Lewisian, Torridonian and Moine Rocks of Scotland

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Chapter 3

Lewisian of the Scottish mainland

INTRODUCTION

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The first comprehensive account of the Lewisian Gneiss Complex of the Scottish mainland appeared in the Geological Survey memoir for the North-west Highlands, in which Peach *et al.* (1907) summarized the results of some 20 years of detailed mapping. The authors recognized that the Lewisian is made up of a wide range of different gneisses derived from igneous rocks of various ages, together with minor meta-sedimentary rocks, all of which have been subjected to strong deformation and high-grade metamorphism. It was realized that the Lewisian outcrop is a 'complex', affected by a series of events over a lengthy timespan.

Peach *et al.* (1907) established the following simple chronological sequence. An older assemblage of rocks termed the 'fundamental complex', mainly consisting of quartzofeldspathic gneisses, was intruded by a younger assemblage consisting of various intrusions, including mafic to ultramafic dykes of the 'Scourie Dyke' Suite. Both assemblages were subsequently affected by deformation, which caused severe structural and metamorphic modifications in certain areas, notably the northern and southern parts of the mainland, leaving the central part comparatively unscathed. These movements did not affect the oldest of the overlying sedimentary sequences, the Torridonian, and were termed the 'Pre-Torridonian movements'.

The chronological subdivision of the Lewisian was addressed again half a century later by Sutton and Watson (1951) in a classic paper based on their work in the Loch Torridon and Scourie areas. Sutton and Watson interpreted the chronology of the complex in terms of successive orogenic cycles: the older (corresponding to the 'fundamental complex' of Peach *et al.*, 1907) termed the 'Scourian', and the younger the 'Laxfordian'. The two cycles were separated by the intrusion of the Scourie dykes, which they regarded as anorogenic and emplaced essentially contemporaneously. Thus the concept arose of Scourian *rocks*, formed during Scourian *time*, which were reworked during Laxfordian *time*. This work followed on from Sederholm's studies in Finland which pioneered the use of igneous events as 'stratigraphical' markers to separate different periods of tectonothermal activity (Sederholm, 1926). A similar methodology was also devised and applied in the basement areas of south-west Greenland (e.g. Ramberg, 1949). This use of tectonic events to create tectonostratigraphical units in complex basement terrains is a concept that has been much copied subsequently. Allied with later-developed isotopic dating techniques, this approach has opened up new avenues in the understanding of such terrains.

This 'stratigraphical' interpretation was modified by the work of Tarney (1963), Evans and Tarney (1964), Park (1964), and Evans (1965), which showed that a second major tectono-metamorphic event took place before, and possibly during, the period of Scourie dyke emplacement. This event, named the 'Inverian' by Evans (1965), has now been generally recognized throughout much of the Lewisian Gneiss Complex. The similarity of structural style and orientation, and of metamorphic facies, between the Inverian event and the later Laxfordian event has led to considerable confusion and debate. Structures can only be confidently assigned to one or the other event where Scourie dykes can be seen either to cut or be affected by the structures in question.

Park (1970) suggested that the division between the early Scourian event (for which he proposed the term 'Badcallian') and the Inverian event represented the major tectonic break within the Lewisian timespan, and this break is now recognized as occurring in Scotland at *c.* 2500 Ma, at the Archaean–Proterozoic boundary (see Table 3.1).

Division of the mainland Lewisian outcrop

The Lewisian Gneiss Complex of the Scottish mainland has been divided into three separate regions – Northern, Central and Southern (Figure 3.1). The Central Region extends for *c.* 65 km from north of Scourie to south of Gruinard Bay, and is composed mostly of granulite-facies gneisses that have been relatively unmodified by the younger (Laxfordian) amphibolite-facies metamorphism. These rocks are intruded by the typically undeformed but metamorphosed mafic and ultramafic dykes of the Scourie Dyke Suite that generally trend north-west to west.

The Northern and Southern regions, on the other hand, represent belts where the original gneisses have been highly modified by

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

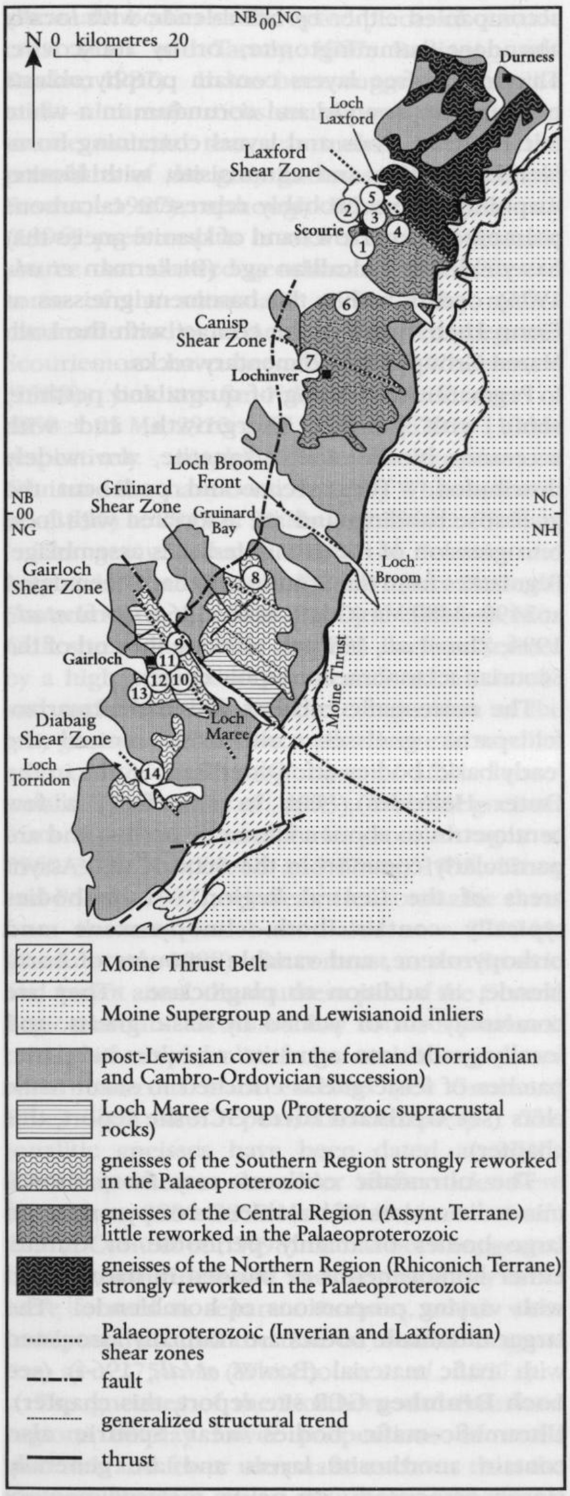
Event	Northern region	Central region	Reference
Laxfordian metamorphism	1750–1670 Ma	1750–1670 Ma	Corfu *et al.* (1994); Kinny and Friend (1997); Zhu *et al.* (1997a,b)
granite sheets	1855 Ma		Friend and Kinny (2001)
Scourie dyke emplacement	no age data	2020–1920 Ma	Heaman and Tarney (1989); Waters *et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

Laxfordian deformation and amphibolite-facies metamorphism (Figure 3.1). The only Proterozoic metasedimentary units within the mainland Lewisian are those of the Loch Maree Group, which crops out in the Southern Region at Loch Maree and Gairloch (Figure 3.1).

The Northern Region extends from Loch Laxford to Cape Wrath on the north coast. It is separated from the Central Region by a transition zone several kilometres wide, which shows a progressive change northwards from granulite-facies gneisses to amphibolite-facies hornblende- and biotite-gneisses in a zone of intense Inverian and Laxfordian deformation (Beach *et al.*, 1974).

The Southern Region extends from south of Gruinard Bay to Loch Torridon, and includes the islands of Rona and Raasay. It is separated from the Central Region by a wide transition zone extending from Gruinard Bay to Fionn Loch, north of Loch Maree, where Inverian deformation and amphibolite-facies metamorphism have strongly modified the gneisses (see **Gruinard River** GCR site report, this chapter). The Scourie dykes are little affected here by Laxfordian deformation, which only becomes intense at the southern margin of the transitional zone, around Fionn Loch and Loch Maree, and farther south.

The original extent of the Scourian 'complex', and the proportion of distinctly younger material within the Lewisian outcrop, have been the subjects of considerable debate in the past. Peach *et al.* (1907), followed by Sutton and Watson (1951), considered that the 'fundamental complex' or Scourian (now known to be Archaean in age) extended throughout the whole of the mainland belt. They based their belief on the presence of amphibolite sheets similar to the Scourie dykes within both the



◄**Figure 3.1** Simplified map of the Lewisian Gneiss Complex of mainland Scotland. GCR sites: 1 – **Badcall**; 2 – **Scourie Mor**; 3 – **Sìthean Mòr**; 4 – **Scourie Bay**; 5 – **Tarbet to Rubha Ruadh**; 6 – **Loch Drumbeg**; 7 – **An Fharaid Mhòr to Clachtoll**; 8 – **Gruinard River**; 9 – **Creag Mhòr Thollaidh**; 10 – **Kerrysdale**; 11 – **Flowerdale**; 12 – **An Ard**; 13 – **Loch Braigh Horrisdale to Sidhean Mòr**; 14 – **Alligin (Diabaig)**. After Park and Tarney (1987).

Northern and Southern regions. However, others (e.g. Bowes, 1968a,b; Holland and Lambert, 1973) suggested that much of the material of the Laxfordian 'complexes' may have represented post-Scourian supracrustal sequences, and that there were several generations of amphibolitic mafic dykes.

Isotope geochronology has thrown considerable light on this debate. Early Sm-Nd data were interpreted as indicating that much of the crust of the mainland Lewisian belt formed during the interval 2900–2700 Ma (Hamilton *et al.*, 1979; Whitehouse, 1988, 1989). However, on the basis of Sm-Nd model ages, Whitehouse (1989) suggested that the accretion of the mainland Lewisian may have been diachronous, with the crust of the Northern Region being younger than that of the Southern Region. More recently, high-precision (SHRIMP) U-Pb zircon dating has shown that some of the gneisses around Scourie, in the Central Region, have protolith ages of *c.* 2960 Ma (Friend and Kinny, 1995). By contrast, the protolith ages for samples from Gruinard Bay, in the southern part of the Central Region, lie in the range 2850–2750 Ma (Whitehouse *et al.*, 1997a; Corfu *et al.*, 1998). Samples from the Northern Region have similar protolith ages of 2840–2800 Ma (Kinny and Friend, 1997).

Pidgeon and Bowes (1972) gave an estimate, based on lead isotopic compositions, for the Archaean granulite-facies metamorphism (Badcallian) of *c.* 2700 Ma. More-recent U-Pb zircon and monazite dates confirm that the main magmatic and high-grade metamorphic events occurred at *c.* 2710–2760 Ma (Corfu *et al.*, 1994, 1998; Zhu *et al.*, 1997b). The Archaean age of the 'fundamental complex' of the mainland is thus firmly established, although there are clearly complex variations in age and composition of the various components (e.g. Kinny and Friend, 1997). Indeed, Friend and Kinny (2001) have suggested that the regions should be renamed to reflect these differences, with the Northern Region termed the 'Rhiconich Terrane', and the northern part of the Central Region the 'Assynt Terrane'. The southern part of the Central Region, around Gruinard Bay, would be termed the 'Gruinard Terrane', but the dividing line between the Assynt and Gruinard terranes is problematic (C.R.L. Friend, pers. comm., 2002). Although these names are now in the literature, they do present some problems and have been the subject of discussion (e.g. Park, 2005). Hence, the division into Southern, Central and Northern regions is retained in this review.

The granulite-facies gneisses

Lithologies

In common with the earliest elements of many other Archaean high-grade terrains, the early gneisses of the Lewisian Gneiss Complex are predominantly banded, and less commonly massive, grey gneisses of tonalitic or granodioritic composition, with minor sheets or lenses of granitic gneiss. Mafic and ultramafic layers and enclaves are common in the Central Region, but metasedimentary gneisses are relatively uncommon. The grey gneisses in the unmodified parts of the Central Region make up roughly between 75% and 80% of the complex, and typically contain pyroxene and/or hornblende. Pyroxene-hornblende felsic gneisses in which hornblende aggregates have replaced pyroxene are the most abundant type. Biotite- and muscovite-bearing felsic gneisses are common in the Central Region only in areas of later reworking, but are universally present in the Northern and Southern regions, where it is much more difficult to determine the original nature of the gneisses due to the effects of Laxfordian reworking.

Metasedimentary rocks formed prior to the Badcallian event are comparatively rare in the mainland outcrops. A few narrow bands of metasedimentary rock are associated with the mafic–ultramafic layered bodies described below (e.g. see **Tarbet to Rubha Ruadh** GCR site report, this chapter). Others solely within the grey tonalitic gneisses are found around Scourie Bay (see **Sìthean Mòr** GCR site report, this chapter). These bands consist mainly of rusty-weathering, biotite-muscovite semipelitic schists and gneisses, but include minor calc-silicate rocks and possible feldspathic sandstones (Okeke *et al.*, 1983; Cartwright *et al.*, 1985). A 75 m-thick metasedimentary band occurs within the grey gneisses near Stoer in the Assynt district (Cartwright *et al.*, 1985). These brown-weathering gneisses are quartzofeldspathic and contain abundant garnet and biotite, accompanied either by hornblende with locally abundant cummingtonite, or by muscovite. Thin quartz-free layers contain porphyroblasts of staurolite, kyanite and corundum in a white mica matrix. Pods and layers containing hornblende, epidote and clinozoisite, with biotite-scapolite augen, probably represent calcareous psammites. A narrow band of kyanite gneiss that has yielded a Badcallian age (Bickerman *et al.*, 1975) occurs within the basement gneisses at Fionn Loch, north of the contact with the Loch Maree Group metasedimentary rocks.

Pegmatites consisting of quartz and perthite, some with graphic intergrowth, and with accessory biotite and magnetite, are widely distributed. These veins and pods cut the gneissose banding, and are associated with local retrogression of the granulite-facies assemblage. Pegmatites from the Scourie area have been dated at 2490–2480 Ma (Giletti *et al.*, 1961; Corfu *et al.*, 1994; Zhu *et al.*, 1997b;), marking the end of the Scourian tectonometamorphic event.

The more-mafic enclaves within the quartzofeldspathic gneisses, collectively termed the 'early basic' bodies (cf. 'Older Basic' Suite in the Outer Hebrides), vary in size from a few centimetres to about a kilometre across, and are particularly common in the Scourie and Assynt areas of the Central Region. Such bodies typically contain both clinopyroxene and orthopyroxene, and variable amounts of hornblende, in addition to plagioclase. They are commonly cut or veined by felsic gneiss, and locally grade into agmatite or, ultimately, into patches of felsic gneiss enriched in small mafic clots (see **Gruinard River** GCR site report, this chapter).

The ultramafic enclaves vary from monomineralic masses of hornblende or pyroxene, to large bodies of mainly peridotite or dunite, either homogeneous or banded in nature, and with varying proportions of hornblende. The larger ultramafic bodies are normally associated with mafic material (Bowes *et al.*, 1964) (see **Loch Drumbeg** GCR site report, this chapter). Ultramafic–mafic bodies near Scourie also contain anorthosite layers and are generally closely associated with pelitic metasedimentary rocks (Davies, 1974).

The mafic–ultramafic bodies appear to be generally older than the felsic gneisses and to have been invaded by them; one speculative possibility, supported to some extent by geochemical evidence, is to interpret the mafic–

ultramafic bodies as disrupted pieces of oceanic crust (Park and Tarney, 1987; Rollinson and Fowler, 1987). It has been suggested that the mafic–ultramafic rocks could possibly represent source material that was melted to form the protoliths of the grey gneisses (Rollinson and Fowler, 1987), although Whitehouse *et al.* (1996) preferred to invoke a separate basaltic source that showed geochemical similarities to some of the ultramafic rocks. The mafic–ultramafic bodies at Achmelvich, Drumbeg and Scouriemore have been dated by Whitehouse (1989), yielding Sm-Nd whole-rock ages of 2850 ± 95 Ma, 2910 ± 55 Ma and 2670 ± 110 Ma respectively. Amphibolitic mafic intrusions at Gruinard Bay have been dated by Whitehouse *et al.* (1996) at 2943 ± 91 Ma and 2846 ± 73 Ma.

The granulite-facies terrain of Scourie and Assynt in the Central Region (see **Badcall**, **Scourie Mor**, **Scourie Bay** and **Sìthean Mòr** GCR site reports, this chapter) is characterized by a high proportion of intercalated ultramafic and mafic material, and the composition of the grey gneisses varies from mafic diorite to tonalite with only a small proportion of silicic leucotonalite (Sheraton *et al.*, 1973). Tonalitic gneisses from the Scourie area have protolith ages of 2960–3030 Ma (Friend and Kinny, 1995; Kinny and Friend, 1997), whereas a leucotonalite sheet from the area has been dated at *c.* 2720 Ma (Corfu *et al.*, 1998). In contrast to the Scourie and Assynt areas, the southern part of the Central Region around Gruinard Bay consists predominantly of amphibolite-facies tonalitic gneisses with numerous mafic enclaves (see **Gruinard River** GCR site report, this chapter). The tonalitic gneisses have been dated at 2730–2750 Ma, whereas the older mafic rocks were formed at 2800–2850 Ma (Whitehouse *et al.*, 1997a; Corfu *et al.*, 1998). It has been suggested that the Scourie–Assynt and Gruinard Bay areas were formed as separate terranes, which were juxtaposed around the time of tonalitic magmatism at *c.* 2750 Ma (Whitehouse *et al.*, 1997a).

The gneisses of the Northern and Southern regions display lower proportions of mafic material, and fewer ultramafic enclaves than the Central Region; they are more silicic and potassic, with a significant proportion of granodioritic material. The gneisses of the Northern Region were shown to be geochemically distinct from those of the Central Region by Holland and Lambert (1973), and Sheraton *et al.* (1973) concluded that the Northern Region gneisses had not reached granulite facies during the Badcallian event.

Park *et al.* (1994) suggested that these petrological and geochemical variations could reflect differences in original crustal level across the Lewisian outcrop; the gneisses of Scourie experienced granulite-facies metamorphism at high pressure, whereas the gneisses to the north and south were metamorphosed at lower pressures and temperatures and could represent originally higher crustal levels. However, Kinny and Friend (1997) have shown that gneisses in the Northern Region have protolith ages of 2800–2840 Ma, significantly younger than gneisses from the Scourie area of the Central Region. On this basis, they suggested that the two regions represented different blocks with separate accretionary and early metamorphic histories.

Origin of the gneisses

It is now generally accepted that the bulk of the gneisses are of plutonic igneous origin, as originally suggested by Peach *et al.* (1907). Geochemical studies (Weaver and Tarney, 1980; Rollinson and Fowler, 1987; Tarney and Weaver, 1987a) indicate that the gneisses have an essentially bimodal character, and that the two components display different petrogenetic characteristics. The mafic components show a range of Fe/Mg ratios and their trace-element and rare-earth-element (REE) patterns are consistent with low-pressure crystal fractionation of a tholeiitic magma. The common association of ultramafic–mafic bodies with metasedimentary layers suggests that this material represents fragments of ocean-floor crust, intercalated tectonically within the continental crust. The tonalitic to leucotonalitic gneisses, on the other hand, have REE patterns consistent with partial melting of a mafic source under high-pressure hydrous conditions. Rollinson and Fowler (1987) suggested that the mafic rocks of the Lewisian Gneiss Complex could represent a possible source material for the tonalitic gneisses. Tarney and Weaver (1987a) suggested that a subduction zone is the only environment where large volumes of mafic material could be melted in order to generate the tonalitic crustal material. They envisaged a process of shallow melting of oceanic crust in a low-angle subduction zone, where melts generated under hydrous conditions would have yielded relatively dense tonalitic magmas, which solidified at deep levels and progressively thickened the crust by underplating. Thus the mafic igneous–sedimentary (oceanic crust) association would have first experienced a high-grade metamorphic phase at the base of the continental crust before being uplifted by further underplating. The severe tectonic disruption of the deeper parts of the Lewisian Gneiss Complex may be attributed to long periods of ductile shear deformation affecting the base of the accreting crust as underplating proceeded. This model explains the concentration of mafic igneous and sedimentary material, originating at shallow crustal levels, in the deeper parts of the complex.

Deformation and metamorphism

The extreme heterogeneity of the Lewisian Gneiss Complex, coupled with the almost ubiquitous compositional banding, indicates generally intense deformation. The banding or foliation is typically subhorizontal or gently inclined over large areas of the Central Region (see Sheraton *et al.*, 1973), although it is steepened locally in Badcallian shear-zones.

The granulite-facies metamorphism is a characteristic feature of the gneiss complex in the Central Region, although retrogression to amphibolite facies is widespread (see Sills and Rollinson, 1987). This granulite-facies metamorphic event, termed the 'Badcallian' (Park, 1970), is generally accepted to have occurred at *c.* 2700 Ma, based on Sm-Nd and U-Pb isotopic age systems (Pidgeon and Bowes, 1972, Lyon *et al.*, 1973, Humphries and Cliff, 1982; Corfu *et al.*, 1994; Zhu *et al.*, 1997b). However, Kinny and Friend (1997) suggested on the basis of U-Pb SHRIMP zircon ages that the main granulite-facies metamorphism occurred at 2490–2480 Ma and they re-assigned the Badcallian event to this younger age (Kinny *et al.*, 2005). Their conclusions disagreed with those of Corfu *et al.* (1994) and Zhu *et al.* (1997a,b), who suggested that there were two granulite- or upper-amphibolite-facies events separated by some 200 million years. It is probable that high-grade metamorphic conditions persisted for a considerable time and the ages reflect intermittent closure of the isotopic systems and/or fluid input and metamorphic equilibration. Cohen *et al.* (1987) argued from Pb and Sm-Nd isotope data that temperatures did not fall below 650°–800° C until 2440–2420 Ma, and Zhu *et al.* (1997a) reached similar conclusions based on ^{207}Pb-^{206}Pb SIMS data from monazites. Barnicoat (1987) reviewed the geothermometric and geobarometric data for the Badcallian, which indicate peak temperatures of 1000° C and pressures of 10 kbar, with a subsequent steady decrease in both temperature and pressure.

The Inverian event

Major Inverian shear-zones have been recognized at the northern and southern margins of the Central Region. The zone at the northern margin is approximately 4 km wide and extends from near Scourie to Loch Laxford (see **Tarbet to Rubha Ruadh** GCR site report, this chapter; Beach *et al.*, 1974; Davies, 1978). On its south-west side, it cuts Badcallian structures and causes retrogression of the granulite-facies gneisses to amphibolite facies. On its north-east side, it is overprinted by the strong Laxfordian deformation associated with the Laxford Shear Zone.

A second major shear-zone occurs at the south-west margin of the Central Region between the Gruinard River and Fionn Loch, with a width of about 8 km (see **Gruinard River** GCR site report, this chapter). This zone is a mirror image of that to the north, being overprinted and obscured by the major Laxfordian deformation of the Southern Region on its south-west side (Crane, 1978; Park *et al.*, 1987). A third major shear-zone is the 1–2 km-wide Canisp Shear Zone (Tarney, 1963; Evans, 1965; Attfield, 1987), which cuts through the middle of the Central Region in the Assynt district (see **An Fharaid Mhòr to Clachtoll** GCR site report, this chapter).

U-Pb zircon and monazite dating techniques have been used to constrain the age of the Inverian metamorphic event. The age of amphibolite-facies reworking north of Scourie was determined at 2490–2480 Ma (Corfu *et al.*, 1994; Zhu *et al.*, 1997b). Similar dates have been obtained using the Sm-Nd system (Humphries and Cliff, 1982), although they were originally interpreted as reflecting cooling from an earlier high-grade metamorphic event. The Inverian event is considered to represent an early phase of upper amphibolite-facies metamorphism, followed by a progressive decrease in temperature and an increase in activity of fluid phases, so that injection of pegmatites and development of shear zones occurred under mid- and even lower-amphibolite-facies conditions (Corfu *et al.*, 1994; Zhu *et al.*, 1997a). The deformational and metamorphic event is deemed to have pre-dated most of the intrusions of the Scourie Dyke Suite and hence is bracketed between *c.* 2490 Ma and 2400 Ma. Evidence for the Inverian event has not been recognized in zircons from the Gruinard Bay area (Corfu *et al.*, 1998) or in the Northern Region (Kinny and Friend, 1997).

Thus, between 2500 Ma and 2400 Ma the mainland Lewisian Gneiss Complex apparently consisted of at least two separate blocks (the Central and the Northern regions). The history of the Southern Region during this period is not well known. The Central Region was by this time at low to mid-crustal level, cut by many minor steep shear-zones and by the larger Canisp Shear Zone, and bounded on both sides by major steep NW-trending shear-zones. The effects of the Inverian event appear to have been localized around the Scourie–Lochinver area, whereas the Gruinard Bay area seems to have largely escaped these events, although it may have undergone some deformation and retrogression (Corfu *et al.*, 1998).

The Scourie Dyke Suite

The Scourie dykes are typically steep, with a north-westerly to westerly trend, and for the most part appear to have been emplaced dilationally, implying considerable crustal extension. They are thickest and most numerous between Gruinard Bay and Torridon in the Southern Region, and decrease in abundance northwards towards Durness. In many areas, especially between Gairloch and Loch Torridon, they are significantly controlled by the pre-existing structure, becoming thinner and more numerous in zones of strong Inverian foliation (Park and Cresswell, 1972, 1973) (see **Alligin (Diabaig)** GCR site report, this chapter).

Tarney and Weaver (1987b) defined four types of Scourie dyke on the basis of petrology and geochemistry: bronzite picrites, norites, olivine-gabbros, and quartz-dolerites. The quartz-dolerites are by far the most abundant and correspond to the main 'epidiorite suite' recognized by Peach *et al.* (1907). There is evidence in the Central Region of dyke emplacement at depth into hot country rock (O'Hara, 1961b; Tarney, 1963).

The timing and duration of Scourie dyke intrusion has been investigated by a number of authors. The early K-Ar and Rb-Sr dating of Evans and Tarney (1964) gave a range of ages interpreted as indicating a date of *c.* 2200 Ma for the emplacement of the main swarm and *c.* 2000 Ma for two alkali-basalt and tholeiitic-basalt dykes. Subsequently Chapman (1979) obtained an Rb-Sr whole-rock age of *c.* 2400 Ma from three typical quartz-dolerites, and Humphries (1982) obtained an Sm-Nd isochron date of 2260 ± 40 Ma on a metadolerite dyke. Heaman and Tarney (1989) reported U-Pb baddeleyite ages of 2418 + 7/–4 Ma for a bronzite picrite and 1992 + 3/–2 Ma for an olivine-gabbro, and hence suggested that there were two discrete episodes of emplacement of the Scourie Dyke Suite. Waters *et al.* (1990) obtained Sm-Nd mineral ages of 2015 ± 42 Ma, 2031 ± 62 Ma, and 1982 ± 44 Ma for olivine-gabbros, and 1982 ± 44 Ma for a quartz-dolerite.

These data are generally consistent with the interpretation that there were two phases of Scourie dyke emplacement: a first around 2400 Ma, at crustal depths of 10–20 km, during or shortly after the Inverian metamorphism (see Dickinson and Watson, 1976); and a second, much later phase at *c.* 2000 Ma. All these dates are for dykes from the Central Region, and no emplacement ages have been obtained from Scourie dykes in the very extensive areas of Laxfordian reworking.

