product of crystallization of relatively anhydrous basic magma in already hot country rocks at mid-crustal levels.

Coward *et al*. (1970) ascribed the main Laxfordian reworking to the second and third deformational events. Although the former $D2_L$ event was more penetrative, the latter $D3_L$ event produced a series of regional-scale folds, whose steep axial planes trend north-west. These F3 folds have cuspate profiles with broad antiformal crests and narrow pinched-in synforms. In parts of the Outer Hebrides, areas of low Laxfordian strain commonly correspond to the broad antiformal F3 hinge zones, but the Loch Sgioport area does not follow this pattern. Here, $D3_L$ effects are slight and overall Laxfordian reworking is low but this does not appear to be reflected in the earlier Laxfordian $D2_L$ stuctures, which are moderately to strongly developed, nor in the $D3_L$ structural features (Coward, 1973b). It is probable that the Scourian granulite-facies metamorphism was patchy and confined to the eastern and southern parts of the southern islands (Moorbath *et al*., 1975). Thus, the pyroxene-bearing gneisses of Loch Sgioport are probably not relics of a widespread granulite-facies terrain preserved in a zone of low reworking. Rather, the granulite-facies gneisses themselves may have been instrumental in determining the nature of the reworking, focusing strain into the adjacent more-hydrous amphibolite-facies gneisses (Coward, 1973b). Strangely, as noted above, the greatest development of $D4_L$ deformation in the Uists is in the Loch Sgioport area. It is unclear why this is the case, and equally puzzling why high degrees of gneiss remobilization occurred during $D4_L$ in what were previously relatively anhydrous rocks. Even if the $D4_L$ strain had allowed a high degree of fluid access, the preservation of the orthopyroxene is still surprising. Coward (1973b) noted the anomaly but was unable to explain it.

Conclusions

The Loch Sgioport GCR site contains a variety of Lewisian gneiss lithologies and Archaean and Proterozoic features unique to the Outer Hebrides. Pyroxene-bearing felsic gneisses with relict granulite-facies mineralogies occur in association with metasedimentary units and mafic amphibolite bodies of the 'Older Basic' Suite. These Archaean elements are cross-cut by mafic dykes of the 'Younger Basic' Suite. The Scourian (Archaean) gneisses are commonly migmatitic and in places contain abundant quartz-feldspar pegmatite and leucogranite veins and pods. The main Laxfordian reworking events have not greatly affected this part of South Uist and many key Scourian and early-Laxfordian relationships can still be discerned. Similar features are well seen in eastern Barra (see **Leinis** GCR site report, this chapter) but the Loch Sgioport occurrences are the only Hebridean examples that lie to the west of the Outer Hebrides Fault Zone.

The metasedimentary and 'Older Basic' mafic rocks both contain pyroxene-bearing assemblages in the Loch Sgioport area. Relict orthopyroxene is also present locally in the quartzofeldspathic gneisses. It is believed that these assemblages are Scourian, recording a local area of granulite-facies metamorphism. The consequent relatively anhydrous rocks resisted the subsequent main

Laxfordian reworking phases and even allowed the pyroxene to locally recrystallize during early-Laxfordian times. However, during the late-Laxfordian, the intensity of deformation was greater in this region than elsewhere in the Uists, with the accompanying remobilization of the gneisses retrograding most of the pyroxene-bearing assemblages. Although some areas of the Outer Hebrides with low degrees of Laxfordian reworking are coincident with the antiformal hinge zones of large- or medium-scale Laxfordian F3 folds (cf. western Benbecula and Ardivachar Point, South Uist), the Loch Sgioport area does not appear to lie in such a structural position. The medium-scale folds of the gneissose banding in this area have E–W-trending axial planes and relate to the Laxfordian $D4_L$ deformation episode.

The Loch Sgioport GCR site is particularly important in that it provides evidence of the relationships between the various Lewisian lithologies. It also shows the controlling effects of the early high-grade rocks on the subsequent Laxfordian deformational and metamorphic pattern. Hence, it is a key area in deciphering the early history of the Outer Hebrides. As such the site is nationally important and its ready accessibility makes it useful for teaching purposes. It is also suitable for further work, particularly on the metamorphic mineralogy of the various different elements of the Lewisian Gneiss Complex.

CNOCA BREAC (RUBH' AIRD-MHICHEIL), SOUTH UIST (NF 733 337)

D.J. Fettes

Introduction

The Cnoca Breac GCR site on the western coast of South Uist provides a section across one of the most spectacular examples of an Archaean layered or banded mafic–ultramafic meta-igneous body, part of the 'Older Basic' Suite (Fettes *et al.*, 1992). These bodies, which are among the oldest rock-types found in the Outer Hebrides, occur throughout the archipelago but are particularly common in the Uists. Although typically only a few tens of metres wide, they may be traceable through intermittent exposures for considerable distances along the strike of the regional foliation. They are commonly associated with metasedimentary rocks, and the two lithologies are believed to be the remnants of a supracrustal layered mafic–ultramafic sequence dating from at least *c.* 2900 Ma. These early-formed elements of the Lewisian Gneiss Complex were subsequently enveloped by granodioritic and tonalitic intrusions, the protoliths of the dominant quartzofeldspathic gneisses, at deep crustal levels during the Scourian (*c.* 2900–2750 Ma).

The banded mafic bodies characteristically exhibit mineralogical banding, commonly with repeated mafic–ultramafic cycles, mainly marked by variations in the ratio of hornblende to plagioclase. Felsic bands also occur but are less common. The banding is believed to have originated as a form of igneous layering, now modified and enhanced by metamorphic recrystallization. The mass at Cnoca Breac is one of the largest and best-exposed examples of these bodies, with a notably wide range of lithologies present. The well-developed layering occurs on several scales from tens of centimetres upwards and with an overall trend from ultramafic to felsic mineralogies across the width of the body.

The GCR site lies in the South Uist synformal zone (see 'Introduction', this chapter), a locus of very high Laxfordian reworking. However, despite its undoubted long tectonometamorphic history the essential elements of the layered intrusion are still readily identifiable. The rocks were mentioned but not described by Jehu and Craig (1925). Coward *et al.* (1969) were the first to recognize the significance of the banded 'Older Basic' bodies, but did not provide detailed information about this site. The first comprehensive description was included in Fettes *et al.* (1992). Although large 'Older Basic' bodies do occur in parts of Lewis and Harris (e.g. in the Gress and Coll river sections north of Stornaway), banded mafic–ultramafic bodies appear to be absent from the northern islands. The lithologically comparable banded meta-gabbros and meta-anorthosite in South Harris are now known to be Palaeoproterozoic in age and hence unrelated to the Archaean 'Older Basic' Suite. Nesbitt (1961) reported the only other possible Hebridean correlative to the occurrences in the Uists from North Rona, some 72 km NNE of the Butt of Lewis. Interestingly, Nesbitt (1961) records the presence of garnet-sillimanite pelitic gneiss adjacent to the banded basic rocks. However, similar banded mafic–ultramafic bodies have also been described more widely from the Scottish mainland, for example in the Scouriemore and Gorm Loch areas near Scourie (Davies, 1974), and from near Drumbeg and Achmelvich (Tarney, 1978).

Description

The GCR site lies immediately to the north of Rubh' Aird-mhicheil, on the western, generally sandy coast of South Uist. In fact the site locality and the banded mafic body have commonly been named after this promontory. Rock is exposed throughout the coastal section of the site on a low, dissected, wave-cut platform, which is partly intertidal. A notable shingle beach backs the site with flat machair behind.

The rocks in the general area from Rubh' Aird-mhicheil northwards to Eilean Bheirean (Verran Island) are characterized by a regular gneissose foliation that is generally subvertical and strikes NNW. Very tight folds, up to several metres in amplitude, are common within the gneisses. In this part of South Uist the 'Younger Basic' dykes are conformable, pervasively recrystallized to amphibolite, and commonly strongly boudinaged. A concentration of mafic amphibolite sheets and pods occurs on the south-western side of Rubh' Aird-mhicheil. It is unclear if these bodies relate to the banded mafic–ultramafic body on Cnoca Breac, or more probably that they are members of the 'Younger Basic' Suite. It is clear that this area is one of very high Laxfordian strain. The dominant lithology is the ubiquitous coarse-grained, biotitic and hornblende-bearing quartzo-feldspathic gneiss containing a variety of mafic sheets and agmatitic lenses and patches. The spectacular development of banded mafic rocks dominates the GCR site and the main body is *c.* 250 m wide (Figure 2.22). Despite its size at Cnoca Breac, the body appears to be lenticular as it is not seen along strike to the north-west on Eilean Bheirean (Verran Island), nor to the south-east around Loch Olaidh an Iar (Ollay).

The body exhibits well-defined mineralogical layering, which is parallel to the regional foliation. The layering is defined by varying proportions of hornblende, garnet, plagioclase ± quartz, and occurs on a variety of scales (Figure 2.23). Individual layers, typically 10–20 cm wide, are defined either by a gradual increase in felsic minerals across their width or by the rapid

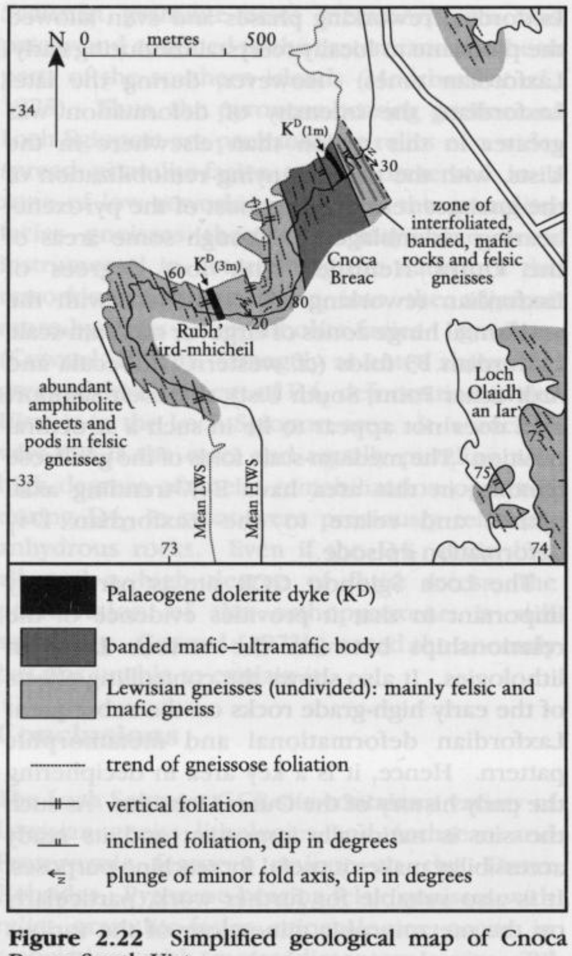


Figure 2.22 Simplified geological map of Cnoca Breac, South Uist.

alternation of more-uniform felsic and mafic units. Groups of layers also define units 1–2 m thick, each unit ranging from ultramafic to felsic lithologies and grading in the same sense as the overall body. These units are dominated by mafic lithologies with individual layers defined by the relative abundance of garnet. Locally the garnets exhibit plagioclase rims, which have been partially flattened within the foliation. The garnets in the ultramafic layers are less susceptible to retrogression to plagioclase than those in the more-mafic layers. Overall the body becomes more felsic towards the north-east, with the easternmost 50 m being effectively a banded metagabbro–meta-anorthosite (Figure 2.24), implying that the body had an original top to the north-east. Screens of felsic gneiss, locally with abundant pyrite and pyrrhotite, occur within the body and these intercalations are more abundant in the eastern part of the body.

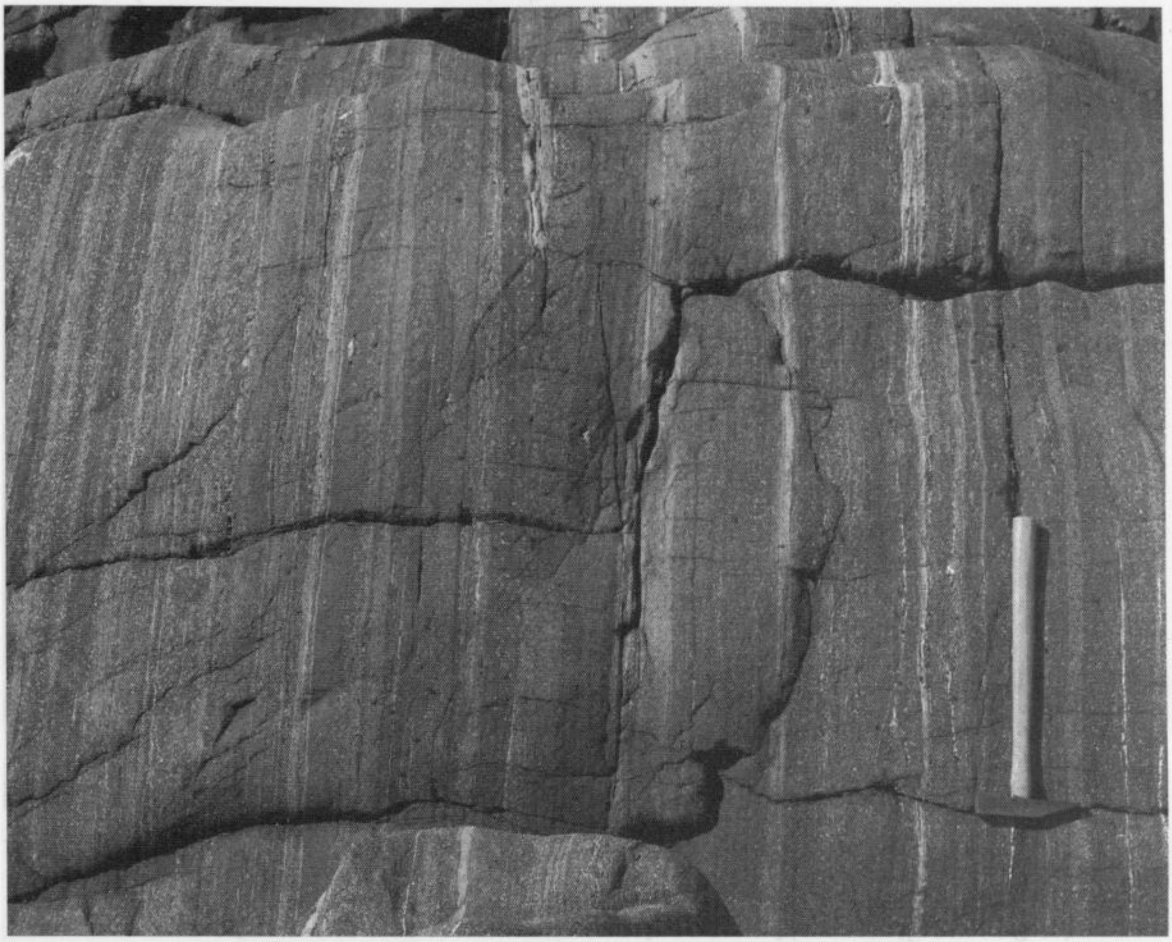


Figure 2.23 'Older Basic' body at Cnoca Breac (NF 7338 3385), showing attenuated and metamorphosed mafic, ultramafic and felsic igneous layering. The hammer is 42 cm long. (Photo: British Geological Survey, No. P008306, reproduced with the permission of the Director, British Geological Survey, © NERC.)

In thin section the textures and mineralogy are seen to be entirely metamorphic with no evidence of relict cumulate or ophitic igneous textures. The rocks are normally sub-equigranular, but in parts locally incipient planar fabrics are defined by aligned hornblende. Although clinopyroxene has not been recorded here, it is common in similar rocks elsewhere in the Outer Hebrides and on the Scottish mainland (Fettes *et al.*, 1992). No systematic geochemistry has been carried out on the Cnoca Breac body but similar, banded, mafic bodies elsewhere in the Outer Hebrides plot as quartz-normative tholeiites (Fettes *et al.*, 1992).

Within the regular, broadly parallel layering, tight minor folds are common locally; as in the surrounding gneiss. These folds have poorly developed axial fabrics in parts, and generally their axes plunge moderately to steeply to the north-east. Several factors confirm that this is an area of very high Laxfordian reworking, namely, the internal structures within the banded basic body and in the surrounding gneiss, the general parallelism of the mafic bodies with the local and regional gneiss foliation, and the pervasive amphibolite-facies mineralogies.

Small pseudotachylite veins are common on the northern side of the banded mafic body linked to minor offsets and brecciation. These veins are of late-Laxfordian or younger age, probably related to movements along the Outer Hebrides Fault Zone (see **Cnoc an Fhithich** GCR site report, this chapter).

The NW-trending dolerite dykes exposed at the northern end of the Cnoca Breac section (*c.* 1 m thick) and on the northern shore of Rubh' Aird-mhicheil (3 m thick) are members of the Palaeogene Mull Swarm (Figure 2.22).