The Loch Maree Group

Two belts of metasedimentary rock, with a combined outcrop area of about 130 km^2, were first described in detail by Peach *et al.* (1907) around Loch Maree and Gairloch in the Southern Region. Both outcrops exhibit intense polyphase deformation. Peach *et al.* (1907) were unable to decide whether the sedimentary rocks were older than the igneous rocks of the 'fundamental complex', or lay unconformably upon them (see discussion in Peach and Horne, 1930). They noted that the boundaries were tectonically modified and that gneisses appeared to be thrust over metasedimentary rocks at Loch Maree. Park (1964, 1965) compared the structural and metamorphic histories of the orthogneisses and metasedimentary gneisses, and concluded that the metasedimentary rocks were younger. O'Nions *et al.* (1983) obtained Sm-Nd model ages of 2490 Ma and 2190 Ma on two samples of clastic metasedimentary rock that supported this view. The model ages have been interpreted as a product of mixing of late Archaean source material with a component of juvenile material having an age closer to the depositional age of the sediments. This model is supported by U-Pb zircon dating (Whitehouse *et al.*, 1997b) that indicates a range of ages for the source material, with significant components between 3100 Ma and 2500 Ma, and between 2200 Ma and 2000 Ma. Geochemical arguments have been used to suggest that basic volcanic rocks in the Loch Maree Group itself are a likely source of the younger material (Floyd *et al.*, 1989). The younger age limit for deposition of the supracrustal rocks is constrained by the date of intrusion of the Ard Gneisses at *c.* 1900 Ma and by the subsequent Laxfordian metamorphism (Park *et al.*, 2001). Hence, the age range for sedimentation of the Loch Maree Group lies between *c.* 2000 Ma and 1900 Ma.

The supracrustal assemblage consists of a thick sequence of amphibolites, of probable volcanic origin (Park, 1966, 2002; Johnson *et al.*, 1987), intercalated with semipelitic schists and minor layers of metacarbonate rock, banded-iron formation and graphitic schist (see **Flowerdale** and **Kerrysdale** GCR site reports, this chapter). From their geochemical work on the supracrustal rocks, Johnson *et al.* (1987) suggested that the Loch Maree Group represents the fill of an extensional rift basin in which early, relatively rapid, extension was marked by voluminous outpourings of tholeiitic basalts on thinned continental crust. Park *et al.* (2001) studied the geochemistry further and suggested that the Loch Maree Group represents a deformed Palaeoproterozoic accretionary complex in which slices of ocean-floor material have been tectonically juxtaposed with continentally derived clastic material at an active margin. In this interpretation, the outcrop of the Loch Maree Group would represent a Palaeoproterozoic collisional suture, with the accretionary complex 'sandwiched' between two blocks of Archaean continental crust.

The Loch Maree Group shares the same Laxfordian deformational and metamorphic history as the basement gneisses of the Southern Region, and the metamorphic assemblages are typical of middle- to upper-amphibolite facies. Droop *et al.* (1998) studied the metamorphic assemblages of the Loch Maree Group, and concluded that at the peak of metamorphism temperatures attained 530 ± 20° C, and pressures 6.5 ± 1.5 kbar. Over most of their outcrop, the rocks of the Loch Maree Group do not exhibit any migmatization or veining by granite or pegmatite, but along the north-west margin of the outcrop at Gairloch is a belt of foliated and gneissose tonalite and granodiorite (the Ard Gneisses) which enclose amphibolite sheets veined by granitic and pegmatitic material (see **An Ard** GCR site report, this chapter). The Ard Gneisses have been dated at 1903 + 3/−2 Ma (Park *et al.*, 2001) and are clearly intrusive into the supracrustal rocks. Their geochemistry indicates a primitive arc signature, showing that they represent a significant addition of juvenile material to the Loch Maree Group at that time.

Laxfordian modifications and younger events

A consequence of the recognition of two separate dyke-swarms in the Sourie Dyke Suite is that events following emplacement of the *c.* 2400 Ma dykes but prior to the *c.* 2000 Ma dykes could be regarded as both Laxfordian and Inverian. In practice, structures and metamorphism affecting any of the Scourie dykes have been regarded as Laxfordian, following Sutton and Watson (1951). Laxfordian modifications on the mainland can be divided simply into an earlier set associated with amphibolite-facies metamorphism and emplacement of granites and pegmatites, and a later set accompanied by retrogressive alteration to greenschist-facies or lower metamorphic grades (see Table 3.1). The earlier Laxfordian deformations produced fabrics in the Scourie dykes, associated generally with amphibolite-facies recrystallization of the original igneous assemblages. In many areas, recrystallization has occurred in the absence of deformation, producing the typical 'epidiorite' dyke textures of the Central Region. It is possible that this recrystallization was widespread on the mainland, representing a continuation of the Inverian metamorphic event.

Two distinct phases of Laxfordian metamorphism are recorded in titanite and monazite U-Pb data from across the Central and Northern regions; the earlier, amphibolite-facies event at *c.* 1740–1750 Ma and the later, lower-grade overprint at *c.* 1670 Ma (Corfu *et al.*, 1994; Kinny and Friend, 1997; Zhu *et al.*, 1997b; Kinny *et al.*, 2005). Friend and Kinny (2001) obtained a U-Pb SHRIMP zircon age of *c.* 1855 Ma from the granitic sheets within the Northern Region, close to the Laxford Front, showing that they were emplaced prior to the main metamorphic event. Similar granitic sheets have been recognized south of the Laxford Front, within the Inverian shear-zone, leading Goodenough *et al.* (in press) to infer that the juxtaposition of the Northern and Central regions (Rhiconich and Assynt terranes) occurred prior to granite intrusion, probably during the Inverian. In the Southern Region, the dating of the Ard Gneisses at *c.* 1905 Ma (Park *et al.*, 2001) may indicate that Laxfordian deformation occurred earlier in this region than in the Central and Northern regions.

The earlier Laxfordian structures are very heterogeneous in their development. In the Central Region, they are mainly confined to narrow shear-zones of the order of metres in width, and to reactivation of Inverian shear-zones, in particular the much wider Canisp Shear Zone (see **An Fharaid Mhòr to Clachtoll** GCR site report, this chapter) (Attfield, 1987). The main Laxfordian belts are situated in the Northern and Southern regions (Figure 3.1). In both regions, the first Laxfordian deformation is generally subconcordant with the Scourie dykes, progressing from narrow marginal zones to eventually encompass the whole width of the dyke, and spreading out into the host gneisses (e.g. see **Loch Braìgh Horrisdale to Sidhean Mòr** GCR site report, this chapter). The first Laxfordian fabric is associated with variable, locally very intense, deformation and is typically steep near the margins of the Laxfordian belts. In the Southern Region, Park *et al.* (1987) showed that this fabric, formed during the first phase of the Laxfordian deformation (D1), was folded during a second phase (D2) and is flat-lying between Carnmore and Gairloch, and south of Loch Torridon (e.g. see **Alligin (Diabaig)** and **Creag Mhòr Thollaidh** GCR site reports, this chapter). Thorough reworking of the original gneiss produces a finely banded 'Laxfordian' gneiss with concordant and locally lenticular amphibolite sheets (interpreted as deformed Scourie dykes), and pervaded by granitic migmatite of Laxfordian age. 'Laxfordianized' gneisses of this kind are typical of the Northern Region, north of Loch Laxford, and of the southernmost parts of the Southern Region, south of Loch Torridon. Significant bodies of granite are confined to the Loch Laxford area (see **Tarbet to Rubha Ruadh** GCR site report, this chapter), where several thick subconcordant sheets of pink, gneissose granite occur within a zone 2–4 km wide. North of the granite sheets, thin sheets and veins of granite and pegmatite are abundant.

According to Coward and Park (1987) the main Laxfordian belts of the mainland are linked in a major mid-crustal shear-zone network, which separates and encloses more-stable crustal blocks whose relative movement gives rise to the observed structures. It is considered that the D1 and D2 deformations recognized in the mainland Laxfordian sequence probably represent earlier and later stages of a progressive deformation involving the transport of higher-level crustal blocks relative to lower, on a major subhorizontal, mid-crustal shear-zone. This major shear-zone is exposed in the Northern and Southern regions of the mainland, but passes beneath the Central Region, and is more widely represented in the Outer Hebrides, where a lower crustal level of the Laxfordian reworking zone appears to be exposed.

Later Laxfordian structures include the prominent NW-trending major folds that dominate the outcrop pattern of the Laxfordian belts (Figure 3.1), such as the Tollie and Torridon antiforms in the Southern Region. The Tollie Antiform in the Gairloch area is associated with the formation of the major Gairloch Shear Zone, which is about 6 km wide (Odling, 1984; Park *et al.*, 1987; Park, 2002) (see **Creag Mhòr Thollaidh** GCR site report, this chapter). These structures are attributed to the D3 phase and are associated with the development of a new, locally developed, planar fabric accompanied by retrogression to greenschist facies. This later deformation has been dated at *c.* 1670 Ma in the Central and Northern regions (Corfu *et al.*, 1994; Kinny and Friend, 1997), and at later than 1694 Ma in the Southern Region (Park *et al.*, 2001). It therefore appears that the late-Laxfordian deformation affected the whole of the mainland Lewisian at *c.* 1670 Ma.

The regional D3 Laxfordian folds were superseded by later, more-localized structures of various styles and orientations, together with crush zones containing pseudotachylite (e.g. see **Flowerdale**, **Kerrysdale** and **Creag Mhòr Thollaidh** GCR site reports, this chapter). These later structures in the Gairloch area were assigned to the 'late phase' of the Laxfordian (subsequently re-labelled 'D4') by Park (1964), and have also been described in other parts of the Laxfordian belts (e.g. Bhattacharjee, 1968; Dash, 1969; Cresswell, 1972). The D4 deformation may have occurred around 1500 Ma, corresponding with a period of significant resetting of K-Ar systems in hornblendes (Moorbath and Park, 1972) (Table 3.1).

Two younger K-Ar dates of 1148 Ma and 1169 Ma were obtained by Moorbath and Park (1972) from chloritized biotite in felsic gneisses from Torridon. These ages are close to a Rb-Sr biotite age of 1160 Ma reported by Giletti *et al*. (1961), and raise the possibility that some of the later structures in the Lewisian Gneiss Complex (e.g. certain crush belts) may result from Grenvillian movements at around 1100 Ma or later (Park, 1970; Sherlock *et al*., 2008) (Table 3.1). Evidence for activity of the same age north of the Langavat Belt in South Harris has been presented by Cliff and Rex (1989).

BADCALL (NC 145 421–NC 157 413)

C.R.L. Friend

Introduction

The Badcall GCR site, near Scourie, forms the southern part of the type locality for the Scourian component of the Central Region of the Lewisian Gneiss Complex (Peach *et al*., 1907; Sutton and Watson, 1951). The well-preserved, late Archaean granulite-facies gneisses in this area led to the use of the term 'Badcallian' to describe the high-grade metamorphic event responsible for their generation from mainly plutonic igneous rocks (Park, 1970). The area is one of generally low Proterozoic strain and so preserves many early features, important for understanding the pre-granulite-facies evolution of the Lewisian Gneiss Complex. Palaeoproterozoic mafic dykes of the Scourie Dyke Suite cross-cut the gneisses, and Badcall is also part of the type area for defining the dyke suite.

In addition to being the prime example of granulite-facies gneisses in Great Britain, the Badcall GCR site is of international importance for several other reasons. The gneiss complex in the Scourie–Badcall area was mapped by W. Gunn for the Geological Survey in 1887 and was one of the earliest to be fully described and understood in terms of its protoliths and general geological history (Peach *et al*., 1907). Indeed, the maps produced by the early surveyors are still the basis for the published Geological Survey maps. It was also one of the first gneiss complexes to be studied extensively using various isotopic dating techniques (e.g. Holmes *et al*., 1955; Giletti *et al*., 1961; Moorbath *et al*., 1969; Pidgeon and Bowes, 1972). More recently the area has been the subject of renewed isotopic investigations using ion-probe U-Pb techniques in an attempt to establish more accurately the chronology of the protoliths of the gneisses (Friend and Kinny, 1995; Kinny and Friend, 1997). This gneiss complex is one of the most strongly large-ion-lithophile (LIL) element-depleted pieces of lower crust currently known (e.g. Sheraton *et al*., 1973; Tarney, 1976; Tarney and Weaver, 1987a) and so is a key area for research into the processes of granulite-facies metamorphism and/or the inheritance of chemical characteristics from a source region.

Description

The GCR site covers the south-west part of the large peninsula that culminates to the south in Farhead Point (Figure 3.2). It extends from the coast west of Cnoc an Fhir Bhreige (93 m) to south-east down to the lower rocky point of Rubh a' Bhad Choill. The exposures that best

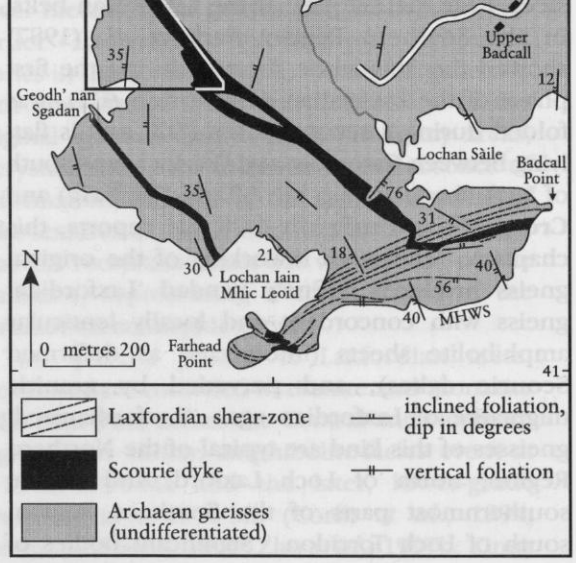


Figure 3.2 Sketch map of the Badcall area, Scourie, showing the major Scourie dykes and later shear-zones. Based on the Geological Survey 1:10 560 Sheet Sutherland 39 (1912), and Beach (1978).

demonstrate relationships and rock types lie in a triangular-shaped, very low-strain area *c.* 1 km west of Upper Badcall, which stretches inland from the small inlet of Geodh' nan Sgadan (NC 146 417) (Figure 3.3). Here, the rocks are cleanly exposed on low crags that rise gently to the north-east to reach *c.* 55 m above OD.

The dominant gneisses are felsic with a tonalitic composition. Typically they are dark grey-brown when fresh, but bleached white where weathered, reflecting their dominant plagioclase feldspar content. On fresh surfaces it is difficult to make out any foliation, lineation or banding, but where weathered the internal structures and mineralogy are more easily discernible. The gneissic banding generally dips 25°–35° to the west and south-west, but around Rubh a' Bhad Choill dips are steeper and more variable. The gneisses preserve extensive orthopyroxene and are equigranular and coarse grained. These characters are very well displayed in the exposures at the car park (NC 154 416) at the end of the road from Upper Badcall.

Typically the felsic gneisses contain rafts and lenses of mafic and ultramafic rocks. One ultramafic body near Upper Badcall is of archaeological significance in that it has been used for the extraction of soapstone. Metasedimentary rocks are also present, typically associated with the rafts of mafic rocks, but form only a minor component of the gneisses. The disparate elements of this complex have all

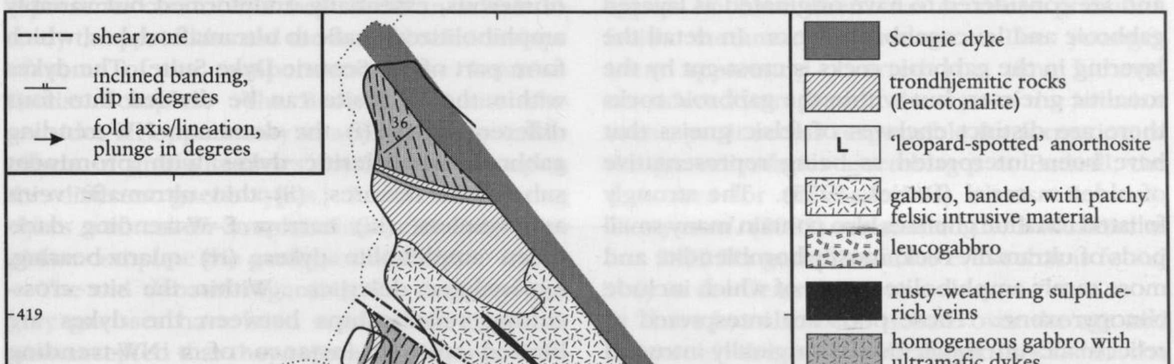


Figure 3.3 Map of the coastal area immediately north of Geodh' nan Sgadan, showing the distribution of the different types of gneisses and the position of some of the later cross-cutting leucotonalite (trondhjemitic) sheets and Scourie dykes. After Rollinson and Windley (1980).

undergone polyphase deformation and high-grade metamorphism, during which cross-cutting leucotonalite ('trondhjemitic') sheets were emplaced. Following these events the complex was intruded by numerous discordant mafic dykes of the Scourie Dyke Suite. Subsequent to dyke emplacement, relatively narrow, hydrous shear-zones developed locally, causing variable retrogression to amphibolite-facies assemblages and generation of new textures and fabrics. The shearing and retrogression are the result of the Laxfordian event, which only affected small parts of the high-grade gneisses in the Badcall area (Sutton and Watson, 1951).

Along the coast, tonalitic gneisses are inter-banded on a large scale with plagioclase-rich mafic rocks that show a mineralogical layering and are considered to have originated as layered gabbroic and leucogabbroic rocks. In detail the layering in the gabbroic rocks is cross-cut by the tonalitic gneisses, but within the gabbroic rocks there are distinct enclaves of felsic gneiss that have been interpreted as being representative of older material (Davies, 1975). The strongly foliated tonalitic gneisses also contain many small pods of ultramafic rock, mostly hornblendite and more rarely amphibolite, some of which include clinopyroxene. These pods are interpreted as relict mafic–ultramafic bodies originally intruded by sheets and veins of tonalitic gneiss. Their present form is a result of strain partitioning during the subsequent deformation.

These banded and foliated rocks are cross-cut by distinct sheets of white to pale-grey leuco-tonalite ('trondhjemite') (e.g. Rollinson and Windley, 1980; Cartwright, 1988), that show mineral assemblages indicative of both granulite- and amphibolite-facies. However, the amphibolite-facies sheets commonly contain blue quartz, suggesting that originally they may have been at granulite facies. In the Badcall area there appear to be two types of leucotonalite: the first forms sharply defined, cross-cutting sheets; the second forms nebulous patches and areas which are clearly derived from the host gneisses as they contain relict, disrupted structures essentially continuous with those in the enclosing rocks. These structures include dismembered fold noses and relict gneissose layering. Cross-cutting relationships suggest that the sharply defined sheets normally post-date the nebulous patches.

Several generations of folds and foliations can be identified within the site. The gneissose enclaves in the gabbroic rocks appear to have an early banded structure (Davies, 1975) and the gabbros themselves appear to have been foliated prior to invasion by the dominant tonalitic rocks (e.g. Cartwright, 1988). These host tonalites then acquired a foliation which was subsequently deformed by tight to isoclinal structures upon which are superimposed the nebulous partial-melting textures. These structures are deformed by open, NW-verging asymmetrical folds, well displayed on a low bluff immediately east of Geodh' nan Sgadan. Because the rocks are essentially not retrogressed, it is probable that all of these fabrics and structures were formed either before, or synchronous with, the granulite-facies metamorphism.

The gneisses at Badcall Bay are cut by numerous, essentially undeformed but variably amphibolitized, mafic to ultramafic dykes, which form part of the Scourie Dyke Suite. The dykes within the GCR site can be divided into four different types: (i) the dominant NW-trending gabbroic to doleritic dykes with prominent sub-ophitic textures; (ii) thin ultramafic veins and veinlets; (iii) narrow E–W-trending dark-green amphibolite dykes; (iv) quartz-bearing, hypersthene dolerites. Within the site cross-cutting relationships between the dykes are limited to one instance of a NW-trending dolerite cutting a hypersthene dolerite. The NW-trending doleritic to gabbroic dykes are typified by the thick dyke (in excess of 30 m) on Cnoc an Fhir Bhreige (NC 146 417), in which many internal textural features can be seen.

Amphibolite shear-zones affect the margins of most of the dykes. Progressive development of a shear fabric from an essentially homogeneous starting material is well demonstrated in these shear zones. Within the dykes, the amount of amphibolitization of the mafic minerals decreases progressively away from the shears until, in places, relics of the original igneous pyroxenes are found. Beach (1978) described a Scourie dyke on the coast at NC 145 415, the northern part of which is undeformed and has a planar contact with the host gneisses. The southern margin, by contrast, has an irregular contact and a strong fabric, defined by orientated horn-blende crystals.

At the summit of the small hill (NC 153 413) above Badcall Bay, a Laxfordian shear-zone that runs from Farhead Point to Badcall Point can be seen (Beach, 1978). Close to the summit a Scourie dyke enters the shear zone from the north-west and is deflected along the zone as far as the coast at NC 157 413. Within the shear zone, the gneissose banding is roughly vertical and strongly attenuated, and the gneisses have been recrystallized under amphibolite-facies conditions. The continuation of the shear zone can be seen on the south side of Farhead Point at NC 149 410. On the northern side of this point, the tonalitic gneisses are deformed into a series of folds with NW-trending axial planes that are in turn deformed by the main shear-zone.

Interpretation

Because of the low post-dyke strain and generally slight subsequent hydrous, retrogressive metamorphism, the Badcall Bay–Scourie area represents one of the best areas in which to study the protoliths and the mutual relationships of some of the components of the Lewisian Gneiss Complex. The Badcall GCR site also provides an opportunity to address the possible effects of granulite-facies metamorphism upon the different gneiss types. Later cross-cutting dykes and minor amphibolite-facies metamorphism complete the geological history.

The old debates regarding the origin of the grey gneisses have been resolved, in that it is now accepted that they represent plutonic, calc-alkaline igneous rocks (e.g. Tarney, 1976) rather than partially to totally melted sedimentary rocks (e.g. Sutton and Watson, 1951) or felsic volcanic rocks (e.g. Pidgeon and Bowes, 1972). Undoubted metasedimentary rocks are present, but they are quite distinct from the orthogneisses and represent only a very minor component of the gneiss complex. Partial melting has occurred in some parts of the tonalitic gneisses and was probably related to dehydration reactions leading to granulite-facies assemblages.

The first direct dating of the tonalitic gneiss protoliths in the Badcall area, using U-Pb single zircon methods, has given an age of *c.* 2960 Ma (Friend and Kinny, 1995; Kinny and Friend, 1997). Previously, the best estimate of the age of the grey gneisses was that of Whitehouse (1989) who used Sm-Nd whole-rock methods to obtain model Nd ages of *c.* 2930 Ma. Earlier age estimates of *c.* 2950 Ma (e.g. Hamilton *et al.*, 1979) were not based upon cogenetic suites of rocks and have now been discounted.

The timing of the granulite-facies metamorphic event is still rather enigmatic. Bulk zircons from rocks at the Badcall road end suggested a U-Pb age of 2660–2700 Ma (Pidgeon and Bowes, 1972) and whole-rock U-Pb isotopic data supported this, giving a *c.* 2700 Ma age (e.g. Chapman and Moorbath, 1977). Most recently, Corfu *et al.* (1994), using modern U-Pb geochronological techniques, have also recognized a high-grade metamorphic event at 2710 Ma or older. However, information from single zircon U-Pb systems from unretrogressed granulite-facies samples has indicated another major event at *c.* 2500 Ma (Corfu *et al.*, 1994; Friend and Kinny, 1995). This proposed metamorphic event correlates well with a similar age obtained by a combined mineral and whole-rock Sm-Nd study of granulite-facies rocks a short distance to the north at Scourie (Humphries and Cliff, 1982). This raises the problem that there appear to have been two or more granulite-facies metamorphic events. The younger event apparently occurred at a time hitherto considered to represent the start of the Inverian event, yet it seems responsible for formation of the granulite-facies assemblages at Badcall, the type area for the Badcallian event. Recently, Kinny *et al.* (2005) reclassified the Badcallian as a *c.* 2490 Ma granulite-facies event that is found only in the Central Region.

There has also been debate over the age and origin of the mafic–ultramafic rocks in the Badcall area, and those to the north on Scourie Mor. Plausibly, they could have two possible origins: either representing dismembered layered bodies (e.g. Sills *et al.*, 1982); or as relict fragments of the mafic source material from which the tonalitic protoliths were derived. Given the preserved cross-cutting relationships it would seem that, in common with other parts of the North Atlantic craton, the mafic–ultramafic rocks are an older component into which the gneiss protoliths were emplaced.

Geochemically the Badcall gneisses represent one of the most LIL-element-depleted gneiss complexes known, and it is important to understand how this came about. The main debate centres on whether the depletion was the result of granulite-facies metamorphism, or whether it reflects a chemical control exerted by the source regions of the different lithologies. Further debate concerns the origin of the leucotonalite sheets; they may have formed by in-situ anatexis of the gneisses under granulite-facies conditions (e.g. Cartwright, 1988), or their emplacement may have largely pre-dated the granulite-facies event (Rollinson and Windley, 1980). One possible explanation, which could link the two different debates, is that the depletion in the tonalitic gneisses resulted from the removal of small amounts of melt during granulite-facies metamorphism (e.g. Pride and Muecke, 1980, 1982; Cartwright, 1988). Alternatively, Rollinson (1994) used new geochemical data to suggest that the leucotonalite sheets are the result of partial melting of lower crustal mafic material. Close examination of the field relationships could be interpreted to indicate that the nebulous leucotonalite patches are the products of in-situ anatexis, whereas the sharply defined sheets represent aggregated and migrated melt of external origin.

Following the *c.* 2500 Ma granulite-facies event, Scourie dykes were intruded at Badcall at around 2400 Ma and possibly also in a further event at about 2000 Ma (Heaman and Tarney, 1989). The shear zones that affect the dykes are presumed to be of Laxfordian age; feldspar and muscovite from pegmatites that cut the dykes and shears have yielded Rb-Sr mineral ages of 1600–1500 Ma (Giletti *et al.*, 1961).

Conclusions

The Badcall GCR site demonstrates some of the best-preserved granulite-facies rocks on the mainland of Britain. The area has been little affected by subsequent hydrous retrogressive metamorphism and has escaped most of the later Proterozoic Laxfordian deformation. Thus, it affords one of the best locations for examination of the early stages of evolution of the Lewisian Gneiss Complex. Several different episodes of pre- or syn-granulite-facies deformation, resulting in the formation of different foliations and folds, can be recognized. Because of the low-strain, textures associated with granulite-facies metamorphism are preserved, including patchy areas of partial melting in the host gneisses.

There are particularly well-displayed relationships between the rock units, which allow the relative ages of different events to be established. The oldest rocks are enclaves of felsic gneiss contained within layered gabbroic material. The gabbros were intruded by the main tonalitic phase around 2960 Ma. This igneous complex was then subjected to granulite-facies metamorphism, possibly in two separate events at around 2700 Ma and 2500 Ma. Post-granulite-facies mafic dykes, part of the Scourie Dyke Suite, cross-cut the structures in the gneisses. Four different lithological types of dyke can be recognized, the most common of which are metadolerites. Subsequent to the intrusion of these dykes there is evidence of restricted amphibolite-facies metamorphism and the progressive development of hydrous shear-zones and associated fabrics within the dykes. The site is of international significance as it not only exposes the earliest features of the Lewisian Gneiss Complex, but is also historically important for lithological, geochemical and geochronological investigations of basement gneiss complexes.