Figure 2.24 Deformed and metamorphosed mafic and felsic (anorthositic) banding in the north-east part of the 'Older Basic' body at Cnoca Breac (NF 7347 3390). The banding reflects the original igneous compositional layering. (Photo: British Geological Survey, No. P008309, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Interpretation

Banded or layered mafic bodies are common in the Uists and Benbecula. Although not generally as spectacular as that at Cnoca Breac, these bodies are all characterized by well-developed mineralogical layering, commonly showing variations from ultramafic to mafic and felsic lithologies. The mineralogies and textures are now wholly metamorphic and recrystallized, but the banding clearly reflects original igneous compositional layering, and the intrusive igneous nature of the banded mafic bodies has not been seriously questioned. The bodies probably formed originally as lenticular gabbroic masses with layering akin to that now seen in younger less-deformed complexes, such as Bushveld, Skaergaard and the Cuillin on Skye.

Coward *et al.* (1969) provided the first comprehensive account of banded mafic bodies in the Lewisian Gneiss Complex of the Outer Hebrides. These authors noted the areal coincidence of these mafic bodies with metasedimentary rocks, and that the metasedimentary rocks apparently pass laterally into the surrounding quartzofeldspathic gneisses. They concluded that this transition resulted from the Scourian gneissification process and hence that the metasedimentary and banded mafic units were present prior to, or at an early stage of, the Scourian event. This conclusion is supported by the occurrence of unmigmatized 'Younger Basic' dykes cross-cutting the migmatitic foliation in the banded metabasic bodies (Fettes *et al.*, 1992, p. 35). Fettes *et al.* (1992) showed that the banded mafic bodies are a major component of the 'Older Basic' Suite. In the Outer Hebrides banded mafic bodies and metasedimentary lithologies commonly form discontinuous narrow linear belts concordant with the local and regional gneissose foliation. The belts are typically only a few tens of metres wide but may be traced along strike for up to 15 km. A notable example runs from north of Loch Druidibeg through the east end of Loch Bee and northwards through the centre of Benbecula, where it is folded and forms the hill of Rueval (NF 825 534).

As discussed in the **Loch Sgioport** GCR site report, Coward *et al.* (1969) postulated that the meta-igneous and metasedimentary units represented the exotic relics of an early supracrustal sequence, most of which had been migmatized and recrystallized to form the bulk of the quartzofeldspathic gneisses. However, Moorbath *et al.* (1975) showed from U-Pb isotopic systematics that the quartzofeldspathic gneisses were derived from igneous protoliths, intruded prior to the main Scourian metamorphic events at 2700–2800 Ma. Also, the analogy with similar rock associations in Greenland, in particular the classic banded mafic–ultramafic and metasedimentary units of the Fiskeneaesset region (see Fettes and Mendum, 1987 for discussion), led later workers to decide that the banded 'Older Basic'–metasedimentary rock belts were xenolithic rafts or screens within the general tonalitic–granodioritic protolith of the quartzofeldspathic gneiss. These correlations date the meta-igneous–metasedimentary association at over 2900 Ma and thus define them as some of the oldest rocks exposed in the Outer Hebrides.

Although intrusions of the banded 'Older Basic' and 'Younger Basic' suites can be distinguished from each other in areas of low Laxfordian strain (see **Gearraidh Siar and Baile a' Mhanaich** GCR site report, this chapter) this is not the case in areas of high strain. Thus, it is not possible to attribute the amphibolitic mafic bodies immediately south-west of the Cnoca Breac body to either the older or younger suite. However, the close spatial connection between this concentration of mafic sheets and the banded mafic body might imply that they are all part of the same assemblage.

Coward *et al.* (1970) ascribed the major folds of South Uist to the Laxfordian $D3_L$ event. These antiforms and synforms plunge steeply to the north-west and have NW-trending axial planes. On the regional scale they have a cuspate form with broad antiformal crests, marked by low Laxfordian strain, and narrow pinched-in synforms, typically with very high Laxfordian strains. The Cnoca Breac GCR site and its associated high degrees of reworking are consistent with its position in the complex axial zone of the South Uist Synformal Zone (Coward *et al.*, 1970, fig. 2; see also Fettes *et al.*, 1992, pp. 124 and 131; and the accompanying 1:100 000-scale structure map (Uist and Barra (south); Institute of Geological Sciences, 1983)).

Conclusions

The Cnoca Breac GCR site exposes one of the best examples of banded or layered mafic–ultramafic rocks of the 'Older Basic' Suite rocks found in the Outer Hebrides. The readily identifiable, dark-green to black, grey, and white banding is defined by alternations of ultramafic, mafic and felsic layers on scales ranging from a centimetre up to several metres thick. This banding is interpreted as representing original igneous layering, albeit now highly deformed and pervasively recrystallized during the Scourian and Laxfordian events. However, the rocks still preserve the essential character of the body and the integrity of its layering. Indeed, in places metamorphism has effectively enhanced the layering, for example where there is an abundance of dark-red metamorphic garnet in the mafic layers.

The intrusion is of Archaean age and lies within dominantly planar, mainly felsic gneisses that have been strongly reworked during the Palaeoproterozoic Laxfordian event. Regionally, the Cnoca Breac GCR site lies in the pinched-in, cuspate, axial part of the South Uist Synformal Zone, a major Laxfordian structure whose steep axial plane trends north-west. This synformal zone is marked by a very high degree of Laxfordian strain and reworking. The foliation and banding in the layered basic–ultrabasic body and the felsic gneisses are concordant and strike NNW and are typically subvertical. Tight to isoclinal folding is present in parts of the layered body, and the rocks have been recrystallized under middle amphibolite-facies conditions.

In the Uists and Benbecula, the Archaean mafic–ultramafic bodies of the 'Older Basic' Suite, such as that at Cnoca Breac, mainly occur as discrete lensoid masses only a few tens of metres wide and up to several hundred metres long. However, they are commonly clustered into linear belts, traceable for up to 15 km, which are also marked by a relative abundance of metasedimentary units. This banded meta-igneous–metasedimentary rock association is thought to include the oldest rocks present in the Outer Hebrides, probably having formed at least 2950 Ma. This sequence was subsequently intruded by numerous granitoid intrusions, the igneous protoliths of the present quartzo-feldspathic gneisses, at the beginning of the Scourian (mainly around 2850 Ma). The meta-igneous–metasedimentary units were preserved as refractory rafts or screens within these major granitoid intrusions.

This GCR site is of national importance because it displays one of the geologically most varied and spectacular examples of a layered mafic–ultramafic igneous intrusion in the Lewisian Gneiss Complex. Such bodies are readily correlated with larger and better-exposed banded basic meta-igneous bodies in West Greenland. As such the Cnoca Breac GCR site is a possible locality for future work as well as being valuable for the teaching of Hebridean and Lewisian geology.

LEINIS (LEANISH), BARRA (NL 706 998–NL 699 988)

D.J. Fettes

Introduction

The Leinis GCR site (formerly termed 'Leanish'), situated on the east coast of Barra, constitutes one of the classic sections in Lewisian geology. Here the degree of Laxfordian reworking is lower than anywhere else in the Outer Hebrides, with very little evidence for any significant deformation after the Scourian events. Consequently, it is possible to examine the host Scourian felsic and mafic gneisses and the various suites of late-Scourian intrusions that are common in this part of Barra. Although intruded subsequently by members of later igneous suites, the field relationships of these Scourian rocks have remained essentially unaltered for over 2000 million years, that is since the Palaeoproterozoic. This effective window into the early geological history is crucial to our understanding of Hebridean geology. Although similar features are present on the small adjacent islands, this unique area provides the most coherent, comprehensive and accessible section, making the site of prime importance.

The Lewisian gneisses of Barra are roughly bisected by one of the major thrusts of the Outer Hebrides Fault Zone (OHFZ). The thrust forms a notable feature on the northern islands of Gighay and Hellisay and can be traced west and then south through the centre of Barra. It forms a prominent ESE-dipping scarp feature running obliquely down across the face of Sheabhal (Heaval) above Castlebay. The rocks exposed on the east coast of Barra thus lie above the thrust plane. The OHFZ normally forms a wide complex area of mixed faulted rocks (see 'Introduction', this chapter), but on Barra the thrust zone is manifest as a relatively narrow feature marked mainly by pseudotachylite breccia (see **Cnoc an Fhithich** GCR site report, this chapter). As a result its hangingwall is virtually unaffected by the thrust-related deformation.

Francis (1973) divided this eastern hanging-wall block into three zones striking approximately NNW. The eastern zone is characterized by the virtual absence of Laxfordian strain and contains pyroxene-bearing granulite-facies felsic and mafic gneisses, with the Scourian metamorphic assemblages dating from Archaean times. The central zone is one of strong Laxfordian reworking and amphibolite-facies metamorphism, and the most westerly zone consists of metadiorite and coarse-grained augened granitic gneiss and felsic gneiss. The Leinis GCR site transects the western part of the essentially undeformed eastern zone. Here, a variety of Archaean-age late-Scourian intrusive igneous rocks that post-date the main Scourian metamorphism, and representatives of the Palaeoproterozoic 'Younger Basic' dyke suite are readily identifiable. Excellent field exposures allow these late-Scourian intrusive rocks to be assessed both in terms of their relative ages and their relationships to the deformational phases. From youngest to oldest the late-Scourian elements comprise:

- Quartz-feldspar pegmatites and rare pegmatitic granites
- Monzonites, granites
- Microdiorites, monzodiorites.