SCOURIE MOR (NC 144 450–NC 144 437)

C.R.L. Friend

Introduction

The rocks on the peninsula of Scourie Mor, which lies south-west of Scourie Bay, form the northern part of the type area for the Central Region of the Lewisian Gneiss Complex (Sutton and Watson, 1951). An extensive array of granulite-facies felsic and mafic gneisses is particularly well displayed between Eilean a' Bhuic (NC 137 449) and Camas an Tairidh (NC 147 438) (Figure 3.4). The exposures are dominated by mafic tonalites that contain rafts and large lenses of mafic and ultramafic rocks up to about 400 m wide and as much as 1 km long (e.g. O'Hara, 1961a, 1965; Whitehouse, 1989). The mafic–ultramafic bodies are largely undeformed and provide some of the best examples seen in the Lewisian Gneiss Complex, contributing to the importance of the site. In places there are minor amounts of metasedimentary material, including calc-silicate lithologies (O'Hara, 1960). The gneiss complex has been subjected to deformation and granulite-facies metamorphism, during which a few discordant leucotonalite sheets were emplaced. Later, in the Palaeo-proterozoic, the rocks were intruded by mafic dykes of the Scourie Dyke Suite (e.g. O'Hara, 1961b), although only relatively thin dykes (< 5 m wide) are seen in this area. Subsequently, all the elements were transected by hydrous shear-zones, which caused variable retrogression, an event associated with Laxfordian reworking (Beach, 1973). The

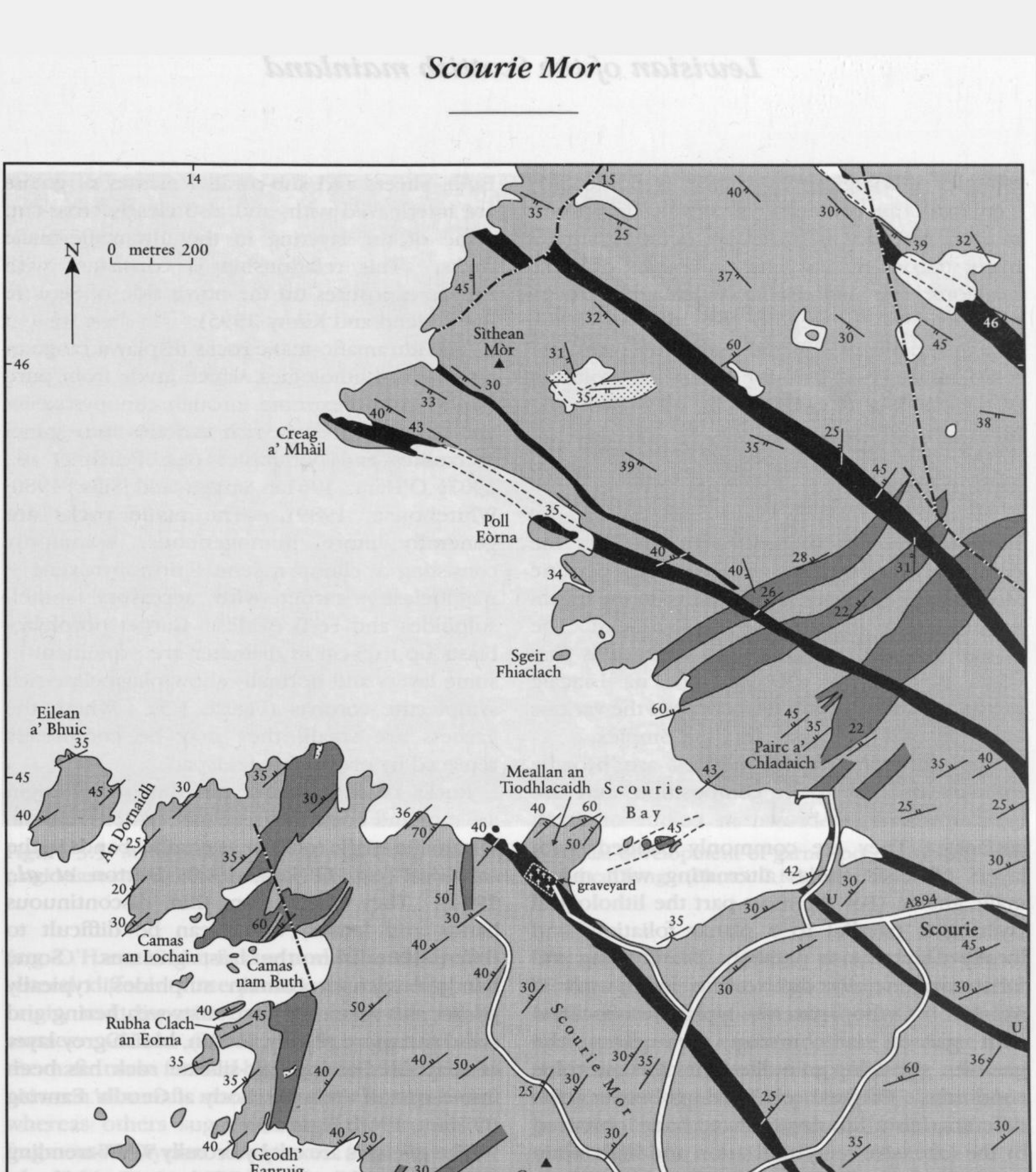


Figure 3.4 Map of the Scourie area, including the areas covered by the Scourie Mor, **Scourie Bay** and **Sìthean Mòr** GCR sites. Based on the Geological Survey 1:10 560 sheets Sutherland 30 (1913), 39 (1912), and O'Hara (1961a).

complex lithological association is particularly significant as evidence of several important mineral reactions is preserved, demonstrating a major decompression event. Studies of these reactions have been used to elucidate the metamorphism of the region (e.g. O'Hara, 1965; Savage and Sills, 1980) and to derive a pressure–temperature (P–T) path for the crustal evolution of the gneisses (e.g. Barnicoat, 1987; Sills and Rollinson, 1987).

Description

The Scourie Mor GCR site encompasses the peninsula that lies west of the crofts of Scourie Mor, extending from Eilean a' Bhuic to the north-west to Camas an Tairidh to the south-east. The craggy indented coastline and rocky hills that reach 80 m above OD at Cnoc na Leacaig provide excellent clean exposures of the various elements of the Lewisian Gneiss Complex.

The dominant felsic gneisses are broadly tonalitic or dioritic in composition and are typically dark grey-brown in colour on fresh surfaces. They are commonly banded, with layers of felsic gneiss alternating with more-mafic gneiss. For the most part the lithological layering is parallel to a planar foliation, and locally a lineation is present. The layering and foliation generally dip to the north-west at 30°–50°. Orthopyroxene, typically associated with garnet, is common throughout the gneisses, signifying granulite-facies metamorphic conditions. Original relationships between the different felsic lithologies have been obscured by the extensive recrystallization and high strain under granulite-facies conditions. The ductile nature of the deformation is indicated by the commonly lineated form of the orthopyroxene and the discontinuous quartz ribbons that partially define the banding and foliation. Low-strain areas are rare, although some localities do occur between Camas an Lochain (NC 140 446) and Camas nam Buth (NC 142 446).

Large bodies of mafic–ultramafic rocks are exposed between Camas nam Buth (NC 142 446) and Geodh' Eanruig (NC 142 442), although there is some debate as to the exact disposition of the units. Cohen *et al.* (1991) suggested that they are lensoid masses, but Sills *et al.* (1982) interpeted them as dismembered parts of a larger-scale body that has been folded. At some localities where overall strain appears to be low, for example on the north side of Camas nam Buth, sheets and sub-parallel masses of gneiss are interleaved with, and also clearly cross-cut, some of the layering in the ultramafic–mafic rocks. This relationship is consistent with similar exposures on the north side of Scourie Bay (Friend and Kinny, 1995).

The ultramafic–mafic rocks display a range of interlayered lithologies, which grade from pure dunite at one extreme through clinopyroxene- and/or orthopyroxene-rich varieties into spinel lherzolites and peridotites (e.g. Peach *et al.*, 1907; O'Hara, 1961a; Savage and Sills, 1980; Whitehouse, 1989). The mafic rocks are generally more homogeneous, commonly consisting of clinopyroxene + orthopyroxene + plagioclase + garnet with accessory spinel, sulphides and Fe-Ti oxides. Garnet porphyroblasts up to 5 cm in diameter are prominent in some layers and normally show plagioclase-rich symplectite coronas (Figure 3.5). Where the garnets are small, they may be completely replaced by plagioclase feldspar.

Rocks of supposed metasedimentary origin are rare and occur either in association with the ultramafic–mafic rocks or as parallel bands in the tonalites (e.g. O'Hara, 1960; Burton *et al.*, 1994). They chiefly form thin, discontinuous bands and lenses, which can be difficult to differentiate from the host gneisses. Some bands or lenses contain sulphides, typically pyrite; as a result they are rusty-weathering and stand out more readily. A thin, bluish-grey layer of scapolite-bearing calc-silicate rock has been found east of the mafic body at Geodh' Eanruig (O'Hara, 1960; Figure 3.4).

The gneisses are cut by broadly WNW-trending mafic dykes of the Scourie Dyke Suite, similar to those in the adjacent **Scourie Bay** GCR site. The dykes are essentially undeformed with a micro-gabbroic texture, but are largely amphibolitized. The area is also cut by shear zones, many of which lie within the marginal parts of the dykes. As these shears and associated amphibolite-facies metamorphism affect the Scourie dykes they are presumed to be of Laxfordian age.

Interpretation

It is generally accepted that the mafic and ultramafic rocks in the Central Region of the Lewisian Gneiss Complex have undergone the same metamorphic history as the gneisses. However, there have been differing views as to the survival of any remnants of the primary igneous minerals

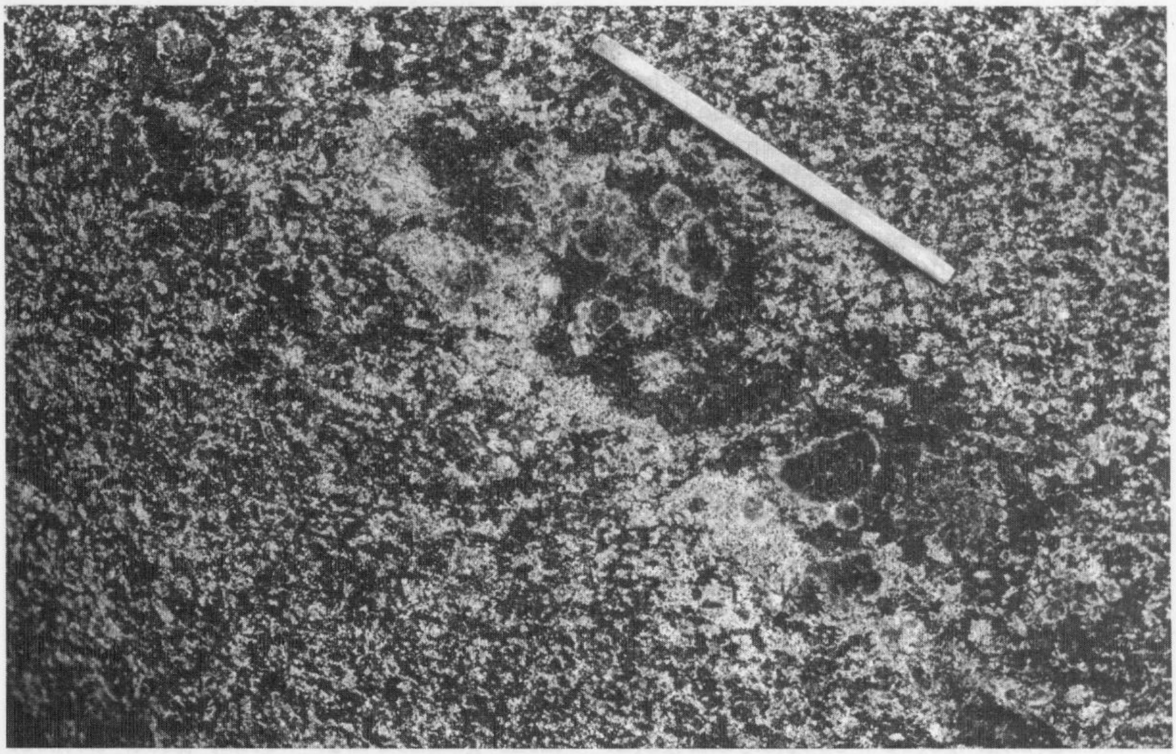


Figure 3.5 Mafic rocks at Camas nam Buth, showing the typical development of garnet porphyroblasts with plagioclase-rich decompression coronas. The matchstick is 4.4 cm long. (Photo: C.R.L. Friend.)

(e.g. O'Hara, 1961a; Savage and Sills, 1980), and several different interpretations regarding the origin and disposition of the mafic–ultramafic masses. O'Hara (1961a, 1965) suggested that the mafic rocks formed by metasomatic reactions between ultramafic material and the host gneisses, whereas others suggested that they represent fragmented layered complexes (e.g. Bowes *et al.*, 1964; Davies, 1974). The latter view was corroborated by Sills *et al.* (1982), who carried out extensive geochemical analyses, particularly from the units at Camas nam Buth. They demonstrated the presence of cryptic layering and established a consistent way-up based on geochemical criteria, which could be traced over fold hinges. They concluded that the mafic–ultramafic lithologies represent the remains of fragmented layered complexes that have been intruded by the tonalitic gneisses and subsequently deformed and metamorphosed. This model is consistent with other Archaean terrains in the North Atlantic region (e.g. Greenland and Labrador). However, because of the chemical imbalance that exists between the ultramafic and felsic gneisses there are clear areas where limited metasomatic exchange, as proposed by O'Hara (1961a, 1965), can be observed. Whereas many of the relationships between the mafic–ultramafic units and the dominant felsic gneisses are equivocal, there are some low-strain areas that preserve cross-cutting relationships, showing that the protoliths of the felsic gneisses cross-cut the igneous layering in the mafic rocks.

The age of the ultramafic–mafic bodies has been equally controversial. Humphries and Cliff (1982) conducted Sm-Nd mineral studies of metamorphic minerals in these bodies and obtained an age of *c.* 2490 Ma. This was interpreted as representing the time at which the rocks passed through the Sm-Nd closure temperature, i.e. the cooling age following earlier granulite-facies metamorphic conditions. Combined with ages of *c.* 2700 Ma for the commencement of the Badcallian event (e.g. Pidgeon and Bowes, 1972), this evidence was taken to indicate that granulite-facies conditions lasted some 150 million years. However, more recently, evidence has been gathered for two metamorphic events in the area, at *c.* 2700 Ma and *c.* 2500 Ma (e.g. Corfu *et al.*, 1994; Friend and Kinny, 1995), so that the date obtained by

Humphries and Cliff (1982) probably represents the time of metamorphic crystallization. Whitehouse (1989) obtained a Sm-Nd whole-rock isochron of 2670 ± 110 Ma for the Scourie Mor mafic–ultramafic bodies, and Cohen *et al.* (1991) used whole-rock U-Pb and Sm-Nd isotopic data to infer an emplacement age of 2707 ± 52 Ma.

U-Pb isotope studies of single zircons in granulite-facies tonalitic gneisses from the Scourie Bay area have given protolith ages of *c.* 2960 Ma (Friend and Kinny, 1995; Kinny and Friend, 1997). One of these samples came from a granulite-facies leucotonalite sheet that cross-cuts an ultramafic body at First Inlet, on the north side of Scourie Bay. This data provides supporting evidence for the hypothesis of Sills *et al.* (1982), that at least some of the mafic and ultramafic rocks are older than the gneisses. On the basis of these dates, it appears that either some of the mafic–ultramafic bodies may be genuinely younger than the tonalitic gneisses or, more probably, that the younger whole-rock and mineral ages represent metamorphic disturbance of the isotope systems. However, the opposing view has been re-iterated by Burton *et al.* (2000), who have used Re-Os data to obtain a date of 2687 ± 15 Ma for the ultramafic body at First Inlet, and who suggested that the cross-cutting leucotonalite sheet may have assimilated zircons from the surrounding gneisses during emplacement.

Conclusions

The Scourie Mor GCR site provides some of the best examples in the Lewisian Gneiss Complex of Archaean tonalitic felsic gneisses and mafic–ultramafic bodies. Sm-Nd and U-Pb isotopic age dating has shown that the protolith igneous bodies were formed at *c.* 2950 Ma and were metamorphosed under granulite-facies conditions at *c.* 2700 Ma. The rocks form part of the oldest gneiss complex found in Britain and preserve some of their original igneous textures and structural relationships. The rocks also provide evidence of the minerals and textures formed during high-grade metamorphism and the subsequent uplift with consequent release of pressure. These delicate textures survive owing to the general lack of later, hydrous deformation that affected many of the granulite-facies gneisses elsewhere. Late metasomatic modification by hot fluids can be demonstrated locally, but these relatively minor reactions are mainly focused along the margins of the ultramafic bodies.

The site includes several 'low-strain' areas that have undergone very little deformation at all, and the original lithological and geochemical layering is well preserved within some of the mafic–ultramafic rocks. Within these low-strain areas, the host felsic gneisses show good cross-cutting relationships, which demonstrate that the mafic and ultramafic bodies are older than the tonalitic felsic gneisses. In other areas such relationships are unclear or contradictory and research is ongoing as to their relative and absolute ages. The site remains one of the best places to study the early history of the Lewisian Gneiss Complex and as such is of international importance.

SÌTHEAN MÒR (NC 150 460)

C.R.L. Friend and J.R. Mendum

Introduction

Rocks of undisputed original sedimentary origin constitute only a small proportion of the granulite-facies gneisses in the Central Region of the Lewisian Gneiss Complex. The most abundant metasedimentary rocks occur as inter-banded and lenticular small units of brownish-weathering gneissose to schistose semipelite and pelite that have been derived from aluminous siltstone and mudstone protoliths. A notable concentration of these pelitic rocks occurs on Sìthean Mòr, on the north side of Scourie Bay, where individual occurrences are up to *c.* 0.5 km long. These rocks and the adjacent orthogneisses have been the subject of detailed petrographical and geochemical studies (Beach, 1973, 1976; Okeke *et al.*, 1983; Barnicoat *et al.*, 1987). No calc-silicate rocks are noted on Sìthean Mòr, but Barooah (1970) has described calc-silicate rocks and possible meta-'arkose' from several localities south-east of Scourie. In addition, some unusual metasedimentary rock-types have been recorded in the Scourie area, such as a unit of banded-iron formation at Pairc a' Chladaich (NC 153 451).

The pelitic rocks have a relatively simple mineralogy when at granulite facies, but where they are cut by later shear-zones the mineral assemblages are retrogressed to amphibolite facies giving rise to a considerably more-complex mineralogy (Beach, 1973; Okeke *et al.*, 1983). Evidence for several significant mineral reactions is preserved, which was originally described by O'Hara (1961b). Subsequently, work by Barnicoat (1987) and Sills and Rollinson (1987) has elucidated a P–T path, tracking changes in pressure and temperature conditions for the metasedimentary rocks during both the original granulite-facies metamorphism and the later Laxfordian lower-grade shearing. These results link with work on the nearby banded-iron formation, which preserves evidence for very high-temperature metamorphic conditions (Barnicoat and O'Hara, 1979).

In the north-east part of the GCR site, a thick metadolerite dyke of the Scourie Dyke Suite cuts discordantly across the granulite-facies felsic gneisses and metasedimentary enclaves (Figure 3.4). The dyke shows evidence of localized deformation and metamorphism focused along narrow ENE-trending shear-zones, whose development is attributed to the Laxfordian event (see **Scourie Bay** GCR site report, this chapter).

Description

The Sìthean Mòr GCR site occupies a restricted area (*c.* 1 km^2) of glacially scoured, rocky ground lying at between 75 m and 100 m above OD on the north side of Scourie Bay. It includes a small lochan beside which the metasedimentary rocks are well exposed at NC 149 459. The metasedimentary gneisses are coarsely foliated, light- to mid-brown-weathering, dark-grey rocks studded with dark-red garnets up to 1 cm across. They are interbanded with felsic and mafic banded gneisses that are essentially similar to, and contiguous with, the tonalitic, granodioritic, and more-mafic gneisses that occur in the **Badcall** and **Scourie Bay** GCR site areas. Both the metasedimentary and meta-igneous rocks show granulite-facies mineralogies and preserve extensive orthopyroxene, which is retrogressed to biotite + kyanite/sillimanite and to hornblende, respectively, in the hydrous shear-zones. The gneisses are cut by essentially undeformed but amphibolitized, ESE-trending mafic dykes of the Scourie Dyke Suite (see **Scourie Bay** GCR site report, this chapter). Several discrete ENE-trending shear-zones transect the gneisses in this area, and as they also cut the Scourie dykes, they are presumed to be Laxfordian (Palaeoproterozoic) in age.

Mineral assemblages in the granulite-facies metasedimentary rocks include orthopyroxene, garnet, antiperthitic plagioclase, quartz, and magnetite ± pyrite (Beach, 1973; Okeke *et al.*, 1983). Locally magnetite is the principal ferromagnesian mineral. The orthopyroxene is relatively magnesian (En_{70}), and its modal composition shows an inverse relationship with quartz. It is comonly absent from the more quartz-rich rocks, in which garnet remains the stable phase. Okeke *et al.* (1983) determined the major- and trace-element geochemistry of representative pelitic and semipelitic samples using XRF methods from the site area and from the Foindle area farther north. The two pelitic rocks from Sìthean Mòr have average SiO_2 values of 54.3%, Al_2O_3 values of 20.3%, and $FeO + Fe_2O_3$ values of 9.22%, confirming their iron-rich and aluminous nature. Average values for eight semipelitic rocks were 68.2% SiO_2, 16% Al_2O_3, and 3.6% $FeO + Fe_2O_3$. Zinc and barium both showed notably high values also. The metasedimentary rock analyses are distinct from those of the host tonalitic and granodioritic gneisses and accord with typical values for pelitic rocks (Okeke *et al.*, 1983).

The granulite-facies rocks commonly show little internal compositional banding, but this develops as the rocks become progressively foliated in the steeply dipping amphibolite-facies Laxfordian shear-zones. Beach (1973) carried out detailed petrographical work on both the granulite- and amphibolite-facies metasedimentary rocks and carried out electron microprobe analyses on some of the minerals. He noted that, as the rocks pass into the shear zones, orthopyroxene disappears, garnet abundance increases and biotite becomes the dominant mineral. In these sheared rocks, Beach (1973) recorded the presence of kyanite, sillimanite, spinel, corundum, staurolite, opaques, muscovite and epidote with minor accessory green spinel, dark-brown perovskite and apatite. He used the mineralogy to determine the likely sequence of metamorphic reactions that had occurred in the metasedimentary rocks during this retrograde alteration. He concluded that the shear zones had focused water-rich fluids and that metamorphic changes had occurred at temperatures of *c.* 600° C and pressures of *c.* 6 kbar.

Interpretation

The presence of undoubted metasedimentary rocks interleaved with, and intruded by, tonalitic and granodiorite gneisses, which themselves were apparently emplaced at middle to lower crustal levels, presents some considerable problems. It is clear that the metasedimentary rocks were laid down on the Earth's surface, probably as marine deposits. Then they were transported down to some 25+ km, where they were intruded by the meta-igneous rocks, and a little later subject to granulite-facies metamorphism. Where they are associated with layered ultramafic rocks an argument can be made that the metasedimentary rocks were deposited on oceanic crust and the two units were subducted to mid- or lower crustal levels (Tarney and Weaver, 1987a). Where metasedimentary rocks occur as isolated lenses and accumulations amongst the felsic and mafic banded gneisses their original depositional environment is unclear, and evidence of subduction is lacking. It is tempting to view the metasedimentary rocks as having been deposited in a later Proterozoic basin and subsequently juxtaposed tectonically with the older Archaean elements, as in the Loch Maree and South Harris metasedimentary belts. However, this explanation is clearly untenable in the Central Region where the protoliths of the felsic and mafic gneisses were emplaced at *c.* 3000 Ma (Friend and Kinny, 1995; Kinny and Friend, 1997), and granulite-facies metamorphism occurred at *c.* 2700 Ma and *c.* 2490 Ma (Corfu *et al.*, 1994; Friend and Kinny, 1995). The corollary of this association of metasedimentary rocks and lower crustal intrusions is that plate-tectonic systems probably did not operate in the same way as at present. Crustal thicknesses, subduction patterns, heat flow, and depths of magma generation were probably different in Archaean times to those that prevailed in Proterozoic and Phanerozoic times.

The metasedimentary rocks of the Sìthean Mòr GCR site admirably display both granulite- and amphibolite-facies mineral assemblages. Beach (1973) documented the main mineralogical changes in the Laxfordian amphibolite-facies shear-zones as: orthopyroxene to biotite; garnet to biotite, aluminosilicate and epidote; and andesine and potash feldspar to a more albite-rich plagioclase. Kyanite and sillimanite both occur locally in the sheared rocks. Two explanations have been put forward for the presence of kyanite. Beach (1973) attributed the formation of kyanite + biotite to the breakdown of garnet, due to the influx of K-rich fluid during the shearing event. Conversely, in the examples reported by Barnicoat *et al.* (1987), the kyanite was described as partly defining a flat-lying fabric (ascribed to the Badcallian event), which is cross-cut by a steeper fabric interpreted to have been formed during the Inverian event. If the kyanite did form during the Badcallian event, this would imply that it was stable under granulite-facies conditions. Clearly this has significant P–T implications, as the assemblage orthopyroxene + kyanite requires pressures of at least 12 kbar at 950° C. It is perhaps significant that detailed U-Pb SIMS ion-probe dating from a sheared gneissose pelite has shown that monazite inclusions within granulite-facies garnets are of Archaean age, whereas monazites within the kyanite and in the matrix are Proterozoic in age (Zhou *et al.*, 1997b).

Conclusions

The Sìthean Mòr GCR site contains some of the best-documented exposures of metasedimentary rocks within the granulite-facies tonalitic and granodioritic gneisses of the Central Region of the Lewisian Gneiss Complex. The metasedimentary rocks, which probably originated as aluminous siltstones and mudstones, lie in juxtaposition with gneissose meta-igneous rocks that were intruded at mid- to deep crustal levels. This highlights the problem as to how metasedimentary rocks could be transposed from the Earth's surface to moderate or deep crustal levels. The lack of associated mafic–ultramafic bodies, as found farther north in the **Tarbet to Rubha Ruadh** GCR site, seems to preclude the metasedimentary rocks from having been originally associated with oceanic crust. Although subduction processes were active in the Archaean, no structural evidence of such processes is preserved in these rocks. The metasedimentary rocks preserve mineral assemblages that reveal the pressure and temperature conditions of the early Archaean granulite-facies metamorphism. They also document some of the stages of hydrous metamorphism under amphibolite-facies conditions that took place during the generation of shear zones during the Palaeoproterozoic Laxfordian event. The site is nationally significant in that it demonstrates the unequivocal nature of the metasedimentary rocks, highlights problems associated with their early tectonic history, and provides a record of both the early high-grade granulite-facies metamorphism and the later partial retrogression linked to shear-zone formation under lower-grade amphibolite-facies conditions.

SCOURIE BAY (NC 148 448, NC 146 461– NC 149 453)

C.R.L. Friend

Introduction

This GCR site comprises two localities on the north and south sides of Scourie Bay that include the type locality for the mafic and ultramafic Scourie Dyke Suite, which Peach *et al.* (1907) first recognized as crucial in interpreting the history of the Lewisian Gneiss Complex. Sutton and Watson (1951) subsequently used the dykes as a time-marker, separating the Scourian structural and metamorphic components of the Lewisian Gneiss Complex that were unaffected by significant Proterozoic deformation, from the Laxfordian components that had been partially to totally reworked under amphibolite-facies metamorphic conditions. They demonstrated that the evolution of gneiss complexes could be mapped and investigated through the use of regional dyke-swarms as deformational markers.