A relatively weak deformational phase occurred following the intrusion of the microdiorites and prior to intrusion of the 'Younger Basic' dykes. This is believed to be equivalent to the Inverian event in the Lewisian gneisses of the mainland.

Jehu and Craig (1923) provided the first comprehensive description of the geology of Barra. Hopgood (1964, 1971) later described the polyphasal nature of the deformation and recognized several of the early intrusive suites. Francis (1969, 1973) noted that the area is marked by low Laxfordian strain and postulated that the 'Younger Basic' Suite had been intruded into hot gneisses at mid-crustal levels. Fettes *et al.* (1992) re-defined the nature of the intrusive suites and suggested a correlation of the late-Scourian deformation with the Inverian of the mainland (see Table 2.1 in the 'Introduction', this chapter).

Description

The GCR site comprises a coastal section on the east side of Barra, from the Leinis peninsula northwards to Sloc nan Each, a distance of *c.* 1.5 km. The exposure is virtually continuous and is formed by low (2–4 m-high) cliffs and clean, craggy, wave-cut platforms, which extend seawards for several tens of metres at low tide. The section is partly tidal; Orosay is a tidal island. The section is backed by low rather rocky hills. The geological elements of the site are shown in Figure 2.25.

In the southern part of the site, on the Leinis peninsula the country rocks are amphibolite-facies hornblende-bearing felsic and subsidiary mafic gneisses, which give way northwards to massive, brownish-weathering, granulite-facies, pyroxene-bearing gneisses. Mafic bodies are present in parts, now represented by amphibolite, normally cross-cut by abundant quartz-feldspar and feldspathic veins. These are members of the 'Older Basic' Suite. A prominent net-veined and coarsely recrystallized hornblendite body occurs around NF 7023 9902, from which Francis *et al.* (1971) recorded the mineral assemblage hornblende-pyroxene-biotite-plagioclase. The 'Older Basic' bodies, the ultramafic hornblendite, and adjacent gneisses, are all probably Scourian elements of Archaean age (see 'Interpretation').

In thin section the granulite-facies mafic rocks are composed of an equigranular assemblage of clinopyroxene, (± orthopyroxene), hornblende, plagioclase and quartz. Accessory magnetite and ilmenite are abundant and biotite is locally present. Hornblende may be a primary metamorphic phase locally, but normally it has formed by replacement of pyroxene. The felsic gneisses contain the assemblage quartz, plagioclase, biotite, (± hornblende), locally with orthopyroxene. Orthopyroxene, where present, is a pinkish hypersthene, commonly with retrograded margins. Both granulite- and amphibolite-facies assemblages are attributed to the main Scourian gneiss-forming events at *c.* 2850–2730 Ma.

The microdiorite sheets and dykes are uniform grey, medium-grained rocks, which form discrete, parallel-sided bodies that normally range from a few centimetres to 1 m in width (rarely up to 2 m). They occur throughout the section and cross-cut the gneissose foliation. In the larger dykes hornblende crystals have commonly aggregated to form mafic schlieren (streaks and elongate clots). Some schlieren show tight minor folding (Figure 2.26), whereas others are aligned parallel to the deformational fabric. The mineralogies and equigranular textures exhibited by the microdiorites are essentially metamorphic. In thin section the dykes are dominated by euhedral to anhedral plagioclase feldspar, with subordinate hornblende and biotite, and minor amounts of quartz and potash feldspar, and abundant accessory apatite. In parts the mafic minerals define a planar fabric. Francis (1973) distinguished two end members of this suite:

- a mafic variety with an abundance of pyroxene, hornblende and biotite; some of the pyroxenes enclosed in the hornblende may be relict igneous grains.
- a leucocratic variety dominated by plagioclase with subordinate potash-feldspar, quartz and biotite.

Monzonite and monzogranite intrusions are particularly numerous immediately to the north of the Leinis peninsula in the southern part of Earsairidh, opposite Osasaigh (Figure 2.25). They are pinkish equigranular rocks with a weak planar fabric, and consist of potash feldspar, plagioclase, quartz, biotite and hornblende. The granites cross-cut members of the microdiorite suite, but are themselves cut by late-Scourian pegmatitic granite veins, which occur throughout the section (Francis *et al.*, 1971). The pegmatite veins generally trend between west and north-west and are steeply dipping to sub-vertical. They range from a few centimetres to 5 m in width and have been traced for up to 80 m. Typically, they have white, quartz-rich cores and red feldspar-rich margins.

The mafic dykes of the Palaeoproterozoic 'Younger Basic' Suite are very prominent in the Leinis section. They show virtually no internal fabrics or deformational effects and clearly post-date the late-Scourian monzonite, granite and pegmatitic intrusive rocks. The mafic dykes

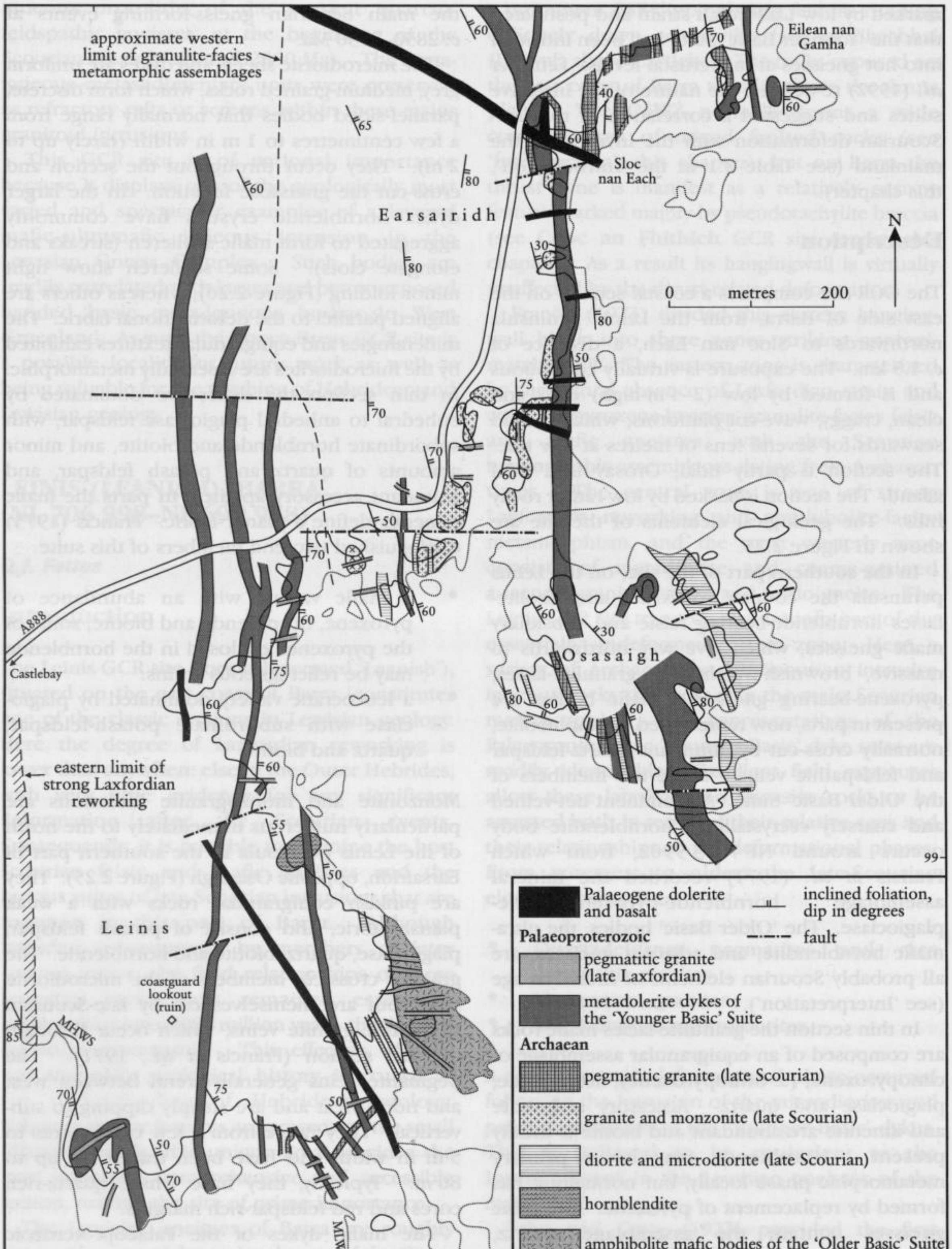


Figure 2.25 Simplified geological map of Leinis (Leanish), Barra. After Francis (1973).

Figure 2.26 Mafic concentrates defining a folded fabric in a late-Scourian microdiorite dyke, Leinis peninsula (NF 7032 9876). The hammer head is 14 cm long. (Photo: British Geological Survey, No. P008327, reproduced with the permission of the Director, British Geological Survey, © NERC.)

trend between north and north-west and range from a few centimetres wide up to *c.* 20 m. They can be traced laterally for up to 800 m. Their near-parallel-sided form and blocky igneous appearance belies their Palaeoproterozoic age. In hand specimen they are mid- to dark-grey, medium-grained, granular metadolerites. In thin section they exhibit two-pyroxene-hornblende-plagioclase assemblages, typical of granulite-facies rocks; small garnets are also present locally. In some cases aggregates of the mafic and felsic minerals appear to mimic an original ophitic texture, but the mineral compositions and equigranular textures are wholly metamorphic.

The age relationships between the various suites are well displayed throughout the section. On the Leinis peninsula, 'Younger Basic' dykes cross-cut quartz-feldspar pegmatite and rare pegmatitic granite veins, which in turn cut microdiorite dykes. All the intrusions cross-cut the Scourian gneissose foliation. For example, at NF 7026 9864, a *c.* 1 m-wide mafic dyke cuts a *c.* 30 cm-wide late-Scourian quartz-feldspar pegmatite vein, with both demonstrably cross-cutting a *c.* 15 cm-thick microdiorite dyke (Figure 2.27; Fettes *et al.*, 1992, plate 7). At NF 7033 9869, a thick (8–12 m) mafic dyke cross-cuts a large (*c.* 3.5 m) quartz-cored pegmatitic granite vein. The mafic dyke is, in turn, cut by Laxfordian pegmatitic granite veins and by a Palaeogene dolerite dyke a short distance to the north-west at NF 7030 9878. Nearby (at NF 7033 9876), a *c.* 1 m-wide microdiorite is cut by a 30 cm-wide offshoot from the large mafic dyke mentioned above. The microdiorite contains well-defined mafic schlieren, which are locally folded, but which generally define a fabric lying at an angle to the margin of the dyke (Figure 2.26).

At the south end of Earsairidh (at NF 7043 9938) a *c.* 4 m-wide microdiorite dyke with mafic lenses is cut by a coarsely foliated granite, both of which are cross-cut by a

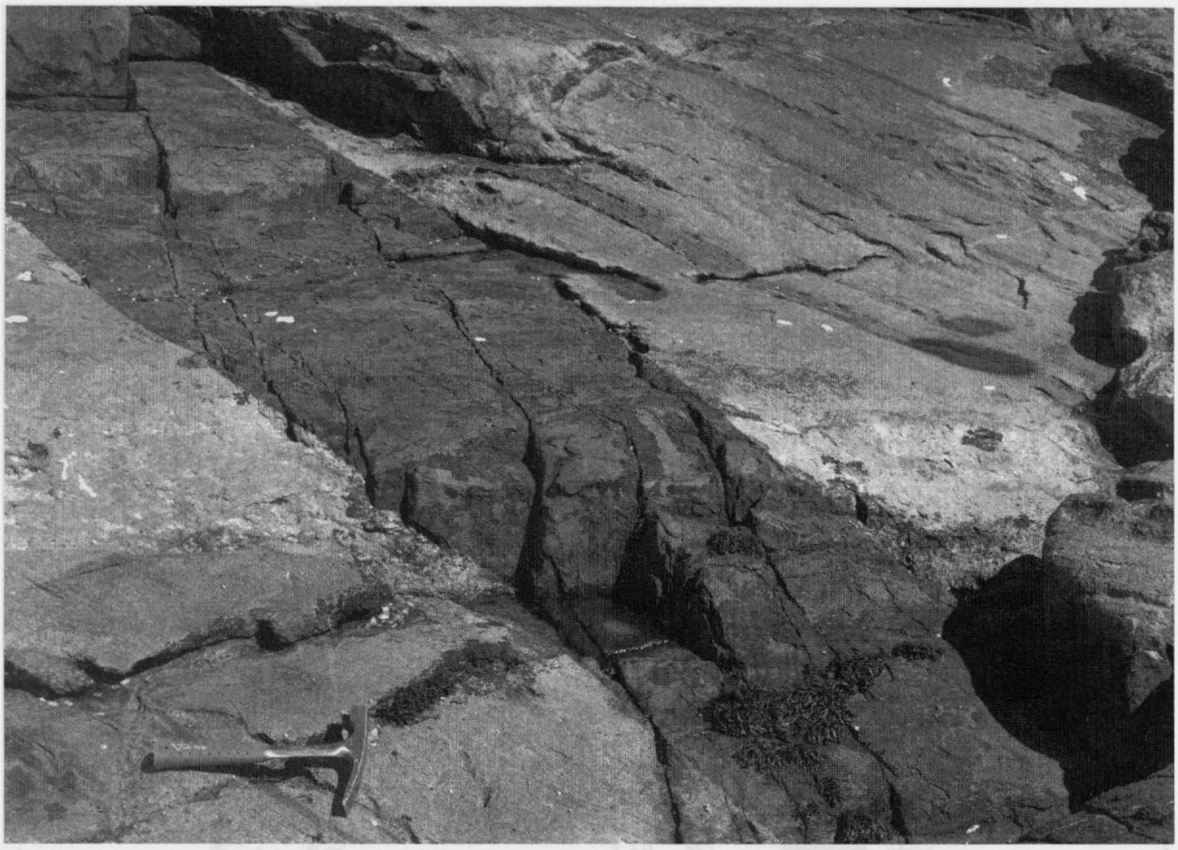


Figure 2.27 Photograph of undeformed 'Younger Basic' dyke cutting a late-Scourian pegmatite, which itself cuts a late-Scourian microdiorite dyke, Leinis peninsula (NF 7026 9836). The hammer is 28 cm long. (Photo: British Geological Survey, No. P219737, reproduced with the permission of the Director, British Geological Survey, © NERC.)

pegmatitic granite vein of either late-Scourian or Laxfordian age. Nearby, a pink, coarse-grained monzogranite encloses fragments of microdiorite. To the north of this locality there are several microdiorite sheets with included mafic schlieren both folded into tight minor folds and defining the internal fabric. Coarse-grained granite veins traverse the microdiorite sheets, and thin quartz-feldspar pegmatite veins cross-cut the biotite and hornblende fabric. North of these localities, towards Sloc nan Each, is a 2–4 m-high cliff which is effectively formed by a large (*c.* 8 m) mafic dyke. A *c.* 10 cm-wide offshoot of this dyke cuts across a pink granite at NF 7056 9959.

Palaeogene dolerite dykes occur throughout the section but are more abundant in the northern part. These later dykes commonly branch, cross-cut one another, and exhibit chilled margins and vesicle-defined flow fabrics.

Interpretation

The late-Scourian intrusive suites described above do occur elsewhere in the Outer Hebrides, although outwith eastern Barra the effects of Laxfordian structural and metamorphic reworking make their recognition difficult, and their original extent is effectively unknown. Microdiorite sheets and dykes have been recorded from the southern islands of Flodday and Mingulay and farther north from South Uist (Fettes *et al.*, 1992). Foliated and augened granite bodies occur extensively in North Uist, generally as kilometre-scale ovoid masses and here, at least, the late-Scourian granite suite is demonstrably of regional extent.

As mentioned above, Francis (1973) divided the area above the thrust in Barra into three NW-trending zones. The north-eastern zone is characterized by very low Laxfordian reworking, with discrete cross-cutting 'Younger Basic' dykes and evidence of several suites of late-Scourian intrusive rocks, as seen at the Leinis GCR site. In contrast, the middle zone shows a high degree of Laxfordian reworking, with the 'Younger Basic' dykes strongly deformed, migmatized and amphibolitized. This Laxfordian deformation masks any evidence of the late-Scourian intrusive suites, which, if present, have become indistinguishable from the earlier Scourian (Archaean) gneiss protoliths. The transition between the two zones is narrow, occurring over about 150 m on the south side of Bàgh Bhrèibhig (Brevig Bay), some 600 m south-west of the Leinis peninsula. The south-western zone is marked by moderate degrees of Laxfordian reworking with the 'Younger Basic' dykes locally folded and broken, but also, in places, displaying discordant contacts and relict granulite-facies mineralogies. No specific evidence of the late-Scourian intrusive suites has been found in that zone, although the gneisses in that area are dominantly of dioritic composition with subordinate bands of felsic gneiss. Hence, the south-western zone may represent a large late-Scourian diorite body modified during the subsequent Laxfordian deformational and metamorphic events.