Sutton and Watson considered the Scourie dykes to belong to a single swarm, but it is clear from field relationships that there is more than one generation of emplacement (Peach *et al.*, 1907). Bridgewater *et al.* (1995) documented the main Proterozoic mafic dyke-swarms in the Labrador, Greenland and Baltic basement cratons, and showed that not only do they vary in age from 2500 Ma to 1900 Ma, but they also differ geochemically. On the basis of petrology and geochemistry, Tarney (1973) and Tarney and Weaver (1987b) divided the Scourie Dyke Suite into four distinct types; bronzite picrites, norites, olivine-gabbros and quartz-dolerites, with the latter being by far the most abundant. Many dykes in the Scourie area are relatively little deformed by Proterozoic and subsequent events, and as a consequence in many places they still preserve discordant relationships with the structures in the host felsic and mafic gneisses.

On the north side of Scourie Bay, the thick quartz-dolerite intrusion is exposed on the beach at Poll Eòrna and in the crags of Creag a' Mhàil and is considered to be the type Scourie dyke. C.T. Clough mapped the area for the Geological Survey in 1887. However, Teall (1885) had earlier described the petrography of the dyke in detail, with further work carried out by O'Hara (1961b). A second important quartz-dolerite dyke (the 'graveyard' dyke of O'Hara, 1961b) is exposed on the south side of Scourie Bay. Both dykes cross-cut the mainly granulite-facies banded felsic and mafic gneisses (Figure 3.4).

Description

The GCR site on the north side of Scourie Bay includes the coastal section at Poll Eòrna and the rocky promontories of Creag a' Mhàil and Sgeir Fhiaclach. Inland, rocky exposures with intervening grassy areas extend up to *c.* 75 m above OD in the north-west part, but the ground becomes lower to the south-east. On the south side of Scourie Bay a *c.* 500 m-long coastal section and its immediate hinterland area lie just north-west of Scourie graveyard.

The type example of a Scourie dyke, at Poll Eòrna, is about 35 m wide, trends ESE, and dips at *c.* 65°–80° to the NNE. The dyke passes offshore but reappears along strike to the WNW, where it occurs in a marked notch cutting through the headland of Creag a' Mhàil (Figure 3.6). The host rocks are typical granulite-facies felsic gneisses whose overall banding normally dips 35°–50° to the south-west.

The southern contact and much of the northern contact of the dyke are sheared and amphibolitized, and in these areas the dyke is made up of hornblende and plagioclase, with a marked shear fabric indicating a dextral sense of movement along the margins. On the south-east side of Poll Eòrna the dyke is cut by many shear zones which have two dominant directions, subparallel to the margins of the dyke and at a high angle across the dyke, causing a marked dextral displacement of the contact by some 2 m on the north side of the beach. The foliation within the dyke can be clearly seen to curve into the shear zone on both sides (Beach, 1978). The host gneisses demonstrate a variable degree of shear-

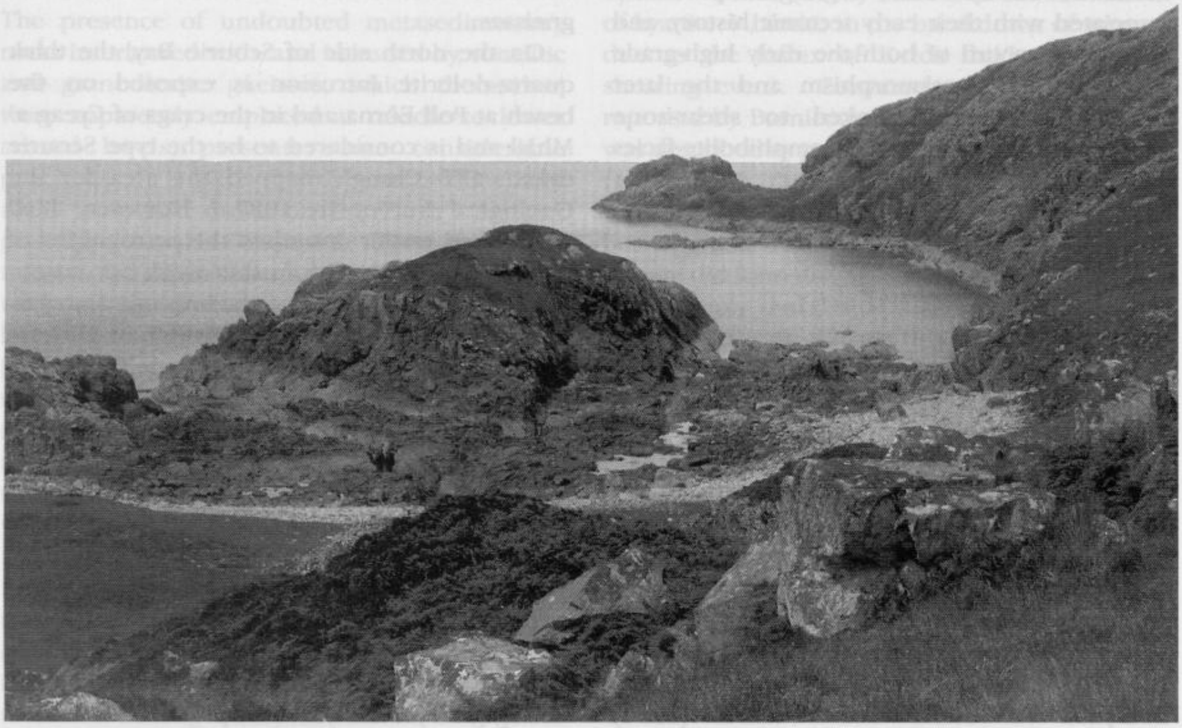


Figure 3.6 Poll Eòrna and Creag a' Mhàil, Scourie Bay. The notch in the distant promontory, the small bay in the middle distance, and the notch in the foreground, are all formed along the line of the type example of a Scourie dyke. (Photo: British Geological Survey, No. P001655, reproduced with the permission of the Director, British Geological Survey, © NERC.)

related fabric development along the contact. In places, structures discordant to the dyke margin are still preserved, but sections where a new amphibolite-facies fabric parallel to the dyke margin has developed are more common. Unsheared contacts may be seen on the Poll Eòrna beach.

The core of the dyke preserves a relict ophitic igneous texture, with pyroxenes showing varying degrees of replacement by amphibole. Garnets were developed at different stages of the metamorphism; they appear within the finer-grained marginal facies of the dyke but are not seen in the sheared rocks (O'Hara, 1961b). In places very thin (1–2 mm) planar to highly irregular veins of garnet cross-cut the fabrics. Some of the planar veins form conjugate sets with south-east and SSE trends, whereas the more-irregular veins appear to have random orientations.

The part of the GCR site on the southern side of Scourie Bay contains two sub-parallel Scourie dykes. The larger dyke, the 'graveyard' dyke of O'Hara (1961b), is a subvertical quartz-dolerite, *c.* 50 m wide, that trends roughly ESE. Just to the north, is a much thinner (*c.* 0.75 m wide), vertical, satellite dyke that displays particularly good cross-cutting relationships with the structures in the surrounding felsic gneisses (Figure 3.7). The main dyke is variably affected by later deformation and metamorphism, in part dependent upon distance from its margin. Both dykes have been hydrated and metamorphosed under amphibolite-facies conditions to varying degrees and contain garnet + amphibole-bearing assemblages.

The thicker 'graveyard' dyke is zoned across its width from north to south. Adjacent to its northern contact is a 1–2 m zone of variably foliated and sheared amphibolite with small, rounded garnet porphyroblasts. Towards the centre of the dyke the foliation becomes weaker, and a relict, ophitic igneous texture becomes apparent. Relict orthopyroxene and clinopyroxene, now mainly replaced by amphibole and some biotite, are present. Within this

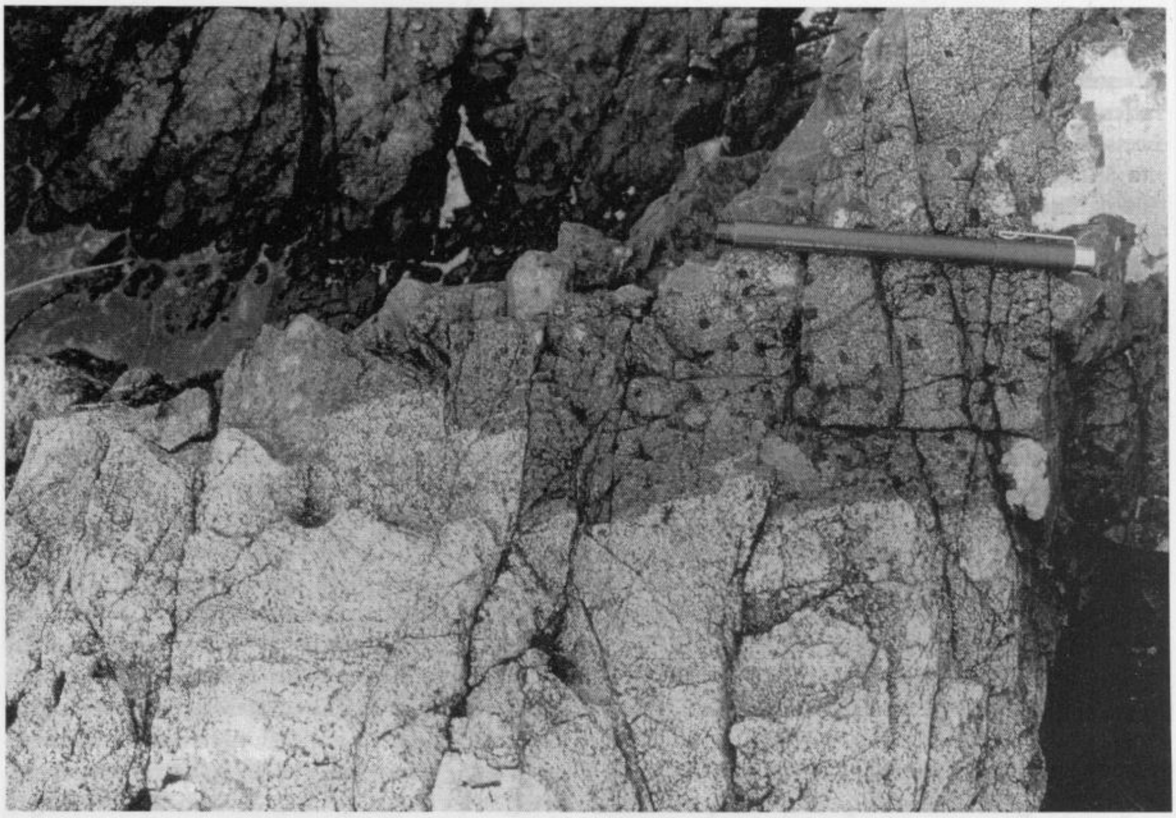


Figure 3.7 Small satellite Scourie dyke showing cross-cutting relationship with the gneisses, about 150 m NNW of the gate at Scourie graveyard, Scourie Bay. The dyke is amphibolitized and has small, rounded garnet porphyroblasts. It also has a steep contact displaced by several minor faults, which seem to be related to early joints in the gneisses. The pen is 15 cm long. (Photo: C.R.L. Friend.)

transition zone, thin (*c*. 1–2 mm), cross-cutting, discontinuous garnet veinlets can be found. Near the centre of the dyke the amount of amphibole decreases, and garnet coronas between plagioclase and pyroxenes give the rock a pinkish colour. This relatively undeformed zone extends towards the southern contact where there is a thin zone of amphibolitized material against the host felsic gneisses.

The contact of the thinner dyke is displaced by numerous small faults (Figure 3.7). The faults appear to be related to joints in the host gneisses but do not go entirely through the dyke and displace it; hence, they may be interpreted to have controlled the geometry of dyke intrusion rather than being later features. No remnants of igneous minerals remain in the dyke, which is now amphibolite, although some small, granular aggregates of plagioclase retain a texture resembling that of a dolerite. Small garnet porphyroblasts (less than 5 mm) are present amongst dark-greenish amphibole and plagioclase (± quartz). This mineralogy replicates that seen at the northern contact of the thicker dyke.

An ultramafic dyke of the Scourie Dyke Suite crops out just north of the GCR site on the beach at the head of Scourie Bay (NC 155 447) (O'Hara, 1961a). Its mineralogy and texture can be readily compared with those in the dolerite dykes.

The felsic gneisses throughout the Scourie Bay GCR site are typically tonalitic in composition and preserve extensive orthopyroxene as evidence for granulite-facies conditions. In shear zones they are retrogressed to amphibole- and biotite-bearing gneisses with development of a new foliation. In a few exposures around the headland of Meallan an Tiodhlacaidh (NC 149 449), north of Scourie graveyard, orthopyroxene is absent, owing to a greater general degree of retrogression under amphibolite-facies conditions. On the beach around Meallan an Tiodhlacaidh the gneissic banding is more attenuated with thin tonalitic layers interbanded with discontinuous, plagioclase-rich layers. This attenuation appears to be related to the granulite-facies conditions, as the gneisses are not retrogressed, and were patently deformed prior to the intrusion of the metadolerite dykes. No distinct lithological units can be discerned in the gneisses, largely due to extensive granulite-facies recrystallization and ductile deformation.

Contained within the foliation and banding, and generally scattered throughout the gneisses, are numerous small, dark-green to black hornblendite pods up to about 1 m in diameter. Even though pre-dyke strain at this site is high compared with, for example, Camas nam Buth, only about 0.5 km to the WSW (see **Scourie Mor** GCR site report, this chapter), these pods are interpreted to be derived from larger mafic–ultramafic bodies, in common with other parts of the area. In one or two places larger pods show possible transitional stages of this fragmentation.

On the north side of Scourie Bay, the host felsic gneisses contain, and appear to break up, layers and lenses of mafic to ultramafic gneisses that are associated with brownish-weathering, biotite-rich gneissose semipelite, interpreted to be of metasedimentary origin (O'Hara, 1960, 1961b). These rocks are similar to those described in the **Sìthean Mòr** GCR site report (this chapter), about 300 m to the north.

Interpretation

The dykes of the Scourie Dyke Suite within this GCR site were emplaced following the granulite-facies metamorphism of the host gneisses. There is still some debate as to whether the dykes were emplaced into hot, cold or warm country rocks, but it is clear from the field relationships that the host gneisses behaved in a relatively brittle manner (e.g. Figure 3.7). Whilst the region as a whole has essentially behaved as a stable block during later events, the dykes demonstrate that the area has suffered localized and variable Proterozoic amphibolite-facies metamorphism, particularly along zones of high strain. The dykes preserve a history of fluid ingress and metamorphic retrogression and alteration, dependent partly on their thickness and the extent to which they have been dissected by shears. The site demonstrates the way that Laxfordian strain is partitioned into narrow shear-zones, in part controlled by lithological discontinuities.

The dykes at this site have been studied by a variety of dating techniques. Chapman (1979) presented Rb-Sr data for three dykes from the Scourie region, including the two main dykes at Scourie Bay, and derived a combined isochron age of 2390 ± 20 Ma. Waters *et al.* (1990) carried out Sm-Nd, Rb-Sr and U-Pb isotope studies on a variety of Scourie dykes. A sample from the Poll Eòrna dyke, which retains some primary igneous mineralogy, gave a mineral isochron age of 1982 ± 44 Ma, whereas the moderately amphibolitized 'graveyard' dyke gave an isochron age of 1758 ± 7 Ma based on the metamorphic minerals. This latter age was considered to represent the timing of metamorphic recrystallization during the Laxfordian event. However, a two-point Rb-Sr age of 2027 ± 11 Ma was also obtained for the 'graveyard' dyke, and Waters *et al.* (1990) thus interpreted both dykes to have been emplaced at *c.* 2000 Ma.

It is clear from wider studies in the North Atlantic cratons that several different mafic dyke-swarms were intruded into Archaean basement terrains during the Palaeoproterozoic. Bridgewater *et al.* (1995) showed that their ages ranged from 2500 Ma to 1900 Ma with high-Mg basic dykes intruded between 2500 Ma and 2200 Ma, and tholeiitic swarms intruded at 2200 Ma in southern Greenland and Labrador. These swarms were emplaced largely under tensional conditions with localized sinistral shearing. However, the thick dykes of the younger (*c.* 2000 Ma) Kangâmiut Dyke Swarm are composed of Fe-enriched hornblende-bearing tholeiites. They are found widely in southern and central Greenland, and were emplaced into the craton at the time of continental break-up. The dykes were subsequently spectacularly deformed and metamorphosed by the Nagssugtoqidian Orogen between 1870 Ma and 1750 Ma (van Gool *et al.*, 2002). The later *c.* 1835 Ma Avayalik Dyke Swarm in the northern part of the Nain Province in Labrador appears to have been emplaced synchronous with tectonometamorphic orogenic activity in the Torngat Orogen and emplacement of calc-alkaline plutons (Bridgewater *et al.*, 1995).

Conclusions

The Scourie Bay GCR site contains two excellent examples of metadolerite dykes of the Scourie Dyke Suite, with the Poll Eòrna dyke considered to be the type locality. Cross-cutting relationships between the quartz-dolerite dykes and their host Badcallian granulite-facies felsic and mafic gneisses are well preserved. The dykes contain remnants of igneous mineralogy in their central parts, but towards the margins they are more strongly foliated and retrograded to amphibolite. The varied geometry of the dykes, internal and external shear-zones, and the amphibolite-facies retrogression is well displayed at the GCR site. Most of this deformation and metamorphism occurred during the Laxfordian reworking, dated here at *c.* 1750 Ma. Following deformation, renewed growth of clinopyroxene and garnet occurred, generating very narrow discordant veinlets. The complex metamorphic history is best understood by combining data from the dykes and the host felsic gneisses. The site is of international importance, as the Scourie Dyke Suite forms part of a more-widespread and long-lasting Palaeoproterozoic metadolerite dyke intrusion event that occurred in Archaean basement areas of Labrador, Greenland and Scandinavia. The Scourie Bay locality is excellent for teaching purposes and suitable for further studies.

TARBET TO RUBHA RUADH (NC 174 506–NC 158 480)

R.G. Park

Introduction

The Tarbet to Rubha Ruadh GCR site on the south side of the entrance to Loch Laxford provides a classic section across the 'Laxford Front' that separates largely unmodified Archaean basement gneisses to the south from Proterozoic reworked gneisses to the north. This orogenic division of the Lewisian Gneiss Complex into 'Scourian' and 'Laxfordian' components, respectively, was first recognized by Peach *et al.* (1907), but it was Sutton and Watson (1951) who established the significance of the Scourie Dyke Suite as an effective 'stratigraphical marker' separating the two major tectonometamorphic events in the basement gneisses. Sutton and Watson recognized four of the major tectonic zones in this area, which they termed the 'Scourie', 'Claisfearn', 'Foindle' and 'Badnabay' zones. The Scourie Zone consists of Badcallian gneisses cut by undeformed Scourie dykes; the Claisfearn Zone corresponds to the margin of a major, steep, Inverian shear-zone, in which Laxfordian effects are locally developed; the Foindle Zone marks the southern margin of penetrative Laxfordian deformation and metamorphism; and the Badnabay Zone contains Laxfordian granite sheets and exhibits later Laxfordian deformation. The site provides a traverse, which illustrates a progression through the main Proterozoic events that affected the Lewisian Gneiss Complex of the mainland.

The area was first mapped meticulously by C.T. Clough in 1887 and was described by him in Peach *et al.* (1907). Subsequent work by Sutton and Watson (1951), and detailed structural studies by Beach *et al.* (1974), Coward (1990), and Wynn (1995) have added considerably to our understanding of the area.

Description

This rugged GCR site extends from *c.* 1 km south of the fishing hamlet of Tarbet northwards to the peninsula of Rubha Ruadh, a total distance of some 3.7 km. The excellent exposure is due to a combination of attack by Atlantic storms along the western coastal section and severe glacial scouring inland. The site includes several rocky knolls, the highest being Cnoc Gorm at 133 m (NC 163 495), commonly separated by small lochans. The generally WNW-trending rocky ridges and hollows give the area a pronounced topographical grain that reflects the overall banding and foliation in the gneisses.

In the southern part of the site area a thick, undeformed Scourie dyke cross-cuts Badcallian gneisses that generally dip moderately to the south-west (Figure 3.8). This corresponds to the 'Scourie Zone' of Sutton and Watson (1951). About 1 km south of Tarbet is the southern margin of a large Inverian shear-zone, where the Badcallian gneisses are thinned and steepened into a near-vertical NW-trending orientation and retrogressed to amphibolite facies. Scourie dykes clearly cross-cut the Inverian fabric in this zone; although they are affected in turn by small-scale, narrow Laxfordian shear-zones. An excellent example of an irregular discordant dyke may be examined on the coast, on the south side of Port Mor (see Figure 3.9). A narrow, steeply S-dipping, Laxfordian shear-zone with a WNW–ESE trend is well exposed on the top of the hill on the south side of Port of Tarbet, where it cuts a Scourie dyke. The shear zone

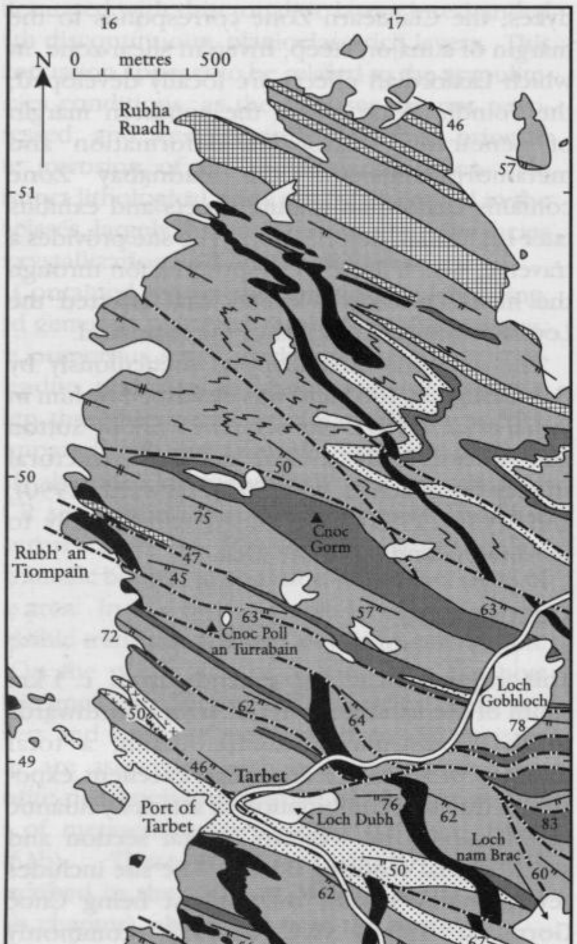


Figure 3.8 Map of the Tarbet to Rubha Ruadh area. Based on Beach (1978), Coward (1990), and Geological Survey 1:10 560 Sheet Sutherland 30 (1913).

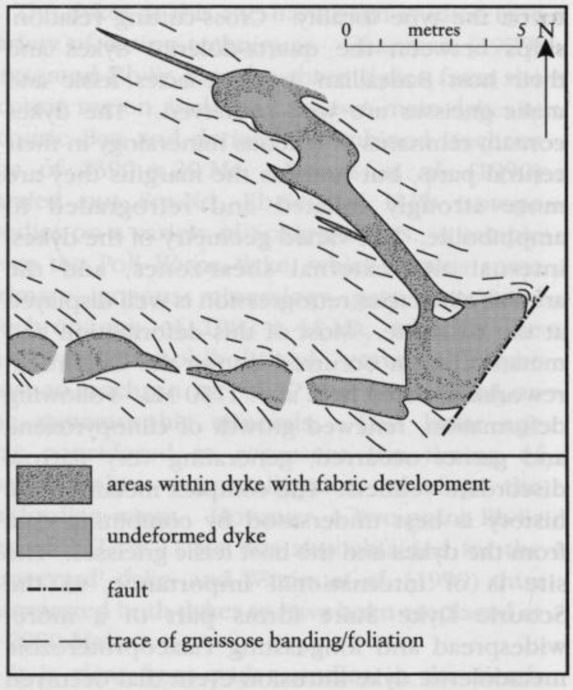


Figure 3.9 Map of an irregular Scourie dyke south of Tarbet. Areas in the dyke with a fabric are stippled, undeformed portions are blank. The discordance with the banding in the gneisses is shown. After Beach (1978).

exhibits a prominent lineation plunging at 45° to the south-east, implying a sinistral, north-up sense of movement.

Immediately north of Port of Tarbet (Figure 3.8), is a thick sequence of finely interbanded felsic and mafic gneisses containing several bands of brown-weathering, flaggy to fissile, schistose garnet-biotite-plagioclase semipelite and some quartzose psammite units, interpreted to be of sedimentary origin. Farther north is a coarse-grained, foliated granitic sheet containing a muscovite-K-feldspar-plagioclase-quartz assemblage. Good exposures of closely foliated, highly strained gneisses displaying abundant tight to isoclinal folds and a moderately SE-plunging lineation occur at the top of Cnoc Poll an Turrabain, about 500 m north of Tarbet. Here the foliation in the gneisses trends north-westerly and dips steeply to the south-west. This foliation must result from Inverian reworking, as farther north-west it is cut by a discordant thick Scourie dyke that is well exposed on the coastal rock platform north of Poll an Turrabain at NC 161 497 (Figure 3.10). The dyke can be traced across the promontory of Rubh' an

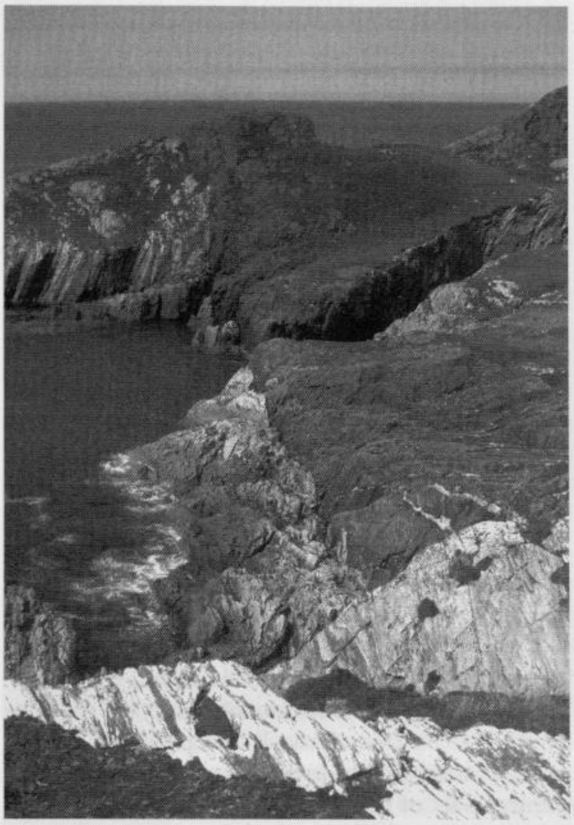


Figure 3.10 Thick Scourie dyke cutting discordantly across banded, mainly felsic gneisses by Rubh' an Tiompain. The dyke is internally deformed and shows partial amphibolitization. It contains shear zones that are notably abundant near the dyke margins. Its markedly lenticular form is interpreted as an original intrusive feature. (Photo: J.R. Mendum.)

Tiompain to the north-west, but it lenses out rapidly to the south-east; the dyke geometry is thought to reflect its original intrusive form rather than the later deformation. The dyke is composed of three intermixed igneous components: 'normal' metadolerite, a more-felsic type and a more-mafic type. It contains numerous xenoliths and also exhibits mafic–felsic segregation banding of presumed igneous origin. Although the dyke shows weak to moderate internal fabric development it also contains numerous narrow Laxfordian shear-zones marked by an intense foliation. Its southern contact can be clearly seen to be discordant to the Inverian gneissose foliation, which is also present within the gneiss xenoliths.

About 1 km north of Tarbet, the ridge of Cnoc Gorm consists of a thick sheet of banded garnetiferous metagabbro, which trends in a WNW direction to the coast. This is one of several mafic bodies found in this area that preserve their original Badcallian mineral assemblages. Still farther north, west of Fanagmore, a thinner sheet consisting of both mafic and ultramafic material, accompanied by brown-weathering schists, forms a complex series of folds with NW-trending axes (Figure 3.8). These folds are cut by a thin, NW-trending, Scourie dyke, which, farther north-west, is itself folded by Laxfordian structures. The pre-dyke folds are thus of Inverian age. The Laxfordian deformation here is more intense and pervasive than farther south, and marks the transition from the Claisfearn Zone into the Foindle Zone.

The most northerly part of the area, at Rubha Ruadh, is marked by a prominent 150m-wide sheet of granite that trends in a north-westerly direction across the peninsula. The southern margin of the granite is sharp, though concordant, and separates the Foindle Zone to the south-west, where granite sheets are minor and uncommon, from the Badnabay Zone to the north-east, where pink to red granite sheets and white pegmatitic veins make up much of the outcrop. This boundary is known as the 'Laxford Front' and marks the south-west margin of a zone along which the granite sheets have been concentrated. The granites are typically foliated and contain pegmatitic segregations. They occur as a number of discrete sheet-like bodies separated by biotitic and hornblendic felsic gneisses. The gneisses of the Badnabay Zone (and also those farther north) have been shown by Holland and Lambert (1973) to be chemically distinct from those of the Central Region.

Interpretation

The Tarbet to Rubha Ruadh GCR site provides a traverse up to the 'Laxford Front' from which inferences about the nature and tectonic history of the Lewisian Gneiss Complex can be drawn. The Claisfearn and Foindle zones represent a major, steep Inverian shear-zone, in which the original Badcallian gneisses, which occur in the Scourie Zone farther south, have become deformed, folded and retrogressed to amphibolite facies. Sutton and Watson (1951) interpreted the reworking of the Badcallian gneisses in these zones as a result of Laxfordian effects, but Beach *et al*. (1974) showed that the reworking was Inverian. From the sense of shear and the lineation direction within the high-strain parts of this shear zone, a dextral, south-up sense of movement (i.e. overthrusting from the south) can be inferred.

The Foindle and Badnabay zones represent the southern part of a major Laxfordian shear-zone, which is superimposed upon the earlier Inverian shear-zone. The Foindle Zone defines the northern margin of the Central Region of the Lewisian Gneiss Complex, and here Laxfordian deformation is weak and localized. The discrete narrow shear-zones that affect the Scourie dykes to the south are replaced here by pervasive Laxfordian deformation. The deformation is manifest as an intense NW-trending, steeply SW-dipping foliation and a SE-plunging lineation, whose orientations are similar to those of the Inverian shear-zone immediately to the south. According to Wynn (1995) the movement on the main Laxfordian shear-zone was dextral, and transpressional, but was accompanied to the south-west by a suite of second-order E- to NE-trending shears along which a sinistral trans-tensional sense of movement can be inferred, as in the minor shear-zones near Tarbet.

Isotopic dating was initially carried out in the area by Lyon *et al.* (1975), who obtained a Rb-Sr whole-rock isochron age of 2745 Ma (i.e. Badcallian) from the gneisses and a whole-rock–muscovite isochron age of *c.* 1750 Ma (i.e. Laxfordian) from a granitic sheet north of Port of Tarbet. These ages were taken to indicate that the rocks formed during the Badcallian event, but were reworked during the Laxfordian. More recently, Kinny and Friend (1997) have shown that there appears to be an abrupt change in the nature of the gneiss basement across the Laxford Front, with gneisses from the Northern Region having protolith ages of 2840–2800 Ma, whereas those immediately south of the Laxford Front have protolith ages of 3030–2960 Ma. This suggests that the Laxfordian shear-zone situated in the Foindle and Badnabay zones represents a major terrane boundary. Evidence for the metamorphic event at *c.* 2480–2490 Ma, which is recorded from gneisses of the Central Region, is absent from those of the Northern Region (Corfu *et al.*, 1994; Kinny and Friend, 1997). Laxfordian granite sheets that are abundant to the north of the Laxford Front appear to represent several periods of emplacement. Friend and Kinny (2001) showed that the granite at Laxford Bridge was intruded at 1855 Ma, but Goodenough *et al.* (in press) have obtained LA-PIMS and TIMS zircon U-Pb ages of 1880 Ma and 1775 Ma from two distinct sets of granitic intrusions in the Laxford Shear Zone. These granites occur in both the Northern and Central regions (Assynt and Rhiconich terranes), implying their juxtaposition pre-dates the Laxfordian events and is probably of Inverian age.

Conclusions

This internationally important GCR site provides a well-exposed traverse from the Central Region northwards across the classic area to the 'Laxford Front'. It was here that Sutton and Watson (1951) originally demonstrated their orogenic division of the Lewisian Gneiss Complex into Scourian and Laxfordian components. The site contains four of Sutton and Watson's five designated tectonic zones, the Scourie, Claisfearn, Foindle and Badnabay zones, and allows the transition to be demonstrated from the Badcallian gneisses in the south, through an Inverian shear-zone in the central part of the area, to the Laxfordian shear-zone in the north.

The traverse demonstrates the effects of the reworking of the earlier high-grade Badcallian gneisses during the later amphibolite-facies Inverian event (*c.* 2490 Ma), and subsequently during the amphibolite-facies Laxfordian event *c.* 1740 Ma. The emplacement of the Scourie Dyke Suite, which plays a vital role as a chronological marker, separates these latter two tectonometamorphic events. Recent U-Pb zircon age dates from the area have also clarified the significance of the Laxford Front as a possible terrane boundary.

The Tarbet to Rubha Ruadh site is of international significance in that it forms a 'type area' for demonstrating the tectonic and metamorphic history of the Lewisian Gneiss Complex in Britain, which can be matched and compared to its counterparts in Greenland, North America and Scandinavia. In historical terms, the Scourie–Laxford area was one of the first places where tectonic events in a basement gneiss complex were separated using an episode of igneous intrusion in order to create a 'pseudo-stratigraphy'. Similar methods have subsequently been widely used in other basement terrains and are now a standard tool in unravelling complex sequences of events around the world.

LOCH DRUMBEG (NC 114 329)

R.G. Park

Introduction

This GCR site, adjacent to the Lochinver–Kylesku road just west of the village of Drumbeg, contains one of the best examples of layered mafic–ultramafic meta-igneous rocks within the Lewisian Gneiss Complex. There are many small examples of such bodies throughout the Lewisian outcrop, and they are generally believed to represent the disrupted remnants of one, or several, large, layered mafic–ultramafic intrusions equivalent to those mapped in the Archaean of Greenland (see Windley *et al*., 1973) and in other Archaean terrains. The intrusion at Drumbeg occurs in the form of a deformed sheet, up to 100 m thick, enclosed within Badcallian tonalitic gneisses. The rocks include metaperidotite (containing olivine and two pyroxenes) and basic meta-igneous rock, in the form of garnet-pyroxene-plagioclase rock ('pyriclasite'), both of which exhibit typical granulite-facies mineral assemblages.

The mafic–ultramafic rocks were first mapped by L.W. Hinxman in 1887, and described by Peach *et al*. (1907). They were subsequently examined and described in detail by Bowes *et al*. (1964), who used the term Drumbeg 'complex', and by O'Hara (1965, 1977). These authors studied the geochemistry and mineralogy in considerable detail. The intrusion has been dated using Sm-Nd whole-rock methods at 2910 ± 55 Ma (Whitehouse, 1989).

Description

The GCR site occupies a relatively small area of rugged but low-lying ground near the shores of Loch Drumbeg. The mafic–ultramafic rocks are enclosed within typical tonalitic to granodioritic felsic gneisses exhibiting Badcallian granulite-facies assemblages, and are disposed in a broad syncline (Figure 3.11). Banded metaperidotites (Figure 3.12) overlain by garnet-pyroxene-plagioclase rocks dip gently to the SSW in the northern part of the site and reappear in the south-west part of the site, south of some unexposed ground, dipping moderately to the north-east. Around the shores of Loch Drumbeg, the structure is more complex, and it appears as though there has been some disruption of the banding, possibly due to the emplacement of the tonalitic gneisses. The garnet-pyroxene-plagioclase rocks are banded in their northern outcrop but are more massive farther south.

The maximum thickness of the mafic–ultramafic sheet as seen in the northern outcrop is about 100 m, but the sheet is thinner in the south, where disrupted by the felsic gneisses. Some small outcrops of ultramafic rock in the southern part of the site appear to be surrounded by felsic gneiss and probably represent isolated lensoid inclusions. The foliation in the felsic gneisses generally has a low dip; in places demonstrably sub-parallel to the compositional banding in the mafic rocks, but elsewhere the gneiss foliation is markedly discordant to the banding. Both banding and foliation are folded by the WNW-trending open syncline. These structures are cut by narrow, steep shear-zones, marked by belts of steep, strongly foliated rocks showing retrogressive effects; for example metaperidotite has been converted to tremolite-talc-chlorite assemblages.

The ultramafic rocks consist of recrystallized aggregates of hypersthene, clinopyroxene and olivine, and are best termed 'metaperidotites'. The olivine is generally altered, and brown-green hornblende is also present in places. The modal proportions of olivine and pyroxene define the banding in the ultramafic rocks, and individual bands typically range from 2–10 cm in thickness, although thinner bands are seen in places.

The garnet-pyroxene-plagioclase rocks are largely composed of aggregates of garnet with rims of plagioclase and interstitial clusters of clinopyroxene. Dark-green hornblende also occurs, and uralitization of pyroxene is evident. The banding in these rocks is not as well defined as that in the ultramafic rocks, and is largely the result of variations in the proportions of plagioclase and hornblende.

The mafic–ultramafic rocks are cut by sheets and irregular masses of quartz-feldspar pegmatite. The K-feldspar-plagioclase intergrowth textures in the feldspars were considered by O'Hara (1965) to indicate exsolution from high-temperature feldspar.

Interpretation

The Drumbeg ultramafic–mafic intrusion has been dated by Sm-Nd whole-rock methods at 2910 ± 55 Ma (Whitehouse, 1989), and is

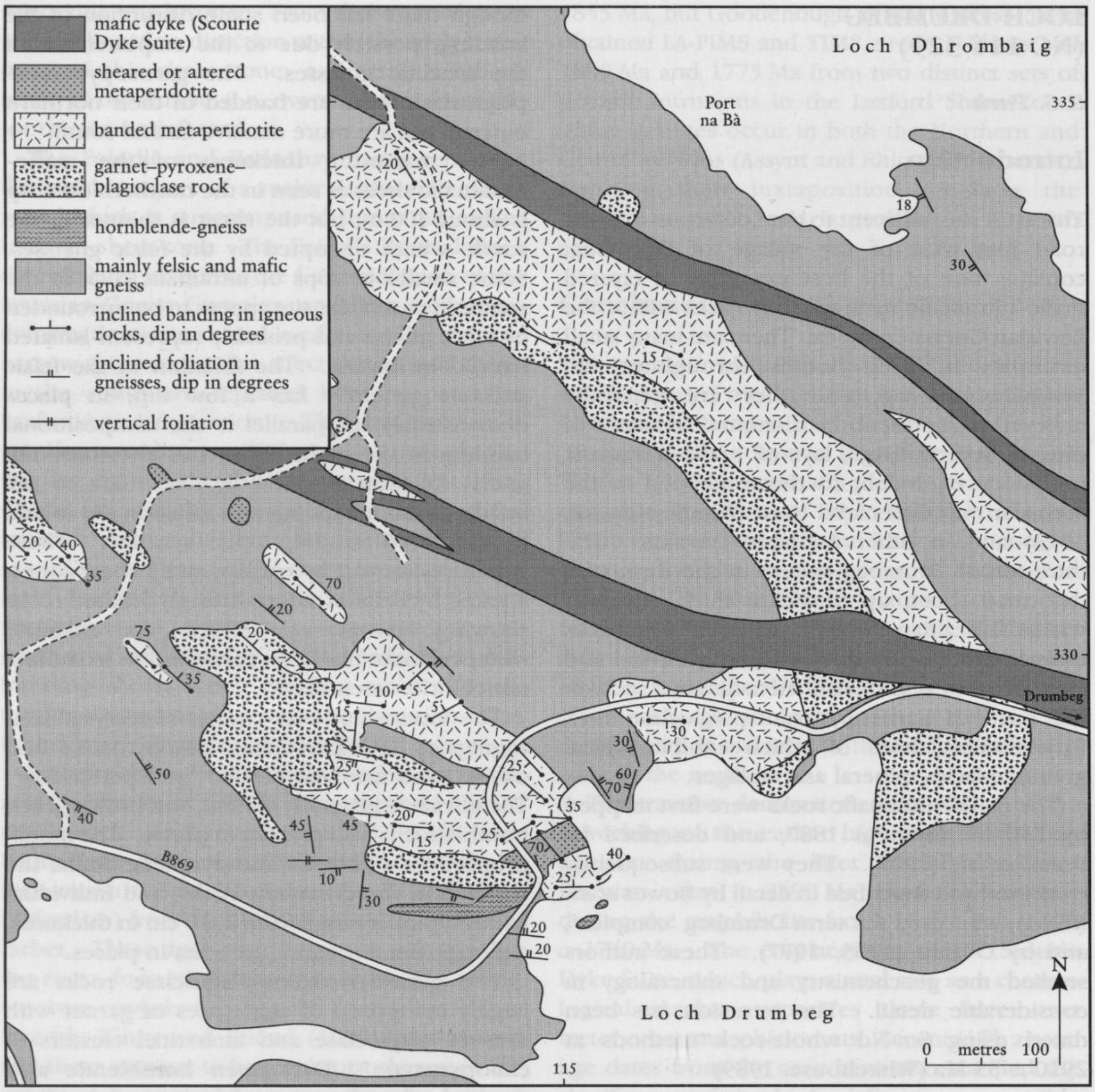


Figure 3.11 Map of the Drumbeg mafic–ultramafic intrusion. After Bowes *et al.* (1964) and Geological Survey 1:10 560 Sheet Sutherland 48 (1888).

believed to represent one of the oldest components of the Lewisian Gneiss Complex on the mainland. Similar mafic–ultramafic bodies are found at a variety of localities in the Central Region (e.g. see **Scourie Mor** GCR site report, this chapter), and Park and Tarney (1987) suggested that these bodies might represent the disrupted remnants of ocean-floor material underplated at the base of the contemporary crust and subsequently invaded by tonalitic magmas.

The rocks were deformed and metamorphosed in the Badcallian event, and exhibit typical granulite-facies mineral assemblages. O'Hara (1977) used the mineral chemistry of the mafic rocks to define the peak metamorphic temperatures at about 1250° C, under pressures of about 15 kbar. Whitehouse (1988) obtained a Sm-Nd whole-rock isochron (errorchron) age of 2600 ± 155 Ma from felsic gneisses from the Scourie–Drumbeg area. He interpreted this age as dating the granulite-facies event that resulted in Nd isotopic homogenization in the gneisses.

Bowes *et al.* (1964) drew attention to structures similar to current bedding and considered that

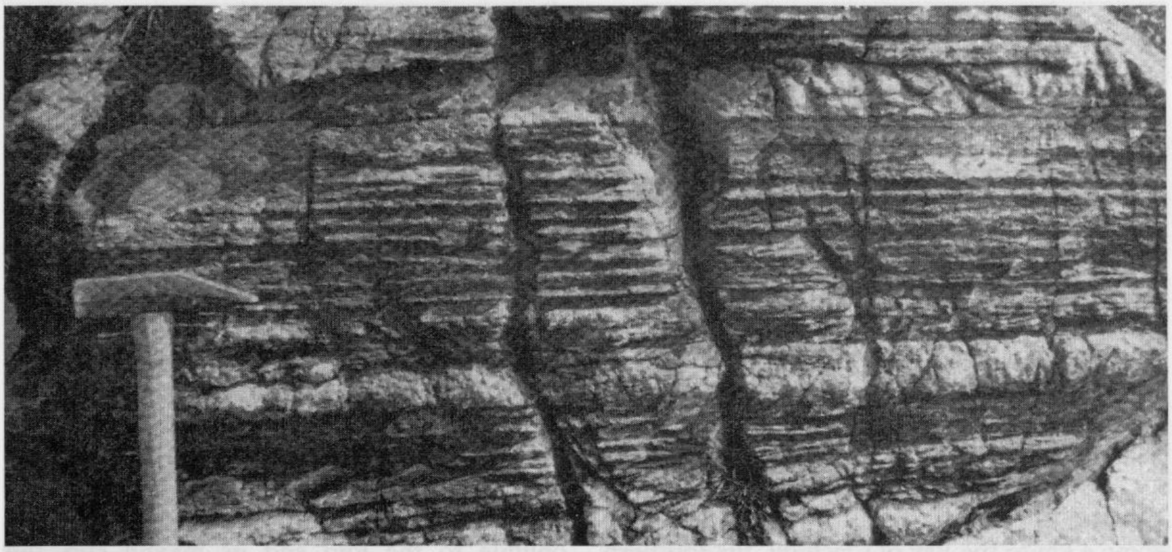


Figure 3.12 Banding in metaperidotite from Drumbeg. The hammer head is 15 cm long. From Bowes *et al.* (1964).

they were an indication of gravitational settling in a magma chamber. However data on the mineral compositions across adjacent layers were considered to be incompatible with the gravity settling model by O'Hara (1977), and the observed wedging and truncation are now thought to be probably deformational in origin.

Conclusions

The Loch Drumbeg GCR site provides an accessible and well-exposed locality on the Scottish mainland at which one of the important Lewisian early mafic–ultramafic igneous intrusions can be studied. It yields good examples of metaperidotites and mafic garnet-pyroxene-plagioclase rocks, which still exhibit clear igneous banding in places. The intrusive relationship of younger felsic gneisses can also be deduced. Geothermometric, geobarometric and geochronological work at this site have played an important part in the evolution of ideas regarding conditions and events during formation of the Lewisian Gneiss Complex in the Archaean; typical granulite-facies mineral assemblages have yielded temperature and pressure estimates of 1250° C and 15 kbar respectively. The mafic–ultramafic rocks have been dated at 2910 ± 55 Ma, and are believed to be among the oldest components of the Lewisian Gneiss Complex. They may possibly represent the disrupted remnants of ocean-floor material underplated at the base of the contemporary crust and subsequently invaded by more-acid magmas. The site is of national importance and remains suitable for teaching and further studies.

AN FHARAID MHÒR TO CLACHTOLL (NC 038 270–NC 069 245)

R.G. Park

Introduction

This exceptionally well-exposed GCR site, north-west of Lochinver, encompasses the peninsula of An Fharaid Mhòr, Achmelvich Bay, and the cliffed and indented coastal section north to Clachtoll. This area has become the type locality for the Inverian tectonothermal event, first recognized by Evans (1965) as a period of deformation and metamorphism distinct from the previously established Scourian and Laxfordian divisions of the Lewisian (Sutton and Watson, 1951). Excellent examples of early layered mafic and ultramafic rocks and mafic dykes of the Scourie Dyke Suite are also present. The site provides a traverse across the 1.5 km-wide Canisp Shear Zone, the largest shear-zone within the Central Region. The shear zone was initiated during the Inverian event and reactivated during Laxfordian reworking.

The area was originally mapped and described by B.N. Peach and J. Horne in 1888, and was described by Peach *et al.* (1907) who first recognized and traced out the Canisp Shear Zone. Modern investigations commenced with the work of Tarney (1963) and Evans (1965), which led to the recognition of the Inverian event (see also Evans and Lambert, 1974). The area was remapped by Sheraton *et al.* (1973) and was described by Tarney (1978). The shear zone itself was the subject of more-detailed structural studies by Jensen (1984) and subsequently by Attfield (1987).

Description

The site extends north-west from Loch Roe for some 4 km to the Bay of Clachtoll. Its southern part includes the area of rocky knolls and boggy hollows east of Achmelvich that culminate in Cnoc an Taighain (88 m above OD). The blown sand area around Achmelvich separates this glacially scoured cnoc and lochan scenery, which is characteristic of much of the Lewisian Gneiss Complex area, from the craggy An Fharaid Mhòr–An Fharaid Beag peninsula. Farther north-west the site area extends south-west from the Lochinver–Stoer road (B869) to the rocky indented coastline that contains cliffed sections up to 60 m high. The small peninsula of A' Clach Thuill is lower and smoother and underlain by Torridonian breccias and sandstones (see **Stoer** GCR site report, Chapter 4). Geologically, it is convenient to describe the area in two parts: a southern part, around An Fharaid Mhòr, and a northern part that traverses the Canisp Shear Zone (Figure 3.13). Much of the description is based on Tarney (1978) and Attfield (1987).

On the peninsula of An Fharaid Mhòr, the majority of the exposures are banded, grey, tonalitic gneisses with abundant pods of hornblendite. On the south-western point of An Fharaid Mhòr, overlooking Loch Roe, the tonalitic gneisses enclose thick sheet-like bodies of mafic and ultramafic gneiss, which form a large recumbent synform with its axis plunging at about 10° to the south-west. The mafic gneisses are typically banded, with anorthositic and mafic components, but show extensive replacement by hornblende. They include hornblendic peridotite and garnet-pyroxene-hornblende gneisses. The gneissose banding strikes uniformly north-east and dips gently to the north-west. The gneisses are cut by several generations of pegmatitic leucosome, with the later generations forming undeformed dyke-like bodies that cross-cut the banding. The Badcallian gneissose banding is also cut by several markedly discordant undeformed mafic dykes of the Scourie Dyke Suite.

Evidence for the Inverian event can be readily seen 300 m south-east of the Youth Hostel, on the east side of the Achmelvich road at NC 063 248. Here, an amphibolitized 8 m-wide metadolerite dyke of the Scourie Dyke Suite follows the vertical limb of an Inverian monoclinal fold for a distance of about 50 m. The monocline has an amplitude of 20–30 m, and its axis plunges about 40° to the ESE. The middle limb is vertical, and the banding is attenuated but not highly sheared. The dyke trends slightly oblique to the fold and its margin cuts the Inverian fabric in the steep limb, although here it is also slightly affected by later Laxfordian deformation.

The south-western boundary of the Canisp Shear Zone can be demonstrated by making a north-easterly traverse along the coast section from Achmelvich beach across the steeply dipping north-east limb of the Lochinver Anticline, a NW-trending structure that folds the Badcallian gneissose banding (Figure 3.14). Immediately north of the northern beach lies part of the Inverian shear-zone, in which the gneisses are little affected by Laxfordian deformation. The gneisses here are thinly banded, and include felsic, intermediate and mafic varieties, all retrogressed to amphibolite facies. The intensity of Inverian deformation can be approximately monitored by the changes to ellipsoidal shapes shown by the mafic inclusions in the gneisses. The gneisses are cut by a metadolerite dyke (Scourie Dyke Suite), which is affected by marginal Laxfordian shearing but undeformed in its central part.

About 500 m from the beach is the well-defined southern boundary of the reactivated Laxfordian part of the shear zone. A small cleft in the rocky cliff (NC 057 256) marks the change from massive Inverian gneisses into much more finely banded gneisses with a steep dip to the south-west and an intense fine lineation that plunges 20°–30° to the south-east. A large metadolerite dyke forms a lens-shaped outcrop on the hillside above the cliff here, and can be examined in the gullies farther west along the coast. This Scourie dyke is intensely deformed locally, especially near its margins where it

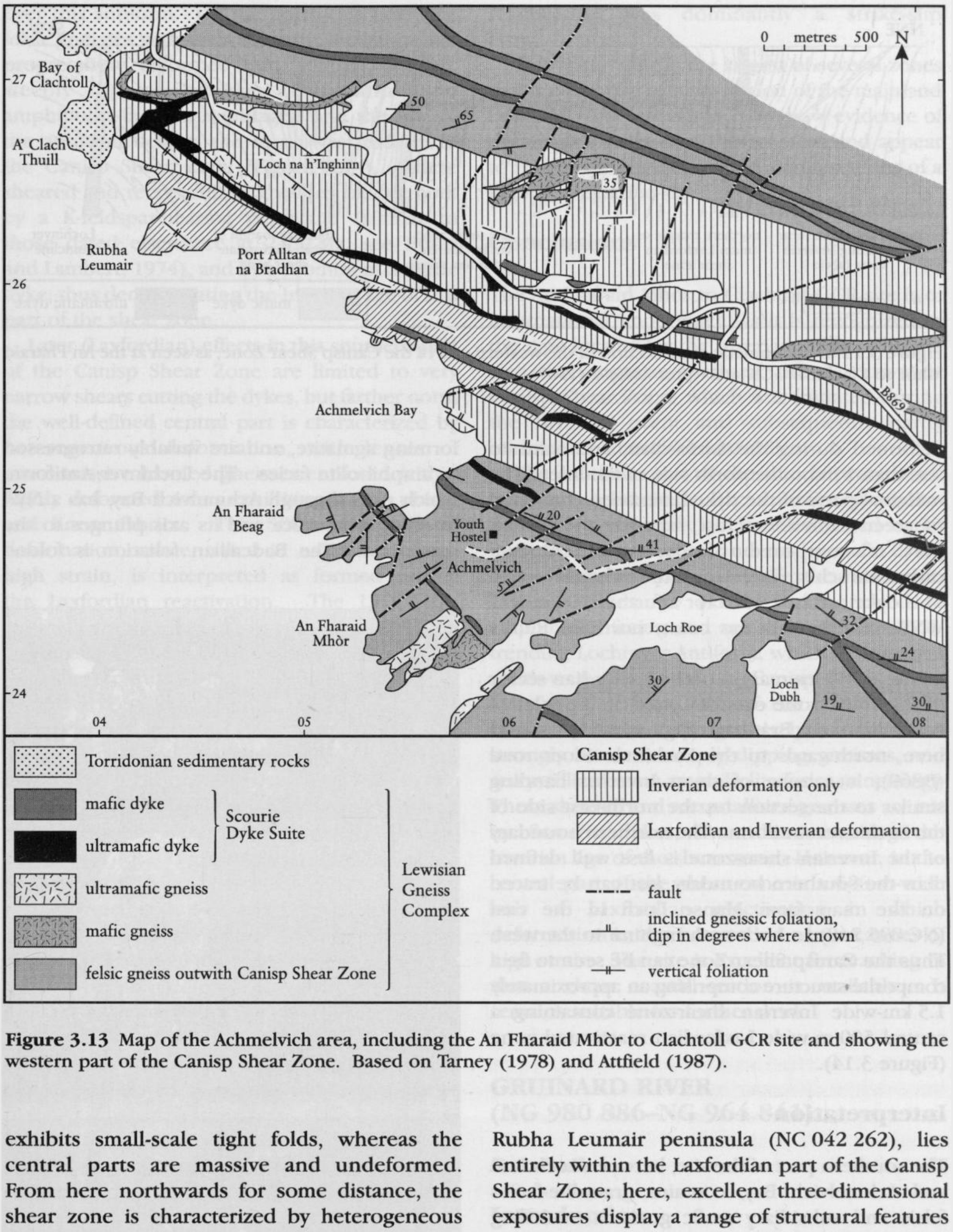


Figure 3.13 Map of the Achmelvich area, including the An Fharaid Mhòr to Clachtoll GCR site and showing the western part of the Canisp Shear Zone. Based on Tarney (1978) and Attfield (1987).

exhibits small-scale tight folds, whereas the central parts are massive and undeformed. From here northwards for some distance, the shear zone is characterized by heterogeneous deformation, with lenses of the more-massive banded gneisses enclosed within highly deformed zones that exhibit strong planar and linear Laxfordian fabrics. Later cataclastic zones are also evident. This section of coastline, which extends for nearly 2 km to the far side of the Rubha Leumair peninsula (NC 042 262), lies entirely within the Laxfordian part of the Canisp Shear Zone; here, excellent three-dimensional exposures display a range of structural features including good examples of interference fold patterns.