Francis (1973) also recognized a zone below the thrust that shows evidence of very low Laxfordian strain, with pyroxene-bearing felsic gneisses and discordant late-Scourian intrusions similar to those at Leinis. This area, termed the 'Oitir Mhòr Zone', comprises the south-eastern part of the island of Fuday and the islands of Gighay, Hellisay and Fuiay. Francis determined that the Oitir Mhòr Zone lies in the core of a regional antiform, the Scurrival Antiform, a steep NW-plunging Laxfordian F3 fold whose axial plane trends north-west and dips steeply to the north-east. Its axial trace runs through Scurrival Point at the northern end of Barra. He also identified a complementary pinched-in synform lying about 1 km to the south-west. Francis (1973) correlated this synform with the Laxfordian strongly reworked 'middle zone' above the thrust and correlated the Oitir Mhòr Zone with the Leinis–Earsairidh area, the fold pattern being effectively foreshortened by the thrust. These relationships are consistent with the overall structural pattern of the Uists and Barra, which is dominated by similarly orientated, regional-scale, cuspate antiforms and pinched in synclines (see **North Uist Coast** and **Gearraidh Siar and Baile a' Mhanaich** GCR site reports, this chapter). However, there is no evidence of such Laxfordian folding in the gneisses above the thrust plane in eastern Barra.

Coward *et al.* (1970) noted that this Laxfordian folding is accompanied by high strain and pervasive recrystallization in the tight synformal zones, but that earlier folds, fabrics and textures are preserved in the lower-strain broader antiformal zones. They suggested that the cuspate fold pattern resulted from the deformation of a boundary running along the length of the islands that separates more-competent rocks to the east from those to the west. Francis (1973) utilized this idea to suggest that in Barra there is a boundary between competent 'eastern' gneisses and less-competent 'western' gneisses. He suggested that this boundary might have some fundamental significance, and may possibly consititute an early infrastructure–suprastructure contact of some form. However, this view was largely discredited by Moorbath *et al.* (1975), who showed from Rb-Sr and Pb-Pb isotopic systematics that the great bulk of the quartzo-feldspathic gneisses was derived from igneous protoliths generated shortly (100–200 million years) before the peak of Scourian metamorphism. They further argued that Scourian granulite-facies metamorphism was probably restricted to the south and east parts of the Uists and Barra. Hence, any differences in gneiss competency at the end of the Scourian reflected variations in the original igneous protoliths and the extent of Scourian granulite-facies metamorphism (see also Fettes *et al.*, 1992). Once formed, granulite-facies rocks are relatively anhydrous and tend to resist reworking. In contrast, zones of highly migmatized gneiss, once established, will tend to focus future strain and fluids. It is probable that in the Leinis GCR site area there was a coincidence of relatively dense protolith, which had had its competency further increased by granulite-facies metamorphism. This circumstance resulted in an exceptionally low level of Laxfordian reworking and the near-perfect preservation of the late-Scourian intrusive relationships.

Francis (1973) noted that the metamorphic orthopyroxene in the gneisses of the Leinis GCR site area is partially retrograded, whereas that found in the 'Younger Basic' Suite mafic dykes is pristine. He also noted that the intrusive granitoid bodies and the microdiorite dykes do not show evidence of granulite-facies metamorphism. To explain these observations he proposed that the granulite-facies metamorphism in the gneisses occurred during the main Scourian events, followed by partial retrogression under amphibolite-facies conditions in late-Scourian time. The intrusion of the microdiorites and granitoid rocks took place under these latter conditions.

The deformational episode that affects the microdiorites and monzogranites is not particularly intense in the Leinis GCR site area. However, in the Oitir Mhòr Zone, and particularly on the island of Fuday, it is significantly stronger. On Fuday the microdiorite dykes are tightly folded, yet are transected by undeformed 'Younger Basic' dykes (Fettes *et al.*, 1992, plates 8 and 9). This deformational episode is constrained to a period of *c.* 180–600 million years as it post-dates the late-Scourian pegmatites (*c.* 2600 Ma), and pre-dates the Palaeoproterozoic 'Younger Basic' Suite (*c.* 2420–2000 Ma). Fettes *et al.* (1992) correlated this deformation event with the similar-age Inverian episode of the mainland Lewisian. Elsewhere in the Outer Hebrides the degree of Laxfordian overprinting is normally too high to distinguish this episode and determine any regional pattern in its effects.

Intrusion of the 'Younger Basic' dykes also took place under amphibolite-facies conditions, probably at mid-crustal levels, although geothermal gradients at the time are unknown. However, the relatively anhydrous nature of the dykes resulted in their recrystallization with granulite-facies mineralogies (see Fettes *et al.*, 1992, for discussion).

The ages of the various intrusive lithologies as determined from field relationships at Leinis are pinned by the ages of the Archaean protoliths, the Scourian metamorphism (*c.* 2850–2700 Ma), the late-Scourian pegmatitic granites (*c.* 2600 Ma), the 'Younger Basic' mafic dykes (*c.* 2420–2000 Ma), and the Laxfordian granitic pegmatites (*c.* 1680 Ma) (see Table 2.1). Francis *et al.* (1971) obtained isotopic ages for the Archaean hornblendite and the two sets of pegmatites present on the Leinis peninsula. These ages were obtained using the K-Ar and Rb-Sr isotopic systems, which tend to record the time of closure or subsequent disturbance of the particular isotopic system (i.e. normally uplift or cooling), rather than the intrusive or metamorphic event itself. However, the low degree of Laxfordian reworking in the Leinis area has minimized such disturbance, and the ages obtained remain consistent with the generally accepted geological history and more-recent U-Pb zircon and Sm-Nd ages from the Lewisian Complex. Hence, although most of the ages will be younger than the age of intrusion the overall inferences are still thought to be valid.

Francis *et al.* (1971) obtained a K-Ar hornblende age of 2583 ± 34 Ma from the net-veined hornblendite pod on the eastern side of the Leinis peninsula confirming its Archaean age. They also obtained a five-point Rb-Sr isochron giving an age of 2610 ± 50 Ma from whole-rock samples of three discordant pegmatites that are cross-cut by 'Younger Basic' dykes at the southern end of the Leinis peninsula. A K-Ar biotite age of 1679 ± 25 Ma was obtained from a nearby, large, E–W-trending, discordant, pink-orange pegmatitic granite vein, dating these later pegmatitic veins as Laxfordian (Francis *et al.*, 1971). This last age is in good agreement with U-Pb zircon ages from the Laxfordian pegmatitic granites of South Harris (Mason and Brewer, 2005) and the Uig Hills–Harris Granite Vein-Complex (Friend and Kinny, 2001).

Conclusions

The well-exposed coastal section at the Leinis GCR site provides a unique insight into the earlier parts of the geological history of the Outer Hebrides. In particular, it provides a virtually undisturbed snapshot of the pattern of structures and rock types that existed at the end of the Archaean, following Scourian gneiss formation around 2900–2700 Ma and intrusion of numerous types of dioritic and granitoid rocks during the late-Scourian. It also contains excellent examples of the Palaeoproterozoic metadolerite dykes of the 'Younger Basic' Suite, intruded between 2420 Ma and 2000 Ma, and of Laxfordian pegmatitic granites. The reason that all these features are so well preserved is that the deformation and recrystallization associated with subsequent Laxfordian events, which took place between *c.* 1800 Ma and 1550 Ma, are virtually absent in this area. Although other areas of low Laxfordian reworking occur in the Hebrides, none show the scale and range of elements seen here.

The greater part of the Leinis GCR site is composed of Scourian felsic gneisses with subsidiary mafic sheets, lenses and pods, and rare ultramafic pods. The protoliths of these rocks were mainly granodioritic, tonalitic and doleritic sheets and dykes that were emplaced during the Archaean at around 2900–2730 Ma.

The presence of orthopyroxene in the gneisses implies that metamorphic conditions accompanying gneiss formation attained granulite facies, reflecting their formation at deep levels in the crust under extreme pressures and temperatures. These early-Scourian gneisses are cut by a sequence of late-Scourian intrusive rocks, which post-date the granulite-facies metamorphism and were intruded under middle amphibolite-facies conditions at mid-crustal levels. These 'later' dykes are markedly discordant to the earlier elements of the Lewisian gneisses and can be grouped into four suites: microdiorite dykes (oldest), granite and monzonite bodies, quartz-feldspar pegmatite veins, and the metadolerite dykes of the Palaeoproterozoic 'Younger Basic' Suite (youngest). A deformational episode post-dates the intrusion of the late-Scourian microdiorite–granite–monzonite suite, but pre-dates intrusion of the metadolerite dykes. It is equated with the Inverian event found in the mainland Lewisian rocks.