On the north-east side of the small peninsula on the south side of Port Alltan na Bradhan (NC 052 263) is a 25 m-wide, amphibolitized, picrite dyke. This dyke has been intensely

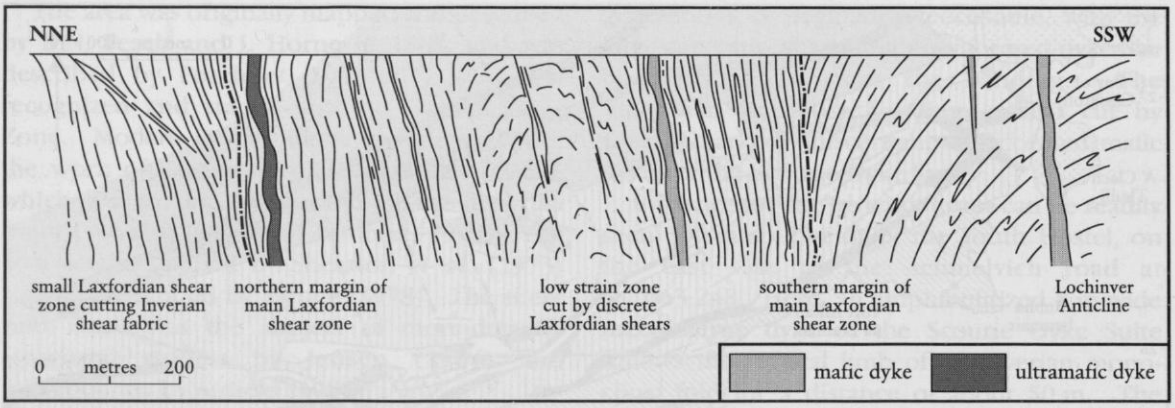


Figure 3.14 Diagrammatic cross-section of the western end of the Canisp Shear Zone, as seen at the An Fharaid Mhòr to Clachtoll GCR site. After Attfield (1987).

deformed during the Laxfordian, and thins to less than 1 m on the north side of the inlet. The marginal parts of the dyke have been converted to green actinolite schist, whereas the central part is composed of fissile talc-chlorite-carbonate schist displaying late-Laxfordian folds. This dyke can be traced for a further 900 m in a WNW direction to the coast, north of Rubha Leumair.

The northern margin of the Laxfordian sector of the shear zone cuts the coast at the inlet of Port Alltan na Bradhan (Figure 3.15). From here, northwards to the Lochinver–Stoer road (B869), is a zone of steep Inverian banding similar to the section on the north-east side of the Lochinver Antiform. The northern boundary of the Inverian shear-zone is less well defined than the southern boundary, but can be traced on the map from Manse Loch in the east (NC 095 248) to Loch na h-Inghinn in the west. Thus the Canisp Shear Zone can be seen to be a composite structure comprising an approximately 1.5 km-wide Inverian shear-zone containing a central 500 m-wide Laxfordian reactivated zone (Figure 3.14).

Interpretation

The southern part of the site, between Loch Roe and Achmelvich Bay, contains granulite-facies felsic and subsidiary mafic gneisses enclosing layered mafic and ultramafic bodies. These rocks are deformed by the Badcallian deformation and cut by mafic dykes of the Scourie Dyke Suite. To the north-east, the country rock gneisses become more felsic, and contain abundant mafic and ultramafic pods, typically forming agmatite, and are variably retrogressed to amphibolite facies. The Lochinver Antiform, which runs through Achmelvich Bay, has a NW-trending axial trace and its axis plunges to the south-east. The Badcallian foliation is folded

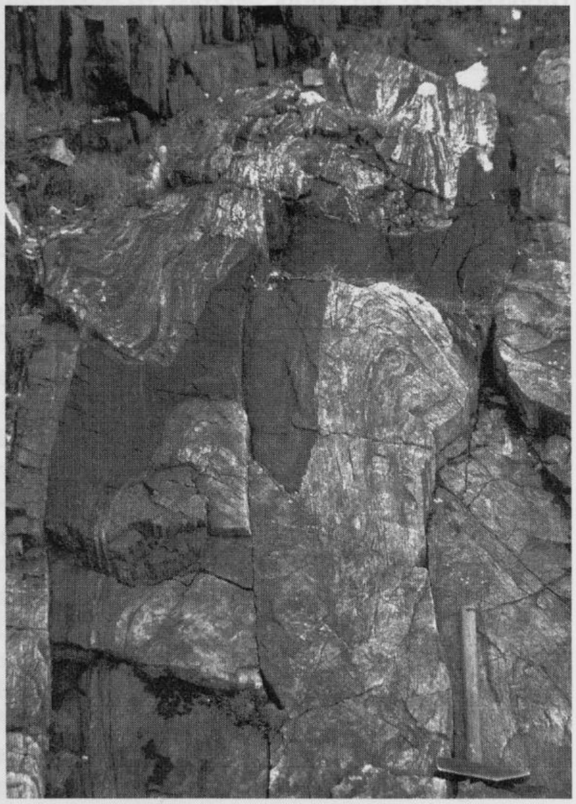


Figure 3.15 Deformed but discordant amphibolitic Scourie dyke in banded felsic and mafic gneisses near to the north-east margin of the Canisp Shear Zone. Port Alltan na Bradhan. The hammer is 37.5 cm long. (Photo: J.R. Mendum.)

over this antiform. On the north-east limb, the felsic gneisses with their agmatitic inclusions are progressively deformed into strongly banded, steeply dipping gneisses, recrystallized to amphibolite-facies assemblages, and the axis of the antiform defines the south-west margin of the Canisp Shear Zone (Figure 3.14). These sheared and recrystallized gneisses are cut both by a K-feldspar-bearing pegmatite (similar to those dated elsewhere at 2450 Ma, see Evans and Lambert, 1974), and by a prominent Scourie dyke, thus demonstrating the Inverian age of this part of the shear zone.

Later (Laxfordian) effects in this southern part of the Canisp Shear Zone are limited to very narrow shears cutting the dykes, but farther north the well-defined central part is characterized by heterogeneous deformation, with lenses of more-massive banded gneisses enclosed within highly deformed zones exhibiting strong planar and linear fabrics. This 500 m-wide belt of deformation, concentrated in narrow zones of high strain, is interpreted as formed during the Laxfordian reactivation. The Laxfordian deformation is generally associated with the generation of a new shear fabric, but in places Inverian structures have been modified and deformed (Attfield, 1987).

Beach and Tarney (1978) investigated the chemical changes in the gneisses and Scourie dykes brought about by the retrogressive Laxfordian metamorphism accompanying the shearing, noting increases in Na and Sr contents and loss of Ca. These changes were attributed to the introduction of hydrous fluids up steep zones formed within the overall shear-zone.

There have been conflicting views on the sense of movement on the Canisp Shear Zone. Sheraton *et al.* (1973) suggested a north-down sense of movement on the shear zone during the Inverian, followed by north-up movement during the Laxfordian. Evans and Lambert (1974) suggested a sinistral south-up sense (presumably referring to the Inverian), whereas Jensen (1984) invoked a dextral, south-up sense of movement for the Laxfordian. Attfield (1987) showed that the linear fabrics of the two episodes could be clearly distinguished, and pointed out that the Inverian lineations plunge steeply to the south-east, whereas the Laxfordian lineations plunge shallowly to the south-east. Both movement phases were therefore dextral, but the Inverian was accompanied by a large dip-slip component, whereas the Laxfordian reactivation was dominantly a strike-slip event.

This shear zone is the largest of several zones that traverse the Central Region of the mainland Lewisian. The zones typically show evidence of dominantly strike-slip displacement and appear to represent the deep-seated manifestations of a higher-level strike-slip fault system.

Conclusions

The An Fharaid Mhòr to Clachtoll GCR site is of international importance, as it is recognized as the type locality for the Inverian event. The site also encompasses part of the 1.5 km-wide Canisp Shear Zone, which was initiated during the Inverian event and subsequently partly reactivated during the Laxfordian.

The southern part of the site, between Loch Roe and Achmelvich Bay, contains granulite-facies felsic and mafic gneisses deformed in the Badcallian deformation and cut by mafic dykes of the Scourie Dyke Suite. To the north-east, these gneisses are variably retrogressed to amphibolite facies, and are affected by the NW-trending Lochinver Antiform, which delimits the south-west margin of the Canisp Shear Zone. On the north-east limb of the antiform, the Badcallian rocks are progressively deformed into strongly banded, steeply dipping gneisses, and recrystallized to an amphibolite-facies mineralogy. These sheared and recrystallized gneisses are cut by Scourie dykes, thus demonstrating the Inverian age of the shear zone. However, in the central part of the shear zone is a 500 m-wide belt of Laxfordian reactivation in which deformation is concentrated in narrow zones of high strain. The site is excellent for teaching in that a clean coastal section is available. It remains suitable for further work.

GRUINARD RIVER (NG 980 886–NG 964 841)

R.G. Park

Introduction

The importance of this large and rather remote site, inland from Gruinard Bay, is that it exposes the transition between the Central and Southern regions of the mainland Lewisian Gneiss Complex. The tripartite division of the mainland outcrop into Northern, Central and Southern regions was first made by Peach *et al.* (1907) and was re-emphasized by Sutton and Watson (1951). The Central Region was viewed as a 'Scourian' block, metamorphosed under granulite-facies conditions, cut by undeformed mafic dykes of the Scourie Dyke Suite, and only locally affected by Laxfordian metamorphism and deformation, whereas the Northern and Southern regions were effectively regarded as Laxfordian orogenic belts in which the Scourian rocks together with the Scourie dykes had been thoroughly reworked.

Unlike the northern margin of the Central Region, which is separated from the Northern Region by a major shear-zone (the Laxford Shear Zone; see **Tarbet to Rubha Ruadh** GCR site report, this chapter), the southern margin is a transitional zone extending over several kilometres and can be adequately studied only in the good exposures south of the Gruinard River. In the northern part of the site, near the Gruinard River, Badcallian gneisses form a large-scale agmatite complex, in which blocks of amphibolite and older gneiss occur as rafts in leucotonalitic ('trondhjemitic') gneiss. Farther south, the gneisses are progressively deformed by NW-trending folds, and an accompanying foliation is developed that becomes more intense to the south-west. Scourie dykes in this part of the area are undeformed and show strong discordance in places, indicating an Inverian age for the NW-trending structures. This part of the site marks the north-east margin of a wide zone of Inverian reworking that extends southwards to the southern limit of the mainland Lewisian outcrop, a distance of about 40 km, with only a few small enclaves (such as that of An Ruadh Mheallan in the **Diabaig** GCR site) revealing the pre-Inverian structure. Towards the south-west boundary of the Gruinard River GCR site, and beyond, towards Fionn Loch, the Scourie dykes are progressively affected by Laxfordian deformation, which also imposes a new foliation in the gneisses.

The site also contains the enigmatic and stratigraphically important 'Gruinard assemblage' of amphibolite and siliceous schist, regarded by some as the equivalent of the Loch Maree Group, but whose relationships with the Inverian foliation and Scourie dykes suggest an older age.

The area was first mapped by W. Gunn and B.N. Peach in 1891 for the Geological Survey, and was described in the resulting memoir by Peach *et al.* (1907). It was remapped and described by Crane (1973, 1978) and Davies (1977). The agmatite complex in the northern part of the area, which represents a zone of very low Laxfordian strain, has attracted particular interest (Davies, 1977). Detailed geochemical studies have been carried out by Rollinson (1987), Rollinson and Fowler (1987), Fowler and Plant (1987) and Whitehouse *et al.* (1996). More recently, abundant U-Pb and Sm-Nd dating studies have investigated the evolution of the gneisses in the area (Whitehouse *et al.*, 1997a; Corfu *et al.*, 1998; Love *et al.*, 2004).

Description

The Gruinard River GCR site extends south-west of the Gruinard River in a roughly kilometre-wide strip for some 3.5 km to include the rocky outcrops that make up Creag-mheall Beag (NG 9745 8615) (348 m above OD) and cross the Uisge Toll a' Mhadaidh. It then dog-legs some 4 km to the south to include the steep north-western craggy and grassy slopes of Beinn a' Chàisgein that rise from 200 m above OD to *c.* 625 m. The description below focuses on the north-east part of the site where the gneisses show the effects of Inverian deformation and folding but are largely unaffected by the Laxfordian reworking (Figure 3.16).

Typical Badcallian gneisses are exposed on Creag Fiaraich, immediately west of the Gruinard River at NG 980 880. Here the country rocks are grey, coarse-grained, tonalitic ('trondhjemitic') and granodioritic gneisses, typically biotite-bearing (Rollinson and Fowler, 1987). The foliation has a general NNE trend, but is very variable in detail. These felsic gneisses contain many inclusions of both mafic and ultramafic material and tonalitic gneisses, which vary in size from a few centimetres to several hundred metres (Figure 3.17). The mafic and ultramafic inclusions are mainly composed of amphibolite, but metaperidotite and metapyroxenite are also found (Davies, 1977). Banded, biotite-rich tonalitic gneisses are also found at a few localities as inclusions within the felsic gneisses (Rollinson and Fowler, 1987). These relationships are considered to represent a large agmatite complex, showing a complete gradation from large bodies of amphibolite and tonalite with leucotonalite veins through to

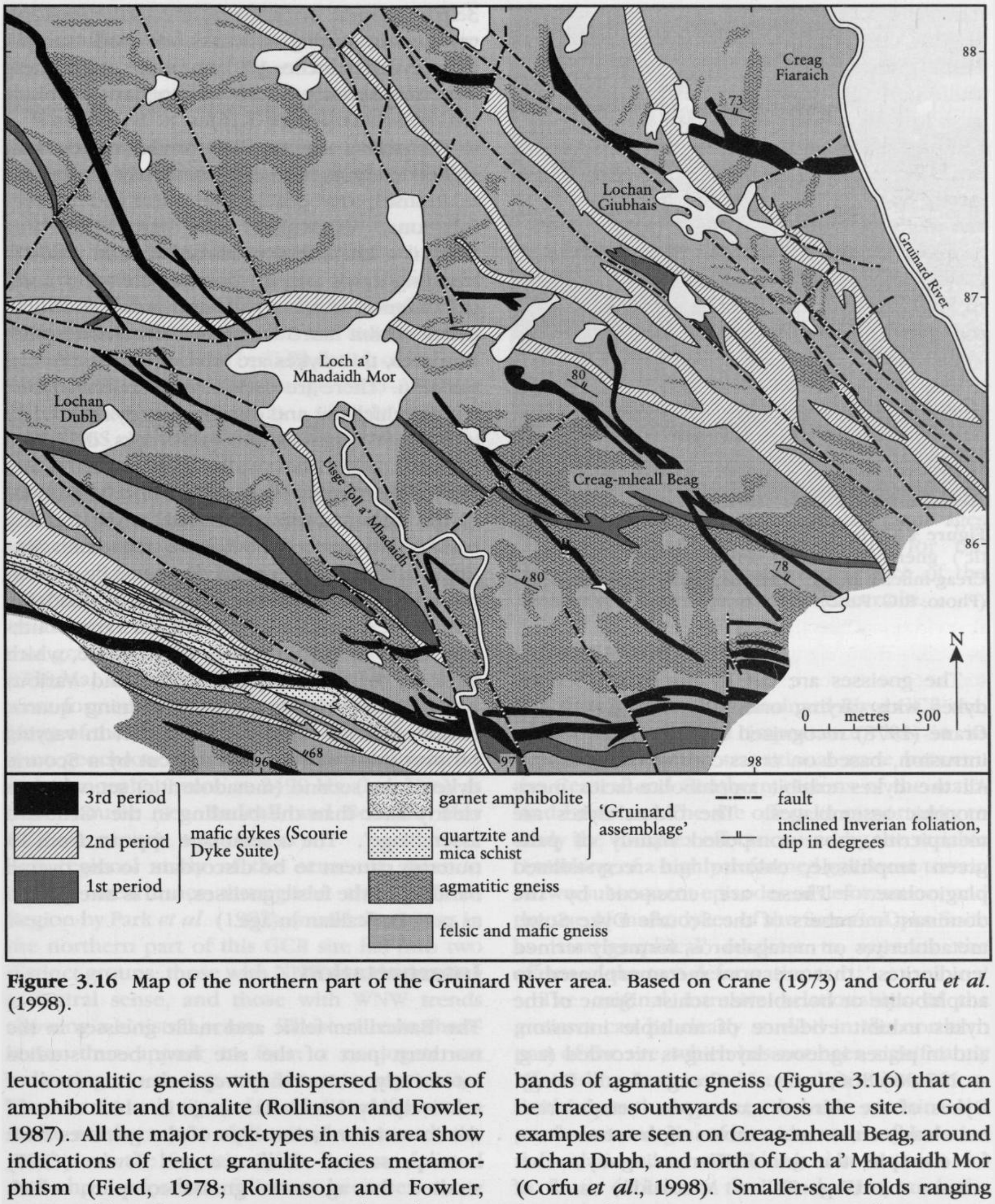


Figure 3.16 Map of the northern part of the Gruinard River area. Based on Crane (1973) and Corfu *et al.* (1998).

leucotonalitic gneiss with dispersed blocks of amphibolite and tonalite (Rollinson and Fowler, 1987). All the major rock-types in this area show indications of relict granulite-facies metamorphism (Field, 1978; Rollinson and Fowler, 1987), although there appears to have been a general retrogression to amphibolite facies prior to the intrusion of the Scourie Dyke Suite.

South of Creag Fiaraich, about 1 km from the Gruinard River, large-scale Inverian folds with steep NW-trending axial surfaces affect the steep, N-trending Badcallian gneissose banding. The folding is shown by the outcrop pattern of the bands of agmatitic gneiss (Figure 3.16) that can be traced southwards across the site. Good examples are seen on Creag-mheall Beag, around Lochan Dubh, and north of Loch a' Mhadaidh Mor (Corfu *et al.*, 1998). Smaller-scale folds ranging from a few centimetres to several metres in amplitude, with steeply plunging axes and a variably developed axial-planar foliation are also seen. On the NW-trending limbs of the tighter folds, the gneissic banding is attenuated and transposed into a new finer-grained Inverian fabric defined by the amphibolite-facies mineralogy.

Figure 3.17 Tonalitic and granodioritic ('trondhjemitic') gneiss containing abundant mafic enclaves, Creag-mheall Beag. The map case is 33 cm deep. (Photo: R.G. Park.)

The gneisses are cut by numerous Scourie dykes with varying orientations (Figure 3.16). Crane (1978) recognized three periods of dyke intrusion, based on cross-cutting relationships. All the dykes exhibit amphibolite-facies metamorphic assemblages. The oldest dykes are metapicritic, now composed mainly of pale-green amphibole, chlorite and recrystallized plagioclase. These are cross-cut by the dominant members of the Scourie Dyke Suite; metadolerites or metagabbros, formerly termed 'epidiorites,' that are now metamorphosed to amphibolite or hornblende schist. Some of the dykes exhibit evidence of multiple intrusion, and in places igneous layering is recorded (e.g. at NG 986 866, east of Creag-mheall Beag). Dykes of the third set are again metadolerites but clearly cross-cut members of the second set, for example, the thin E–W-trending dyke that crosses the Uisge Toll a' Mhadaidh, south of Creag-mheall Beag (Figure 3.16). The general dyke pattern in this area is largely unaffected by later deformation, and is dramatically different from that seen in the Laxfordian areas farther south, such as around Gairloch and Diabaig, where the mafic dykes are generally sub-parallel to one another and strike north-westwards. Here, the trend varies from north-west to west and the margins are commonly highly irregular (Figure 3.16). Several of the large metadolerites form complex branching networks. A good example with several branches 100 m or more in thickness lies immediately south of Lochan Giubhais (NG 978 872) (Figure 3.16).

The dykes are typically undeformed, with chilled margins, and exhibit clearly discordant relationships to both the Badcallian and Inverian foliations. Although in some parts of the area there is a crude concordance between the NW-trending dykes and the Inverian foliation, local discordance is nearly always present. Some dykes exhibit narrow marginal shear-zones and, in places, thin dykes are crossed by a sigmoidal foliation. There are also a few narrow cataclastic zones, which cut and displace the dykes.

A rather enigmatic group of rocks, described in detail by W. Gunn (in Peach *et al*., 1907) and termed the 'Gruinard assemblage' for the purpose of this account, forms a broad, WNW-trending band south-west of the Loch a' Mhadaidh Mor (Figure 3.16). It is cut and displaced by a NNW-trending crush belt at the Uisge Toll a' Mhadaidh but can be traced for a further 3 km to the south-east. The main rock-type is amphibolite, which encloses bands of quartz-schist, and various types of hornblende schist containing quartz, biotite, chlorite, epidote and garnet in varying proportions. These rocks are cut by a Scourie dyke of the second (metadoleritic) set, which is clearly later than the banding in the 'Gruinard assemblage'. The assemblage appears from its outcrop pattern to be discordant to the overall banding in the felsic gneisses, and is interpreted as post-Badcallian in age.

Interpretation

The Badcallian felsic and mafic gneisses in the northern part of the site have been studied intensively, since they represent an area of relatively low Laxfordian strain in which some of the intrusive relationships of the gneisses have been preserved. Rollinson and Fowler (1987) studied the agmatitic gneiss complex, which they concluded was formed by the intrusion of leucotonalitic and granodioritic magmas into older tonalitic gneisses and amphibolites. These rocks were then subsequently metamorphosed under granulite-facies conditions, before being retrogressed to amphibolite facies. On the basis of geochemical data, Rollinson (1987) and Rollinson and Fowler (1987) suggested that the amphibolites were derived from a complex mantle source, possibly representing fragments of ocean crust. The tonalitic and leucotonalitic magmas were derived by partial melting of a basaltic source that may be represented by the amphibolites.

Whitehouse *et al.* (1996) also studied the geochemistry and Sm-Nd isotopic systematics of rocks from the Gruinard Bay area, and concluded that the older amphibolites were formed at *c.* 2940 Ma, with the leucotonalitic magmas forming at *c.* 2800 Ma by melting of a basaltic parent, possibly equivalent to the most light REE-enriched components of the amphibolite suite. The *c.* 2800 Ma age for the leucotonalitic gneisses was supported by U-Pb dating of zircons, which yielded ages in the range 2850–2750 Ma (Whitehouse *et al.*, 1997a). Slightly younger U-Pb TIMS zircon dates for the leucotonalites of *c.* 2730 Ma have been obtained by Corfu *et al.* (1998), who also obtained dates in the range 2825–2790 Ma for the amphibolites. Corfu *et al.* suggested that the 2730 Ma dates represent a period of metamorphism and magmatism, but Love *et al.* (2004) have used U-Pb SHRIMP dates on zircons from Gruinard Bay gneisses to argue that granulite-facies metamorphism occurred at 2730 Ma, and that the leucotonalitic gneisses were formed significantly earlier at *c.* 2850 Ma. Many of the above authors also noted that there is no geochronological evidence in this area for a metamorphic event at 2490 Ma (Inverian) as near Scourie (see **Badcall** and **Scourie Mor** GCR site reports, this chapter).

A regional study of the sense of shear in narrow shear-zones throughout the Southern Region by Park *et al.* (1987), found that zones in the northern part of this GCR site fall into two distinct groups; those with NNW trends showing a dextral sense, and those with WNW trends showing a sinistral sense. These narrow shear-zones thus appear to form a conjugate set indicating north-east–south-west compression. They are the only signs of Laxfordian deformation in the northern part of the site, but towards the south-west the Scourie dykes become foliated and the Laxfordian foliation becomes more pervasive and intense. The dykes become thoroughly deformed around Fionn Loch several kilometres to the south-west.

Gunn (in Peach *et al.*, 1907) was unable to reach a firm conclusion on the origin of the 'Gruinard assemblage' of amphibolite and siliceous schists. He pointed out that, although some of the rock types are similar to the metasedimentary rocks and basic meta-igneous rocks of the Loch Maree Group to the south, they could also be explained by quartz veining and shearing of the amphibolite. The 'Gruinard assemblage' appears to cross-cut the Badcallian banding and is itself cross-cut by a Scourie dyke which is clearly later than the banding and dominant foliation, regarded by Crane (1973) as Inverian in age. The dominant foliation apparently grades into the Inverian foliation outwith the assemblage. Crane (1978) referred to these rocks as the 'Gruinard metasedimentary rocks and basite', and regarded them as equivalent to the Loch Maree Group. However, if they are indeed correlatives of the Loch Maree Group, they should be post-Inverian and their foliation should be Laxfordian, not Inverian. This apparent paradox highlights the problems presented by strict reliance on the use of the Scourie dykes as stratigraphical markers, particularly in view of their large range of likely emplacement ages (*c.* 2400–2000 Ma). Consequently, for the present, the stratigraphical significance of the 'Gruinard assemblage' remains uncertain.

Conclusions

The significance of the Gruinard River GCR site, which is of national importance, lies in its position within the transitional zone between the Central and Southern regions of the mainland Lewisian. The site offers an opportunity to study the complex effects caused by the variable reworking of a highly deformed gneissose terrain in two subsequent episodes of deformation, and the use of mafic dykes of the Scourie Dyke Suite as 'stratigraphical' markers to separate the effects of the two deformations.

The original intrusive relationships of the gneisses can be clearly studied in the northern part of the site, which has not been significantly affected by Inverian or Laxfordian deformation. Farther south however, the site contains the north-east margin of a wide zone of Inverian deformation and reworking that extends for at least 40 km to the south-west, and the relationships between the Badcallian and Inverian structures are clearly evident. Because of the absence of pervasive Laxfordian deformation, the site is also an excellent area for studying the complex outcrop patterns, mutually cross-cutting relationships, and marginal shearing of the three generations of Scourie dykes recognized in this part of the Lewisian Gneiss Complex.

Another important feature of the site is the presence of the stratigraphically important 'Gruinard assemblage', thought by Crane (1978) to be equivalent in age to the Loch Maree supracrustal sequence, but whose relationships to the Inverian foliation and Scourie dykes suggest an older age. Despite its moderately remote location, this is the most accessible locality where these important rocks can be studied.

CREAG MHÒR THOLLAIDH (NG 827 756–NG 863 785)

R.G. Park

Introduction

This large site, between Gairloch and Loch Maree, contains the best-exposed and most accessible section across the 'Tollie Antiform' (Figure 3.18). It was here that C.T. Clough, who first surveyed the area for the Geological Survey in 1889–1890, demonstrated that the gneisses, together with the cross-cutting mafic dykes of the Scourie Dyke Suite, have been deformed into a large-scale antiform. Individual mafic dykes can be traced continuously from the north-east limb of the fold, where they dip steeply to the north-east, through a near-horizontal attitude on the crest of the antiform, to a steep south-westerly dip on the south-west limb. Farther north-east across the trace of a complementary synform, on Creag Mhòr Thollaidh itself, the Scourie dykes are least deformed and pre-dyke Badcallian and Inverian structures can be clearly demonstrated in the gneisses.

The site also includes the north-east margin of the regional Gairloch Shear Zone. A series of exposed outcrops that traverse across the shear zone enable its geometry and the direction and sense of movement across the zone to be worked out. The degree of Laxfordian deformation increases south-westwards across the antiform until, on the south-west limb of the fold, both dykes and gneisses are highly flattened and sheared, with a strong NW-plunging lineation, and all the pre-existing structures converge into parallelism with the intense, steeply dipping, NW-trending foliation.

The area was described by Clough in Peach *et al.* (1907) and was remapped with a revised structural interpretation by Park (1970). Details are given in the memoir on the Lewisian geology of the Gairloch area (Park, 2002).

Description

The Creag Mhòr Thollaidh GCR area extends over an area of *c.* 8 km^2, extending south-west from Loch Maree and Tollie Farm to Meall Fuaraidh. Loch Tollaidh marks its northern extent, and Loch Airigh a' Phuill its southern extent. This glacially scoured area lies mainly between 150 m and 350 m above OD and its ubiquitous rocky outcrops are dissected by numerous ridges and gullies and peppered by lochs and lochans. Creag Mhòr Thollaidh reaches 343 m above OD and Meall Fuaraidh 369 m, but several summits rise above 340 m. In general the topographical features trend either north-west, reflecting the dominant gneissic banding orientation and major lithological units, or north-east, reflecting a prominent fracture set. The only significant exception is the N-trending valley of the Allt an Leth-chreige, which has been eroded along a zone of cataclastic rocks. Unfortunately large parts of the area have been planted recently with conifers, making it more difficult to access.

The country rocks are amphibolite-facies, felsic (quartzofeldspathic) gneisses with layers and lensoid masses of amphibolite ('early basic' rocks). In the central part of the area these gneisses are generally granodioritic biotite gneisses, whereas in the east, on Creag Mhòr Thollaidh, they are typically tonalitic to dioritic, hornblende-bearing gneisses. The mafic dykes of the Scourie Dyke Suite are all metamorphosed to amphibolite facies, but are variably deformed. The Aundrary 'basite', in the south-west part of the site, is an amphibolitic mafic body that is part of the Palaeoproterozoic Loch Maree Group (see **Kerrysdale** and **Flowerdale** GCR site reports, this chapter), and is therefore younger than the adjoining gneisses. However the original relationship between these supracrustal rocks and the basement gneisses has been obscured by intense deformation along a narrow brittle–ductile Laxfordian shear-zone, which lies along the contact.

The site falls into three distinct areas (Figure 3.18): (1) Creag Mhòr Thollaidh in the north-east; (2) the Tollie Antiform in the central part of the site; and (3) the steep south-west limb of the Tollie Antiform that forms the north-east margin of the Gairloch Shear Zone, in the south-west.

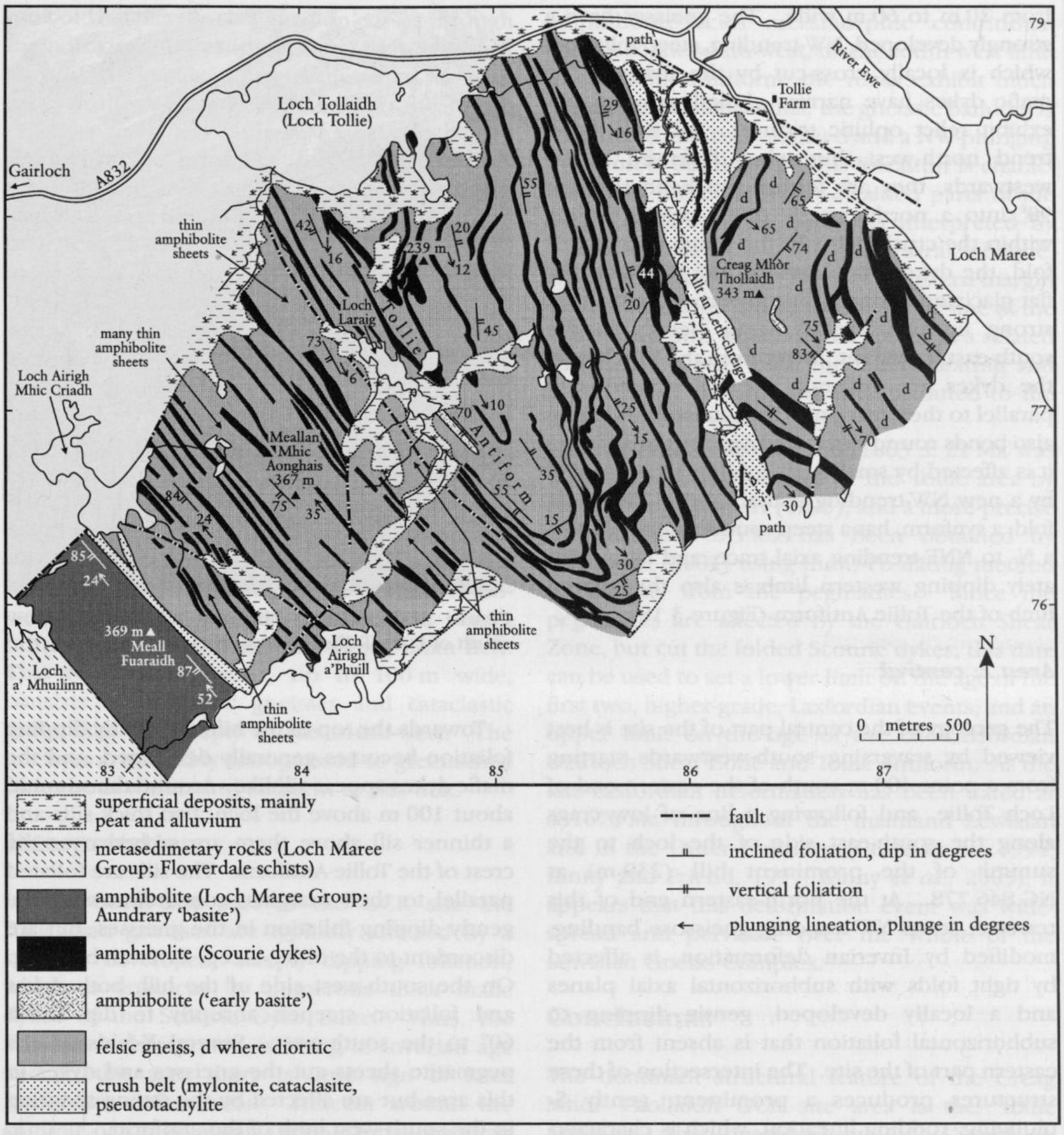


Figure 3.18 Map of the area between Meall Fuaraidh and Creag Mhòr Thollaidh. After Park (2002).

Area 1: north-east

The track leading south from the A832 main road, 1 km east of the eastern end of Loch Tollie, follows a wide cataclastic zone, the Leth-chreige 'crush belt', which separates the Creag Mhòr Thollaidh block to the east from the Tollie Antiform to the west. This zone contains schistose cataclastic gneisses and breccias veined by pseudotachylite. Excellent exposures of these cataclastic rocks occur in the crags on the east side of the track after it crosses the Tollie stream, 1400 m from the road (NG 860 775). On the cliff face of Creag Mhòr Thollaidh to the east of the track, the cataclastic rocks dip eastwards at about 30° beneath the steeply dipping gneisses that form the summit of the hill.

On the top of the rocky crags of Creag Mhòr Thollaidh, about 2 km from the road and above a small loch (NG 862 770), is an area of medium- to coarse-grained, quartz-plagioclase-hornblende gneisses cut by four Scourie dykes that range from 20 m to 60 m wide. The gneisses have a strongly developed, NW-trending, steep foliation, which is locally cross-cut by the dykes. The mafic dykes have narrow chilled margins and exhibit relict ophitic textures. All four dykes trend north-west, but when followed north-westwards, they are folded and bend through 90° into a north-easterly trend before ending within the crush belt. In the hinge area of this fold, the dykes appear to be unfoliated on the flat glaciated surfaces, but in vertical sections, a strong linear fabric plunging steeply to the south-east is evident. Away from the fold hinge, the dykes are generally weakly foliated sub-parallel to their margins. The gneissose foliation also bends round with the dykes, but in addition it is affected by small-scale folding accompanied by a new NW-trending planar fabric. The main fold, a synform, has a steep south-easterly plunge, a N- to NNE-trending axial trace, and its moderately dipping western limb is also the eastern limb of the Tollie Antiform (Figure 3.18).

Area 2: central

The geology of the central part of the site is best viewed by traversing south-westwards starting from a point 400 m south of the eastern end of Loch Tollie, and following a line of low crags along the south-east side of the loch to the summit of the prominent hill (239 m) at NG 846 778. At the north-eastern end of this traverse, steep NW-trending gneissose banding, modified by Inverian deformation, is affected by tight folds with subhorizontal axial planes and a locally developed, gently dipping to subhorizontal foliation that is absent from the eastern part of the site. The intersection of these structures produces a prominent, gently S-plunging, rodding lineation, which is characteristic of the Tollie area (Figure 3.19). The gneisses are cut by amphibolitized Scourie dykes that are generally concordant with the banding, but show rapid changes in dip from steep to shallow in such a way that the dykes step progressively upwards and westwards. The gently dipping foliation affects the dykes in the shallow-dipping sections, but in some steep sections it appears to stop at the dyke margins and deformation is represented within the dykes by a linear fabric. Examination of the shapes of the deformed felsic grain aggregates in the dykes shows that they are strongly elongated parallel to the S-plunging lineation.

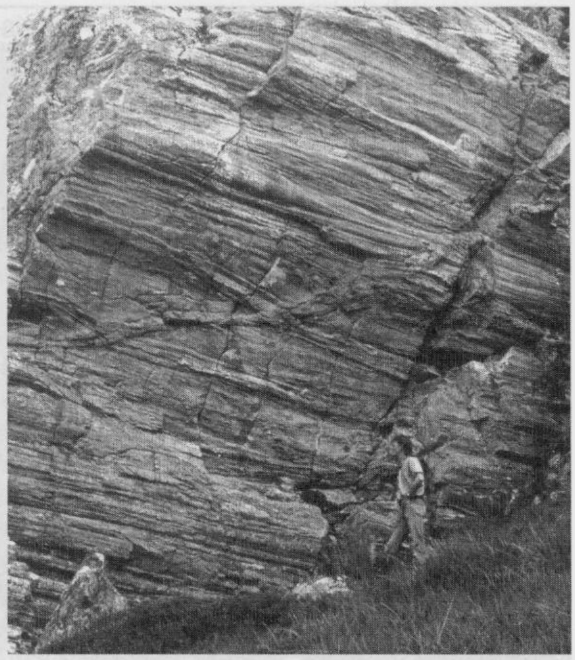


Figure 3.19 Gently plunging rodding lineation, south of Loch Tollie. (Photo: R.G. Park.)

Towards the top of the hill, the gently dipping foliation becomes generally developed, and the mafic dykes appear sill-like. Around the summit, about 100 m above the loch, two thick sills and a thinner sill above them are arched over the crest of the Tollie Antiform. The sills are foliated parallel to their margins, concordant with the gently dipping foliation in the gneisses, but are discordant to the older, steep, Inverian banding. On the south-west side of the hill, both dykes and foliation steepen abruptly to dip about 60° to the south-west. Several K-feldspar-rich pegmatite sheets cut the gneisses and dykes in this area but are affected by the strong shearing in the south-west limb of the antiform.

Area 3: south-west

The south-western area continues the above traverse from the south side of Loch Laraig (NG 846 770), up the slopes of Meallan Mhic Aonghais (367 m), towards Meall Fuaraidh (NG 832 758). From Loch Laraig to Meallan Mhic Aonghais, granodioritic gneisses are strongly flattened and sheared, and exhibit a prominent lineation. This lineation is contiguous with that described in Area 2 and plunges gently south-east near the hinge of the Tollie Antiform. However, about 600 m south-west of Loch Laraig, the lineation passes through the horizontal to plunge moderately north-west, an orientation that is then maintained for over 1 km in the felsic gneisses and into the north-eastern part of the Aundrary 'basite'.

The rocky ridge of Meall Fuaraidh is composed of a 600 m-thick sheet of amphibolite (the Aundrary 'basite') which forms part of the supracrustal Loch Maree Group. Most of the amphibolite is now well-foliated hornblende schist, but there is a central unit of more-massive metagabbro with a coarse relict igneous texture. The NW-plunging lineation, which is characteristic of the Gairloch Shear Zone, appears to stop at the edge of this massive unit and is replaced farther south-west by the earlier SE-plunging linear structure typical of the Gairloch metasedimentary rock belt (see **Kerrysdale** and **Flowerdale** GCR site reports, this chapter). The contact between the 'basite' and the highly sheared gneisses of the south-west limb of the antiform is coincident with a brittle–ductile shear-zone, the Creag Bhan Belt. This NW-trending zone, up to 100 m wide, consists of mylonitic gneisses and cataclastic rocks that dip steeply to the south-west. The gneisses are variably retrogressed to greenschist facies both within and adjacent to this belt.

Interpretation

In the north-east part of the GCR site the Badcallian gneisses are typically affected by a strongly developed, steeply dipping foliation, which is cross-cut by numerous thick mafic dykes of the Scourie Dyke Suite. Thus, the foliation is interpreted as being of Inverian age and in this area there is little sign of later Laxfordian deformation. Indeed, around the summit of Creag Mhòr Thollaidh this Inverian foliation wraps around an enclave in which the earlier NE-striking Badcallian foliation is dominant. Here, the Scourie dykes also trend north-east, generally concordant with the earlier foliation. However, on the western limb of the synform that crops out to the south-west of Creag Mhòr Thollaidh, a gently dipping foliation affects both the dykes, which here are sill-like, and the gneisses, and is ascribed to early-Laxfordian shearing. The synform folds the gneissose banding and the dykes, with the development of a new axial-planar fabric, and is considered to belong to the second phase of Laxfordian folding, which took place under amphibolite-facies metamorphic conditions. Farther to the south-west, on the south-west limb of the Tollie Antiform, the rocks exhibit much higher Laxfordian strains; the gneissic banding is attenuated and recrystallized and a NW-plunging lineation is developed. This lineation is characteristic of the most highly strained parts of the Gairloch Shear Zone, and was interpreted by Odling (1984) as indicating a dextral, oblique, NE-up sense of shear. The north-eastern margin of the shear zone is taken as the hinge line of the Tollie Antiform, which is interpreted as a related structure. Hence, both the main shearing and formation of the antiform are attributed to the late-Laxfordian deformation event.

An imprecise Rb-Sr age of 1663 ± 22 Ma was obtained from pegmatites of the Tollie area by Holland and Lambert (1995), and a more-precise date of 1694 ± 5 Ma has been obtained by Park *et al.* (2001) using the U-Pb dating method on zircons from the pegmatites. Since the pegmatites are affected by the Gairloch Shear Zone, but cut the folded Scourie dykes, this date can be used to set a lower limit on the age of the first two, higher-grade, Laxfordian events, and an upper limit on the age of the late-Laxfordian Gairloch Shear Zone and Tollie Antiform. As the late-Laxfordian deformation has been dated at *c.* 1670 Ma throughout the mainland Lewisian and in the Outer Hebrides (Corfu *et al.*, 1994; Kinny and Friend, 1997; Kinny *et al.*, 2005), it appears that this deformation event was wide-spread and pervasive over the whole of the Lewisian Gneiss Complex.

Conclusions

The dominant structural feature of the Creag Mhòr Thollaidh GCR site area is the 'Tollie Antiform', first described by C.T. Clough in Peach *et al.* (1907). The area also shows the link, first demonstrated by Odling (1984), between this antiformal structure and the regional, Laxfordian, Gairloch Shear Zone. The Tollie area offers perhaps the best example in the British Isles of how a set of dykes may be used as structural markers to elucidate a geometrically complex structure and unravel the complicated sequence of events represented within a basement gneiss terrain.

These structures can be observed by making a coherent traverse from north-east to south-west, across the exposed ground. On Creag Mhòr Thollaidh itself Archaean features of the felsic and mafic gneisses are locally visible and the Scourie dykes cross-cut the generally steep Inverian foliation. On the north-eastern limb of the Tollie Antiform, a gently dipping early-Laxfordian foliation affects both the Scourie dykes, which become sill-like, and the earlier gneisses. The sill-like dykes then arch over the crest of the Laxfordian Tollie Antiform and, within a short distance, become steeply dipping to the south-west. This south-western limb of the antiform exhibits much higher Laxfordian strain; the gneisses are flattened and recrystallized, and a new NW-plunging linear structure is developed, which marks the movement direction on the late-Laxfordian Gairloch Shear Zone.

The Creag Mhòr Thollaidh area is a classic Lewisian area and is of national, and possible international, importance, frequently visited by geologists and used by student parties for mapping exercises.

KERRYSDALE (NG 825 735)

R.G. Park

Introduction

The Loch Maree Group

The Loch Maree Group is a Palaeoproterozoic supracrustal sequence of metasedimentary and meta-igneous rocks, enclosed within the Archaean gneisses of the Lewisian Gneiss Complex. This stratigraphically distinct group occurs in two belts, at Loch Maree and Gairloch, but has not been identified elsewhere in the mainland Lewisian outcrop. It is represented by the Kerrysdale and **Flowerdale** GCR sites, both of which lie within the Gairloch outcrop.

The supracrustal assemblage at Gairloch occupies a NW-trending belt about 3 km wide, bounded on both sides by Archaean felsic gneisses and cut by Scourie dykes (Figure 3.20). Both margins of the belt are tectonic, and the whole area forms part of a steep, NW-trending, Laxfordian shear-zone about 5 km wide, called the Gairloch Shear Zone (see **Creag Mhòr Thollaidh** GCR site report (this chapter), which includes the north-east margin of this shear zone). The south-west side of the supracrustal belt contains granitic gneisses, the Ard Gneisses, considered to represent a deformed and metamorphosed granodiorite sheet intruded into the metasedimentary rocks during the Laxfordian event (see **An Ard** GCR site report, this chapter). The Ard Gneisses have recently been dated at *c*. 1900 Ma (Park *et al*., 2001).

The supracrustal sequence comprises schistose metasedimentary rocks separated by amphibolitic mafic sheets. The metasedimentary rocks consist mainly of semipelitic quartz-biotite-plagioclase schist, and are considered to represent metamorphosed greywackes. The mafic sheets are mainly in the form of hornblende schist but also occur as massive amphibolite. The thicker sheets are thought to represent basic volcanic rocks, but some of the thinner sheets were probably sills. Associated with the amphibolites are narrow bands of chlorite schist, banded-iron formation, quartzite, metacarbonate rock and calc-silicate rock, graphite schist and garnet-grunerite schist.

Park (1964) divided the Gairloch supracrustal sequence into a number of coherent mappable units. However, because of the intense deformation, these cannot be considered to represent an unmodified stratigraphical sequence, and several units have tectonic boundaries. The main part of the sequence comprises, from south-west to north-east: the 'Charlestown schists', the 'Kerrysdale basites and schists', the 'Flowerdale marble belt', the 'Flowerdale schists', and the 'Aundrary basite'. The Ard Gneisses lie immediately south-west of the Charlestown schists. The Charlestown and Flowerdale schists consist mainly of grey, fine-grained, semipelitic quartz-biotite-plagioclase schist, containing minor chloritic and amphibole-bearing bands. The Flowerdale marble belt contains quartz-chlorite schist with thin bands of impure metacarbonate rock, banded-iron formation and graphitic schist (see **Flowerdale** GCR site report, this chapter). The metasedimentary part of the Kerrysdale unit consists of siliceous quartz-biotite schist with thin bands of graphitic schist, banded-iron formation, quartzite and garnet-grunerite schist.

Because of the intense late-Laxfordian deformation, which has resulted in the near-parallelism of all rock units and structures, it is difficult to determine the nature and extent of earlier structures. Most exposures show an intense and pervasive NW-striking, steeply dipping schistosity, which is axial planar to minor tight to isoclinal folds. The schistosity developed in association with amphibolite-facies metamor-

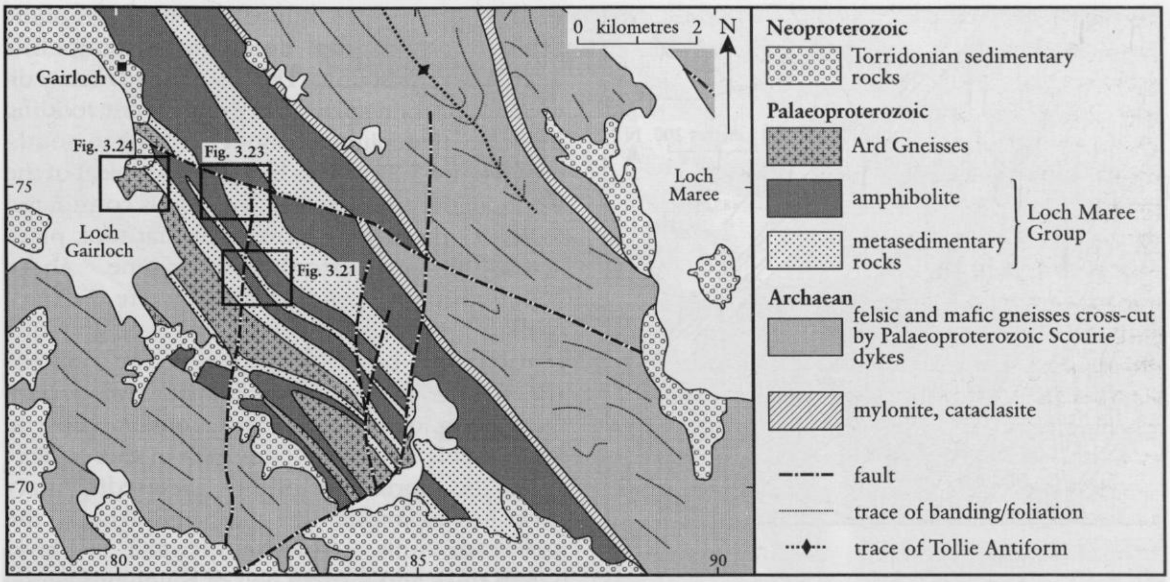


Figure 3.20 Map of the Loch Maree Group outcrops around Gairloch showing the position of the Kerrysdale, **Flowerdale** and **An Ard** GCR sites. After Park *et al.* (2001).

phism, as indicated by the ubiquitous presence of aluminous hornblende and calcic plagioclase in the mafic rocks. These structures are attributed to either the first or second Laxfordian deformations, which cannot be easily separated in this area. The third Laxfordian deformation, associated with the development of the Gairloch Shear Zone, has also produced abundant minor folding, associated with retrogression to greenschist facies. Yet later deformation has produced localized minor folds with steep plunges and narrow brittle–ductile shear-zones containing cataclastic breccia and pseudotachylite, described by Shihe and Park (1993).

The Gairloch area was first mapped in 1889 and was described in detail by C.T. Clough (in Peach *et al.*, 1907) and subsequently by Park (1963, 1964). More-recent revisions of the structural interpretation were made by Odling (1984), Park *et al.* (1987, 2001) and Park (2002). Studies of the geochemistry and petrology of the mafic rocks were carried out by Park (1966), Power and Park (1969) and Johnson *et al.* (1987), and of the metasedimentary rocks by Winchester *et al.* (1980), Williams (1986) and Floyd *et al.* (1989).

The Kerrysdale GCR site

The Kerrysdale GCR site provides a traverse across the Kerrysdale unit in the Gairloch succession of the supracrustal Loch Maree Group (Figure 3.21). It exhibits good examples of typical Kerrysdale amphibolite and siliceous schist, and also contains the most accessible exposures of graphite schist and garnet-grunerite schist in the Gairloch area. A continuation of the Flowerdale marble belt crosses the north-eastern part of the site, which also contains part of the Flowerdale schist unit. Between these latter two units is a brittle–ductile shear-zone marked by mylonitic and cataclastic rocks.

Description

The Kerrysdale GCR site forms a small roughly oblong area measuring some 620 m × 430 m immediately north-east of Kerrysdale Farm, bounded on its western side by a stream running southwards along a narrow valley, and on its eastern side by the lower slopes of Sidhean Mòr (Figure 3.21). The site is wooded in its steep lower western part and a wide sloping, partly wooded and grassy shelf area separates this lower part from the upper steeper eastern slopes that rise to over 190 m above OD.

In the south-west part of the site, an outcrop of garnet-grunerite schist forms a small knoll by the track leading from Kerrysdale Farm, just south of the footbridge (NG 824 734). This schist forms a narrow band within the Kerrysdale

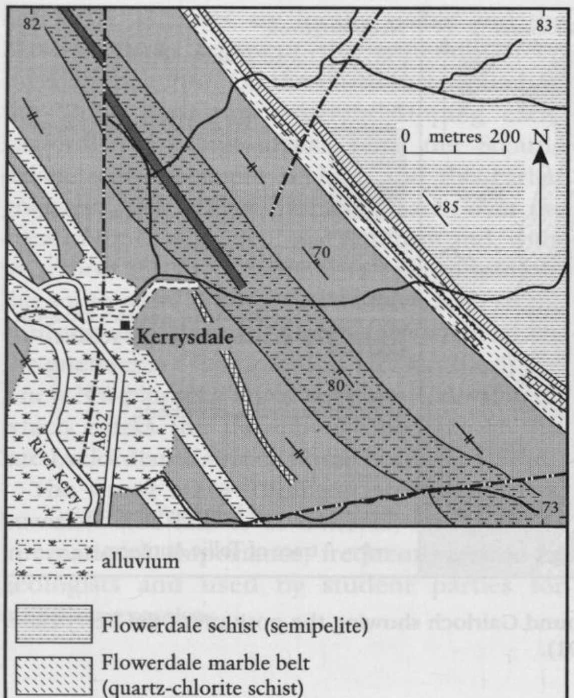


Figure 3.21 Map of the Kerrysdale area, Gairloch. Based on Park (1978) and British Geological Survey 1:50 000 Provisional Series Sheet 91, Gairloch (1999).

amphibolite, and contains abundant manganiferous garnet and sheaves of grunerite (green amphibole) needles in a matrix of quartz and biotite. To the north of this outcrop is a steep, tree-covered ridge, running in a north-westerly direction, consisting of hard siliceous quartz-biotite schists with minor bands of graphitic schist, part of the dominantly semipelitic Kerrysdale schist unit. These schistose metasedimentary rocks display a very prominent rodding lineation that plunges about 30° to the south-east (Figure 3.22). This lineation is typical of the whole of the supracrustal belt, and is considered to reflect the overall movement that took place across the early-Laxfordian shear-zone. About 300 m north-west of the bridge, where the track crosses a small stream, exposures of graphitic schist can be observed in the stream (NG 822 737). The rock is a distinctive, yellow-weathering, quartz-mica schist, containing pyrite and variable amounts of graphite in thin foliae.

To the north-east of the metasedimentary rocks lies an amphibolite sheet belonging to the Kerrysdale unit. This amphibolite is about 125 m thick and forms a belt of rough but gently sloping ground with numerous exposures, which consist of well-foliated hornblende schist with some more-massive amphibolite layers. On the north-east side of this body is an outcrop of the Flowerdale marble belt, which lies along the base of a steep slope (Figure 3.21). The marble belt is here about 80 m wide and consists of greenish-grey calcareous quartz-chlorite schist with additional bands of quartzite, calcareous schist, thin metacarbonate units, and banded-iron formation. Banded-iron formation alternates with quartz-rich units containing grunerite and some calcite. A fuller description is given in the **Flowerdale** GCR site report (this chapter).