The exceptionally low degree of Laxfordian reworking in the Leinis GCR site results from the combination of its structural position in a possible Laxfordian antiformal hinge zone, and the relatively anhydrous and resistant nature of the gneisses. This latter property resulted from two factors, namely, a relatively competent early-Scourian igneous protolith, and the subsequent Scourian metamorphism at granulite facies. These unusual circumstances have given rise to a geological section that is of crucial importance in Hebridean geology. The site is of international importance in terms of understanding the early crustal history of the North Atlantic region and establishing correlations between Scotland and Greenland.

CNOC AN FHITHICH (AIRD GRÈIN), BARRA (NF 658 045)

J.R. Mendum

Introduction

The Cnoc an Fhithich GCR site lies on the Aird Grèin peninsula in north-west Barra and is notable for its stunning examples of pseudotachylite veins and breccias. Although the rocks lie structurally below the Outer Hebrides Fault Zone (OHFZ) in Laxfordian felsic and mafic gneisses, they show features more typical of those found within the fault zone itself. The black to pale-grey, 'cherty' pseudotachylite veins and irregular pods represent the melt formed by frictional heating of the relatively dry gneisses during seismic movements. They appear to lie in a diffuse, moderately ENE-dipping zone discordant to the regional gneissose foliation and may be of Grenvillian (*c.* 1100–1000 Ma) or Caledonian (*c.* 470–425 Ma) age. These fault rocks and others within the OHFZ have provided a focus for studies of the mechanisms of earthquake generation and for models of the nature of faulting at different crustal levels (see 'Introduction', this chapter).

The host Lewisian gneisses on Aird Grèin are coarsely banded, partially migmatitic, felsic and subsidiary mafic gneisses that have been strongly reworked during the Laxfordian event. They contain irregular amphibolitic mafic pods and lenses that probably originated as members of the 'Older Basic' and 'Younger Basic' suites. The migmatitic aspect of the gneisses may relate partly to their earlier Scourian history, but undoubtedly has been enhanced by coarse recrystallization under amphibolite-facies conditions during the Laxfordian event. The gneissose banding has an overall moderate dip to the NNE.

Pseudotachylite breccia occurs widely along the trace of the Outer Hebrides Thrust, a marked feature that defines the base of the OHFZ in the Uists and Eriskay. In Barra pseudotachylite characterizes a major thrust zone that can be traced west from the islands of Fuiay and Flodday to Loch Ob and Beinn Bheireasaigh (NF 684 027). From here it turns south down the central hilly spine of Barra to Sheabhal (Heaval) and Castlebay (see Figure 2.28). There is some doubt as to whether this thrust represents the OHFZ, or whether a more-significant part of the fault zone occurs offshore to the east in the Sea of the Hebrides, which seems more probable (Fettes *et al.*, 1992).

Throughout the Outer Hebrides pseudotachylite veins and breccias are commonly seen structurally below and to the west of the OHFZ (e.g. see **Cnoca Breac** GCR site report, this chapter). In most instances they have caused only minor disruption to the gneissose banding and represent small amounts of seismic fault movement. In Barra occurrences are found on Beinn Mhartainn (NF 664 021), in Bàga Thalaman (Halaman Bay), and on Ben Tangabhal in the south.

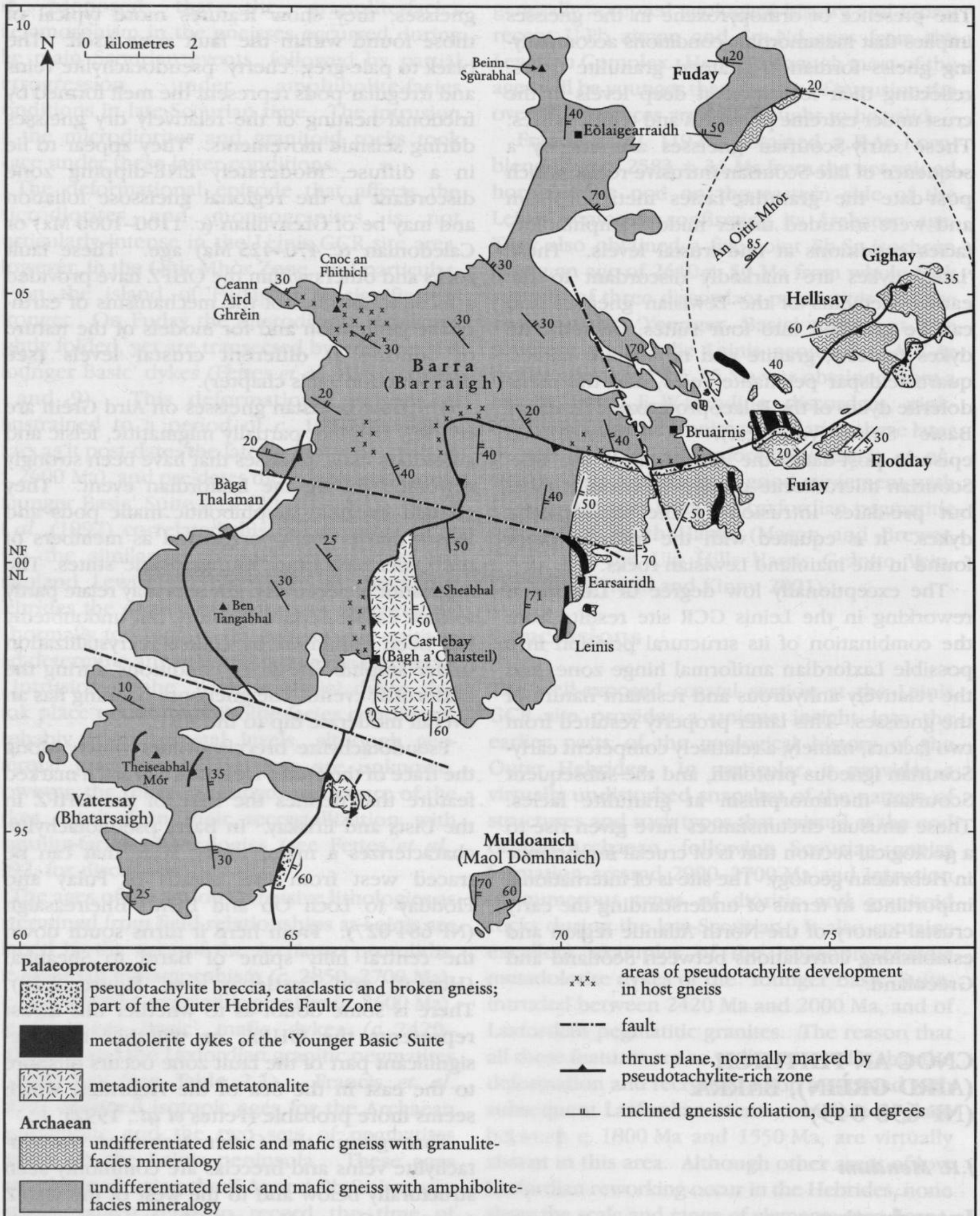


Figure 2.28 Simplified geological map of Barra showing Cnoc an Fhithich and other features related to the Outer Hebrides Fault Zone. Based on 1:100 000 geological map, Institute of Geological Sciences (1981).

Although MacCulloch (1819) made the first reference to 'trap-shotten' gneiss in the Outer Hebrides, it was Jehu and Craig (1923) who mapped out the general distribution of fault rocks on Barra and subsequently delineated the OHFZ on the Uists and on Lewis and Harris

(Jehu and Craig, 1925, 1926, 1927, 1934). In Barra, they recognized the presence of pseudotachylite, described its petrographical nature, and correctly ascribed its origin to melting of the country rock due to intense frictional heating caused by fault movement. Hopgood (1964) and Francis (1969) later carried out mapping as part of PhD studies on Barra, and defined most of the detailed occurrences of pseudotachylite. Bowes and Hopgood (1969) reported that pseudotachylite networks in Mingulay Bay are overprinted by the Laxfordian S3 foliation, but subsequent work by the Geological Survey showed that the fault rocks post-date all the Laxfordian deformation and granite intrusion (Fettes *et al.*, 1992).

Description

The hill of Cnoc an Fhithich forms the highest part of the broad rounded 'hogsback' of the Aird Grèin peninsula and rises to 96 m above OD. It is formed of glaciated, clean, periodically 'sandblasted' exposures, separated by grassy sandy depressions. Much of the site area is now a golf course belonging to the Barra Golf Club.

The Lewisian rocks are grey to buff and pink and white, banded, biotite- and hornblende-bearing felsic gneisses, with subsidiary dark green-black amphibolite bands and pods. Quartz-feldspar pegmatite patches up to a few metres across are moderately common. The rocks have a relatively crude banding and are coarsely recrystallized in parts. The banding and coincident foliation have a regionally consistent dip of *c.* 30° to the NNE. Several WNW- to NW-trending Palaeogene basalt and dolerite dykes, ranging from 1 m to 2.5 m thick, have been eroded into subvertical clefts on the coastal section, and are marked by grassy gullies inland.

The pseudotachylite is a black to charcoal grey, ultra-fine-grained rock that resembles its glassy basaltic namesake (tachylite). Jehu and Craig (1923) and Sibson (1975, 1977b) have reported relict glass from thin-section studies, but in almost all instances the glass is now devitrified (see Fettes *et al.*, 1992). It is commonly weathered or altered to a pale-grey colour. On Aird Grèin, pseudotachylite occurs in millimetre- to centimetre-thick veins and in irregular patches and masses that in places reach up to about 1 m thick. The veins range from planar to irregular, lensoid and bifurcate, and commonly have splays and offshoots. In parts they cross-cut one another and form intersecting networks. Pseudotachylite is commonly very closely jointed, and where planar vein surfaces are exposed, a fine tessellate jointing pattern is commonly seen. Pseudotachylite veins can be related to low- to moderate-angle dislocations and in many instances distinct offsets of the gneissose banding are visible. These dislocation surfaces range from low-angle thrusts to steeper reverse and normal faults.

A characteristic example of a pseudotachylite 'breccia' is seen at NF 6596 0419, where a fault plane dipping moderately to the north-west bounds the main development of pseudotachylite, which is concentrated in the hanging-wall. The gneiss is broken and disorientated to varying degrees, with a more-competent quartz-feldspar pegmatite apparently focusing movement along its margins. The pseudotachylite vein network is probably the result of several small seismic events. Discontinuous planar pseudotachylite veins cut the complex in its upper part and also occur in the footwall gneisses. A smaller-scale example is illustrated in Figure 2.29. Here the generation plane is near-horizontal, but melt has migrated into the foot-wall; net-veining and 'arrested' stages in the development of a 'breccia' or 'conglomerate' can be seen. Although pseudotachylite normally can be related to a specific surface, the main concentrations tend to occur in the adjacent gneisses, reflecting the near-instantaneous melt migration into adjacent fractures. This process can occur to the extent that the gneiss merely forms abundant inclusions in a pseudotachylite 'matrix'. The resultant rock-type, a pseudotachylite breccia or 'conglomerate', typically contains rounded gneiss fragments as well as pre-existing pseudotachylite (Figure 2.29b).

In thin section pseudotachylite is a black or brown isotropic devitrified glass with the colour reflecting the included, very finely divided, opaque minerals. In some of the thicker veins radiating millimetre-size feldspar microlites are present. Quartz and feldspar porphyroclasts are very abundant where the pseudotachylite has formed from quartzofeldspathic gneiss. The quartz inclusions are typically angular with some showing corroded margins. Internally they have strain shadows and commonly show a network of fine cracks defined in part by opaque dust. In contrast, the feldspars are rounded to angular with diffuse margins, but irregular twinning,


(a)


(b)

◂**Figure 2.29** Cnoc an Fhithich. (a) Pseudotachylite veining in Lewisian gneisses on the south side of Aird Grèin (at NF 6582 0402). The hammer is 42 cm long. (Photo: British Geological Survey, No. P008346, reproduced with the permission of the Director, British Geological Survey, © NERC.). (b) Pseudotachylite breccia showing rounded and angular clasts and patchy development of pseudotachylite on Aird Grèin. The hammer is 37 cm long. (Photo: J.R. Mendum.)

internal fracturing and strain shadows are common. Hornblende and biotite are normally consumed by the melting, with wall-rock crystals showing ragged edges. Jehu and Craig (1923) gave admirable descriptions of these phenomena. Some specimens show fine flow-banding textures in thin section and many show evidence of different generations of pseudotachylite. In addition, what appears to be wholly pseudotachylite is commonly an admixture of isotropic material and fine-grained cataclasite and ultracataclasite. Cataclasite is a cohesive, microcrystalline, crush breccia with fragments mostly too small to be seen with the naked eye (< 0.2 mm across).

Interpretation

The Lewisian gneisses in the Cnoc an Fhithich GCR site area have been strongly recrystallized and have a pervasive Laxfordian planar fabric attributed to the combined $D2_L$ and $D3_L$ structural and related metamorphic events. The gneissose banding is somewhat diffuse, with few detailed Archaean features preserved. Zones of granitoid material and pegmatitic patches are common and the mafic bodies are all thoroughly amphibolitic and foliated.

The pseudotachylite occurs in a diffuse zone that represents multiple, small-scale seismic faulting in the Lewisian gneisses of north-west Barra. This zone can be linked to occurrences of pseudotachylite farther south in Bàgh Thalaman (Halaman Bay) and on Ben Tangabhal where discrete thrusts have been mapped (see Figure 2.28). The occurrences together constitute an ESE-dipping zone that mimics the main thrust outcrop on Barra and may well represent a structurally lower part of the OHFZ. The age of faulting and pseudotachylite generation is not known, but is probably Grenvillian (*c.* 1100–1000 Ma) or Caledonian (*c.* 470–425 Ma) (see Fettes *et al.*, 1992; Imber *et al.*, 2001).

Jehu and Craig (1923) correctly interpreted pseudotachylite to be a product of frictional melting on fault planes during seismic movement, based on the features seen in the rocks on Barra. Later work by Sibson (1975, 1977b), mainly in the Uists and on Lewis, documented the nature of the pseudotachylite and its relationship to other fault rocks (see Fettes *et al.*, 1992; and 'Introduction', this chapter). It is clear from theoretical studies that the time frame for the generation of frictional melts during seismic movement and their cooling time are very small, normally only a few minutes in total (e.g. McKenzie and Brune, 1972; Sibson, 1977a). The fluid pressure of the melt, and brief but extreme temperature gradient, enable the melt to penetrate fractures or exploit inherent weaknesses in the rocks adjacent to the generation surface. Hence the melt may inject upwards, downwards, or sidewards, giving rise to lensoid and irregular masses of pseudotachylite. Blocks surrounded by the melt tend to be corroded and rotated, and Sibson (1975) documented examples from the Outer Hebrides. He suggested that with continued melt development the sudden heating would overpressure fluid inclusions in the gneiss blocks and consequently explosive decrepitation would occur in their marginal parts. Such effects would be maximized at their corners and hence the blocks or fragments would become rounded, resulting in a pseudotachylite 'conglomerate'. Sibson (1975) showed that such a process was geologically feasible and also documented relationships between amounts of fault movement and thicknesses of pseudotachylite generated. He noted that the zones of pseudotachylite, once formed, are stronger than the surrounding gneisses, and hence further fault movements occur adjacent to existing concentrations. The end results are wide zones of pseudotachylite net-vein and breccia development such as that seen at Cnoc an Fhithich (e.g. Figure 2.29b).

Sibson (1975) also postulated that the pressure (P) and temperature (T) conditions that prevailed at the time of seismic faulting were less than 3 kbar and 300° C respectively. Such values are typical of brittle fracture conditions above the frictional–viscous (brittle–ductile) transition that normally lies between 10 km and 15 km depth in the crust. He suggested that the P–T conditions at the time of pseudotachylite formation in the Outer Hebrides were compatible with crustal depths between 2 km and 10 km. Sibson (1977a) erected a fault-zone model based on his work in the OHFZ that envisaged frictional movement occurring at shallow crustal levels, coeval with ductile movement at mid- to lower crustal levels. However, Imber *et al.* (2001) have rejected the Sibson–Scholz model based on their more-recent work on the OHFZ (see 'Tectonic history of the Outer Hebrides Fault Zone' in the 'Introduction' to this chapter).

Conclusions

The Cnoc an Fhithich GCR site provides excellent examples of pseudotachylite vein and breccia development. Pseudotachylite represents frictional melts of the country rock formed by fault movements. The resultant melted rock solidifies very rapidly as a glass but devitrification normally occurs rapidly so that the rock is now a pale- to dark-grey and black, apparently cherty material. The complex geometry of these veins and lenses and their interaction with pre-existing features of the Laxfordian felsic and mafic gneisses are beautifully exposed on clean, etched crags and gently sloping surfaces within the site area. The pseudotachylite was generated on relatively planar fault surfaces but has migrated into the adjacent gneisses, so that offshoots, pods, lenses, breccias, and even pseudo-conglomerates are common. Displacements across the fault surfaces range from a few centimetres to a few metres.

The zone of pseudotachylite development at Cnoc an Fhithich lies structurally below the Outer Hebrides Fault Zone (OHFZ) and forms part of an embryo thrust zone in western Barra. It represents one of the main types of fault rock seen in the OHFZ and may be of Grenvillian (1100–1000 Ma) or Caledonian (*c.* 470–425 Ma) age. These occurrences have been a prime area of study since Jehu and Craig (1923) first recognized the true frictional melt origin of the material. The site is very valuable for educational purposes and of national and even international importance.