The north-eastern part of the Flowerdale marble belt lies within a shear zone, about 20 m wide, which contains both brittle cataclastic rocks and more-ductile mylonites. The mylonitic rocks include a highly deformed fragmental rock consisting of flattened and elongate fragments of quartzite, up to several centimetres across, together with minor quantities of calcareous and chloritic schist, in a matrix of calcareous chlorite schist. Very high prolate strains are indicated by the shapes of the quartzite fragments, with typical axial ratios of X:Y:Z = 50:2:1. A strong elongation lineation plunges at 50°–70° to the south-east. This rock extends for a few hundred metres in a south-easterly direction, but is not seen elsewhere in the Gairloch area. The brecciation is considered to pre-date the ductile shearing and the rock may represent an olistostrome, a sedimentary slide breccia, or a tectonic breccia, which was subjected to very high strains during early-

Figure 3.22 Quartz-biotite-rich schistose semipelite with strongly developed rodding lineation, Kerrysdale. The hammer is 37 cm long. (Photo: R.G. Park.)

Laxfordian shearing (Park *et al.*, 2001). The cataclastic part of the zone, which lies on the north-eastern side of the outcrop, consists of microbreccia veined by pseudotachylite. North-east of, and above this crush zone lies a smooth, steep, featureless slope, underlain by the Flowerdale schists. The schists are uniform, fine-grained, semipelitic schists typically composed of essential quartz, biotite, and plagioclase, with some hornblendic bands forming low ridges, marked by green grassy patches. The steep slope leads up to the prominent rocky crags of Sidhean Mòr (NG 836 740), which is formed by the Aundrary basite.

Interpretation

The exposures within the Kerrysdale site throw light on the nature and origin of the Loch Maree Group. The quartz-biotite-rich semipelitic rocks of the Kerrysdale and Flowerdale schist units are interpreted as meta-greywackes that were originally derived from a source in the continental upper crust and deposited in a continental-margin setting (Floyd *et al.*, 1989). Whitehouse *et al.* (1997b) studied detrital zircons from the Flowerdale schists and found that they fall into two age groups, Archaean and Palaeoproterozoic. The Archaean zircons are believed to have been derived from a local continental source, but a suitable source for the younger component has not been identified; Whitehouse *et al.* (1997b) suggested that this source may have been a contemporaneous volcanic arc.

The geochemistry of the Kerrysdale amphibolites is consistent with their formation as volcanic rocks in an oceanic plateau setting, and the associated quartz-chlorite schists are thought to represent hydrothermally altered basaltic volcanic material (Park *et al.*, 2001). The banded-iron formation, garnet-grunerite schists, metacarbonate rocks, and graphitic schists associated with the amphibolites are believed to be metasedimentary rocks, the precursors of which were deposited through chemical precipitation in a shallow-marine setting, onto the basaltic substrate of the oceanic plateau. The banded-iron formation units form impersistent zones from a few centimetres up to 10 m in width. This lithology is described and discussed in more detail in the **Flowerdale** GCR site report (this chapter). The Gairloch occurrences are linked with stratiform sulphide deposits that occur within the Kerrysdale amphibolite along strike to the south-east. The main sulphide deposit, some 4 m wide but up to 500 m long, consists of pyrite, pyrrhotite and chalcopyrite with some sphalerite, galena and native gold (Jones *et al.*, 1987).

The association of an oceanic plateau sequence with Archaean gneisses, together with arc-like magmatic rocks (the Ard Gneisses; see **An Ard** GCR site report, this chapter) has been interpreted as an accretionary complex representing a possible Palaeoproterozoic collisional suture zone between two Archaean continental blocks (Park *et al.*, 2001; Park, 2002).

The pervasive, well-developed foliation and strong, SE-plunging, elongation lineation exhibited by most lithologies in the succession are ascribed to the early-Laxfordian deformation, (D1/D2), developed under amphibolite-facies metamorphic conditions. This deformation is thought to be responsible for the generation of a major low-angle shear-zone, subsequently rotated and reactivated in the later Laxfordian to result in the major Gairloch Shear Zone (Park, 2002). The mylonites seen at Kerrysdale are also interpreted to have developed initially during the early-Laxfordian deformation.

Conclusions

The Kerrysdale GCR site provides a traverse across the main metasedimentary and metavolcanic rock units of the Loch Maree Group in the Gairloch area. The main lithologies are amphibolites and semipelitic rocks of the Kerrysdale unit, but subsidiary rock-types include garnet-grunerite schist, siliceous quartz-biotite schist, and graphitic pelitic schist. Calcareous rocks are found in the adjacent Flowerdale marble belt and the site also includes excellent exposures of cataclastic and mylonitic rocks in a brittle–ductile shear-zone along the boundary between the Flowerdale marble belt and the quartz-biotite schists of the Flowerdale schist unit to the north-east.

This Palaeoproterozoic supracrustal sequence occurs in only two areas of the mainland Lewisian outcrop, at Gairloch and Loch Maree, and the Gairloch exposures are more readily accessible. The significance of the Loch Maree Group lies in its providing the only evidence on the Scottish mainland of sedimentation and volcanic activity of Palaeoproterozoic age, from which attempts can be made to reconstruct the palaeoenvironment of that period. As such the GCR site is of national interest and is eminently suitable for teaching and for research purposes.

FLOWERDALE (NG 818 748)

R.G. Park

Introduction

The compact Flowerdale GCR site provides easily accessible exposures of the Flowerdale marble belt, the most varied and distinctive metasedimentary unit within the Gairloch sequence of the Loch Maree Group. The Palaeoproterozoic Loch Maree supracrustal sequence is enclosed within Archaean gneisses, and forms a stratigraphically distinct part of the Lewisian Gneiss Complex that occurs only around Gairloch and Loch Maree (see **Kerrysdale** GCR site report (this chapter) for a full description of the group). Quartz-chlorite schist is the main lithology in the marble belt, but the subsidiary lithologies include banded-iron formation, quartzite and metacarbonate rock. Banded-iron formation consists of finely interbanded quartzite and magnetite-rich layers and is found only within Precambrian-age rocks in various parts of the world.

The area was first mapped by C.T. Clough for the Geological Survey in 1889, and later by Park (1963, 1964). Park (2002) summarized the work done in this area in the memoir on the Lewisian geology of the Gairloch area. Al-Ameen (1979) and Williams (1986) have carried out detailed petrographical and geochemical studies of the banded-iron formation in the Gairloch area, including the Flowerdale exposures.

Description

This GCR site is an area of low, undulating, partly wooded ground on the south-west side of the valley of the Abhainn Ghlas, by Flowerdale Mains Farm, some 2.4 km SSE of Gairloch village. The site is bounded to the north and north-east by alluvium in the valley floor, which conceals a WNW-trending fault that offsets the units of the Loch Maree Group dextrally by over 1 km. North of the fault a thick amphibolite sheet of the Kerrysdale unit forms the steep wooded valley slope that rises rapidly to over 200 m above OD. To the west of the site is the prominent wooded ridge of Druim Obair-latha that rises to *c.* 100 m above OD, again formed by an amphibolite sheet of the Kerrysdale unit. On the south-west edge of the alluvium a lower ridge extends in a north-westerly direction. The north-east side of this ridge is composed of banded-iron formation and a metacarbonate rock unit occurs a short distance to the south-west (Figure 3.23).

The Flowerdale marble belt is sandwiched between the semipelitic Flowerdale schists to the ENE and a thick amphibolite sheet to the WSW. Some shearing has occurred at its ENE margin (cf. **Kerrysdale** GCR site). The units dip very steeply south-west. The main lithology is a mid-green-grey, soft, calcareous schist composed mainly of quartz, chlorite and calcite with minor plagioclase, a greenish mica, and scattered small hornblende porphyroblasts in places. Within this lithology are distinctive units of quartzite, banded-iron formation, thin metadolostone beds and graphitic pelite.

The banded-iron formation forms a unit 10–20 m thick here and consists of alternating fine stripes of quartz and magnetite together with minor amounts of the green amphibole, grunerite. The magnetite-rich stripes are typically 1 mm thick but can reach 10 cm in places. They alternate with quartz-rich stripes containing variable anounts of grunerite, generally forming minute needles and small amounts of calcite.

The rocks are intensely deformed, with tight to isoclinal folding, a steep NW-trending foliation, and a prominent SE-plunging lineation. At the south-east end of the ridge, near the edge of the trees, a small fold, about 1 m across, plunges about 30° to the south-east. This folds the foliation and isoclinal folding exhibited by the magnetite stripes.

About 50 m to the south-west of the low ridge, quartz-chlorite schist with thin yellow-weathering metadolostone bands are exposed. A thicker band of impure metacarbonate rock ('marble') has been quarried and forms a slight depression along the length of the outcrop.

Interpretation

Al-Ameen (1979) and Williams (1986) have carried out detailed petrographical and geochemical studies of the banded-iron formation in the Gairloch area. Williams concluded that the lithology originated as a primary layered chert–iron-oxide sequence, deposited in a shallow-water environment. He postulated that the grunerite was derived from iron silicates (e.g. greenalite) by dehydration and reaction with silica during later metamorphism. Fe-bearing aluminosilicate phases, possibly chamosite, must also have been present to give rise to chlorite, garnet and biotite associated with the banded-iron formation. As the adjacent Kerrysdale

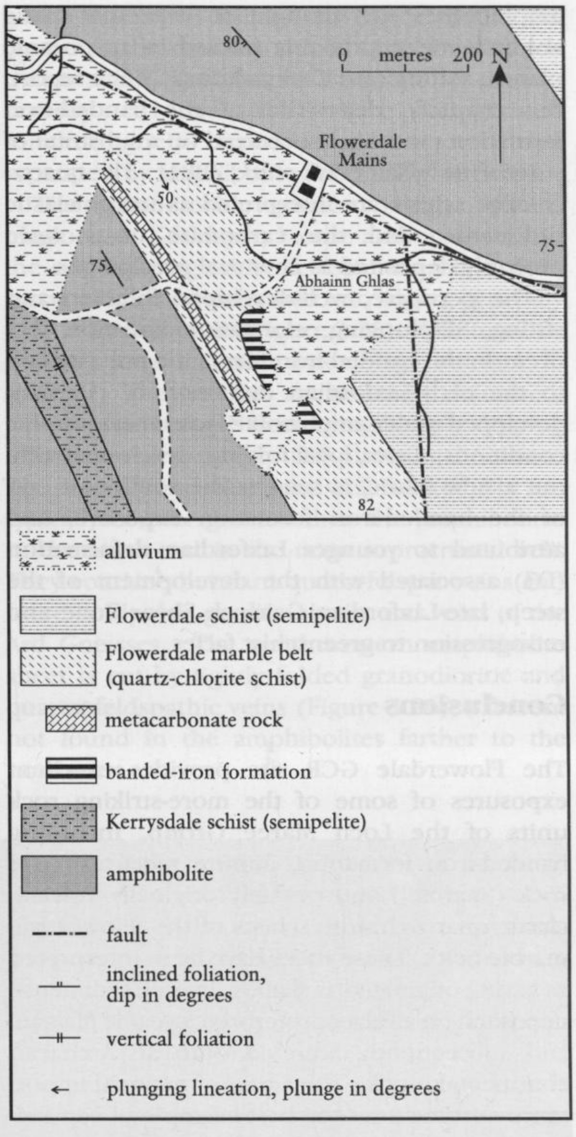


Figure 3.23 Map of the Flowerdale area, Gairloch. Based on Park (1978) and British Geological Survey 1:50 000 Provisional Series Sheet 91, Gairloch (1999).

amphibolites are thought to represent basic volcanic rocks, probably formed in an oceanic plateau setting (see **Kerrysdale** GCR site report, this chapter), deposition of the banded-iron formation most likely occurred on a substrate of submarine basalt (Park *et al.*, 2001). The quartz-chlorite schists are interpreted as volcaniclastic sediments, and the carbonate units were probably deposited as chemical precipitates.

The pervasive, well-developed foliation and strong, SE-plunging, elongation lineation that occur in the banded-iron formation are ascribed to the early-Laxfordian deformation, (D1/D2), developed under amphibolite-facies metamorphic conditions. Later, local folding, developed without a new fabric, is seen at the south-east end of the banded-iron formation exposure, and attributed to younger Laxfordian deformation (D3) associated with the development of the steep, late-Laxfordian Gairloch Shear Zone and retrogression to greenschist facies.

Conclusions

The Flowerdale GCR site provides excellent exposures of some of the more-striking rock units of the Loch Maree Group, including banded-iron formation, impure metacarbonate rock ('marble') and possibly originally volcaniclastic quartz-chlorite schists of the 'Flowerdale marble belt'. These rocks have been interpreted as having originated as shallow-marine sediments, deposited on a Palaeoproterozoic oceanic plateau, and subsequently accreted onto an Archaean continental block. The site is of national importance as it includes the best example of banded-iron formation in Britain and provides an insight into marine processes occurring in an active arc environment during the Palaeoproterozoic. The readily accessible exposures remain suitable for teaching and research purposes.

AN ARD (NG 805 751)

R.G. Park

Introduction

This small GCR site on the peninsula of An Ard, 2 km south of Gairloch village, is the type locality for the Palaeoproterozoic-age Ard Gneisses. The gneisses occur as foliated granodiorite and tonalite sheets that intrude the metasedimentary and mafic volcanic and intrusive rocks of the Loch Maree Group. They lie adjacent to the semipelitic Charlestown schists that occur to the north-east (Figure 3.24). Plagioclase megacrysts, now forming augen, are well developed in parts, and the gneisses contain screens and inclusions of the mafic amphibolite. The rocks lie within the Gairloch Shear Zone and have a prominent foliation and lineation that formed during the Laxfordian event.

The site was originally mapped by Clough in 1889 (Peach *et al.*, 1907), and was remapped by Park (1964). Park (1964) interpreted the Ard Gneisses as formed by granitization of the Charlestown semipelitic schists, but subsequently Park (1978) recognized that mylonitic gneisses marked their boundary with the semipelitic schists. Hence, he revised his initial view and regarded the transitional zone as a tectonic junction between older Scourian gneisses and metasedimentary rocks. More-recent work including U-Pb zircon age dating has revealed that the Ard Gneisses represent granitic sheets, originally intruded into the supracrustal rocks of the Loch Maree Group at 1903 Ma, and deformed

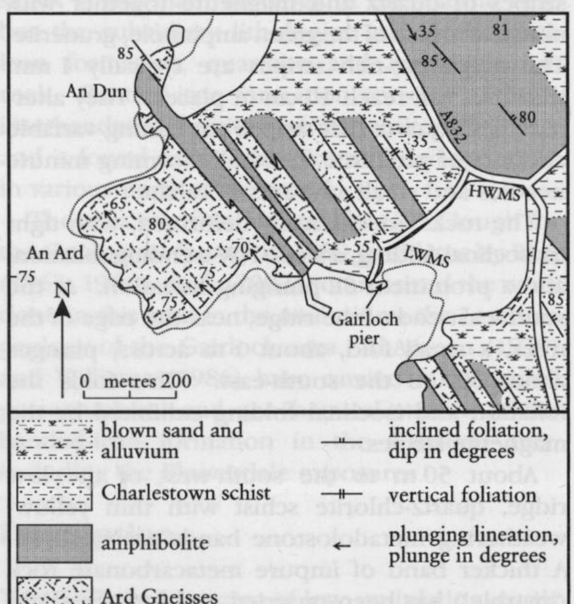


Figure 3.24 Map of the An Ard area, Gairloch. Based on Park (1978) and British Geological Survey 1:50 000 Provisional Series Sheet 91, Gairloch (1999).

and metamorphosed during the Laxfordian reworking (Park *et al.*, 2001; Park, 2002).

Description

An Ard peninsula protrudes south-westwards into Loch Gairloch, dividing the beach of Gaineamh Mhòr to the north from Gairloch pier and the habitations of Charlestown to the south-east. The peninsula is rocky with grass and scrubby woodland and rises gently to 48 m above OD. Clean exposures of the Ard Gneisses occur along the rocky northern coast of the peninsula, and on the south side around Gairloch pier and at the back of the fish factory (Figure 3.24). Protruding from its north side is the rocky promontory of An Dun, with its Stone Age fort. The metasedimentary schists are exposed along the main road from Gairloch, and the transitional zone between the schists and the Ard Gneisses is exposed along the foot of the raised sea cliff adjacent to the approach road to Gairloch pier.

The Ard Gneisses consist of two main components: a western outcrop, *c.* 280 m wide, of relatively coarse-grained, granodioritic, augen gneiss that forms the south-western part of the peninsula, beyond the amphibolite sheet which trends south-east from An Dun; and an eastern outcrop, *c.* 140 m wide, where finer-grained tonalitic gneiss forms three narrow strips separated by amphibolite sheets (Figure 3.24).

The granodioritic gneiss contains quartz, plagioclase, K-feldspar, biotite and epidote, and the original plagiocalse feldspar megacrysts are recrystallized and deformed into augen, generally only 2–5 mm across (Figure 3.25). The tonalitic gneisses have a similar assemblage but lack K-feldspar. The gneisses are intensely deformed, with a penetrative NW-trending steeply dipping foliation and a steeply NW-plunging lineation. The amphibolite sheets are well foliated, but are typically coarser grained than the amphibolites to the north-east in the main supracrustal belt. They contain abundant quartz-felspar veins and more rarely thin granitic sheets and veins of the Ard Gneisses. The south-western amphibolite sheet is cut by tightly folded granodioritic and quartzofeldspathic veins (Figure 3.26), a feature not found in the amphibolites farther to the north-east.

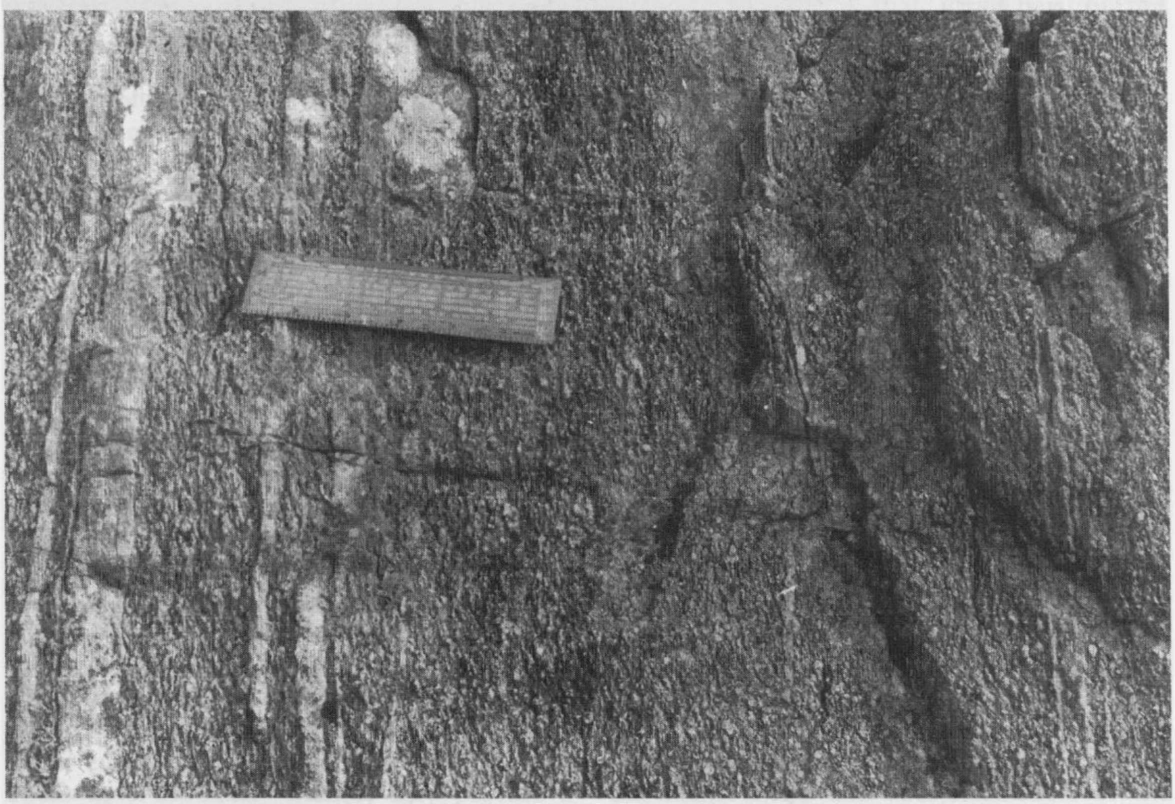


Figure 3.25 Gneissose granodiorite (Ard Gneisses) showing augen structure and well-developed foliation, An Ard peninsula (NG 803 753). 6-inch ruler for scale. (Photo: R.G. Park.)

Figure 3.26 Amphibolite (Loch Maree Group) cut by pale-grey granodiorite sheets (Ard Gneisses) that themselves are tightly folded. Note the steeply plunging lineation parallel to the fold axes. The hammer is 37 cm long. An Ard peninsula (NG 803 753). (Photo: R.G. Park.)

North-east of the tonalitic gneiss is a 250 m-wide outcrop of the Charlestown semipelitic schists. These are quartz-biotite-plagioclase schists similar to the Flowerdale schists (see **Kerrysdale** GCR site report, this chapter) but rather coarser grained. This outcrop includes a narrow amphibolite band. The transitional zone between the tonalitic gneisses and the metasedimentary rocks is about 20 m wide and consists of mylonitic gneisses, which resemble the metasedimentary schists except for the presence of small augen. There appears to be some interbanding of metasedimentary and igneous material within this zone but because of the high degree of deformation, the two rock-types are difficult to distinguish from each other.

Interpretation

This site allows the relationships between the Ard Gneisses and the surrounding metasedimentary and metavolcanic rocks of the Loch Maree Group to be demonstrated. The gneisses contain evidence for only one deformation episode and enclose foliated amphibolite sheets of Loch Maree Group type, which are veined and cut by granitic sheets and migmatitic veins. The tight folding of the veins is evidence that the granitic material was intruded into the amphibolites before the folding and foliation were developed in the gneisses. The deformation increases in intensity north-eastwards towards the transitional zone, and appears to be younger than that responsible for the main foliation and lineation in the metasedimentary rocks; it is considered to possibly relate to the third Laxfordian deformation. There is no sign of earlier structures in the Ard Gneisses, which are interpreted as igneous sheets, intruded during the earlier Laxfordian deformation (Park *et al.*, 2001).

Park *et al.* (2001) obtained a U-Pb zircon TIMS age of 1903 + 3/–2 Ma from the Ard Gneisses exposed behind the fish factory on the south-east side of the An Ard peninsula. This Palaeoproterozoic age is considered to represent crystallization of the granodiorite protolith, probably during the Laxfordian D1/D2 event. As the Ard Gneisses intrude the metasedimentary and metavolcanic rocks of the Loch Maree Group, these units must have formed prior to 1900 Ma.

Holland and Lambert (1973) and Park *et al.* (2001) presented geochemical data for the Ard Gneisses. The data plots give a primitive arc signature on discrimination diagrams and show many of the characteristic features of the so-called TTG ('trondhjemite'–tonalite–granodiorite) suites. The geochemical patterns are distinct from those of the metasedimentary rocks of the Loch Maree Group, indicating that these do not represent a significant component of the source material for the gneisses (Park *et al.*, 2001). Winchester *et al.* (1980) analysed a number of samples of the 'transitional' schists from several localities along both sides of the Ard Gneisses outcrop and concluded that they are chemically distinct from the metasedimentary rocks but similar to the meta-igneous Ard Gneisses. The Ard Gneisses are thus now considered to represent a component of primitive magmatic material intruded into the Loch Maree Group, probably above an active subduction zone. Calc-alkaline plutonic suites of similar ages have been found across other Palaeoproterozoic continent–continent collision belts of the North Atlantic region (e.g. in East Greenland; Kalsbeek *et al.*, 1993), allowing the possibility of inter-regional correlation across a wide area.

Conclusions

The An Ard GCR site is the type area for the Palaeoproterozoic Ard Gneisses, foliated granodioritic and tonalitic gneisses that intrude the metasedimentary and metavolcanic Loch Maree Group. The site essentially complements the **Flowerdale** and **Kerrysdale** GCR sites that represent the Loch Maree Group. The Ard Gneisses are an important element in the tectonostratigraphical history of the Lewisian Gneiss Complex, as they represent deformed early-Laxfordian granites. U-Pb zircon age dating implies that granodiorite and tonalite sheets were emplaced into the Loch Maree Group rocks at *c.* 1900 Ma. Hence, they provide a minimum age for the Loch Maree Group deposition and formation. Geochemical data suggests that the gneisses were intruded above an active subduction zone. The strong foliation and lineation developed in the gneisses are interpreted as a result of the later Laxfordian deformation episodes linked to the formation of the Gairloch Shear Zone.

Confirmation of the Palaeoproterozoic age of the Ard Gneisses has allowed correlation to be made with similar intrusions in east Greenland and Scandinavia, allowing the main Laxfordian tectonothermal event to be placed in its North Atlantic context. For this reason, the site is considered to be of national and international importance.

LOCH BRAÌGH HORRISDALE TO SIDHEAN MÒR (NG 788 699–NG 811 721)

R.G. Park

Introduction

This GCR site provides a cross-section through Archaean gneisses and mafic dykes of the Scourie Dyke Suite that form part of the Southern Region, immediately south-west of the outcrop of the Loch Maree Group. The site lies *c.* 4.4–7.4 km south of Gairloch and provides a complete, well-exposed, traverse across the south-west side of the regional Gairloch Shear Zone (Figure 3.1). It demonstrates the relationships between Badcallian, Inverian and Laxfordian structures and the Scourie dykes, thus enabling the sequence of tectonothermal events in this part of the Lewisian Gneiss Complex to be deduced.

Badcallian gneisses are unmodified to the south-west of Loch Braìgh Horrisdale, but north-east of the loch they are affected by Inverian deformation, resulting in intense folding and a steep axial-plane foliation. Both the Badcallian and the Inverian structures and fabrics are cross-cut by the later Scourie mafic dykes. In the south-west part of the site Laxfordian deformation is manifest only as scattered discrete narrow shear-zones affecting the mafic dyke margins, but deformation increases progressively north-eastwards, resulting in the superimposition of a generally pervasive Laxfordian planar fabric in the mafic dykes and recrystallization of the gneisses. This change in intensity of Laxfordian deformation marks the transitional south-western margin of the Gairloch Shear Zone. C.T. Clough and W. Gunn originally mapped the area for the Geological Survey in 1889, and it was described by Peach *et al.* (1907). It has been been remapped recently by the author (see Park, 2002).

Description

The Loch Braìgh Horrisdale to Sidhean Mòr site lies south of Shieldaig and occupies an oblong area *c.* 3.2 km × 1 km with its long dimension trending north-east. It consists of glacially scoured rocky gneiss outcrops that lie at *c.* 100 m above OD around Loch Braìgh Horrisdale, but form higher knolls to the north-east at *c.* 150–180 m above OD, culminating in Sidhean Mòr (225 m). Numerous lochs, gullies and small stream valleys are present. The Lewisian rocks lie just beneath the Torridonian unconformity with patches of the overlying Applecross Sandstone Formation impinging on the site area (Figure 3.27).

Based on the degree of tectonic reworking, the GCR site can be divided into three areas: south-western, central and north-eastern (Figure

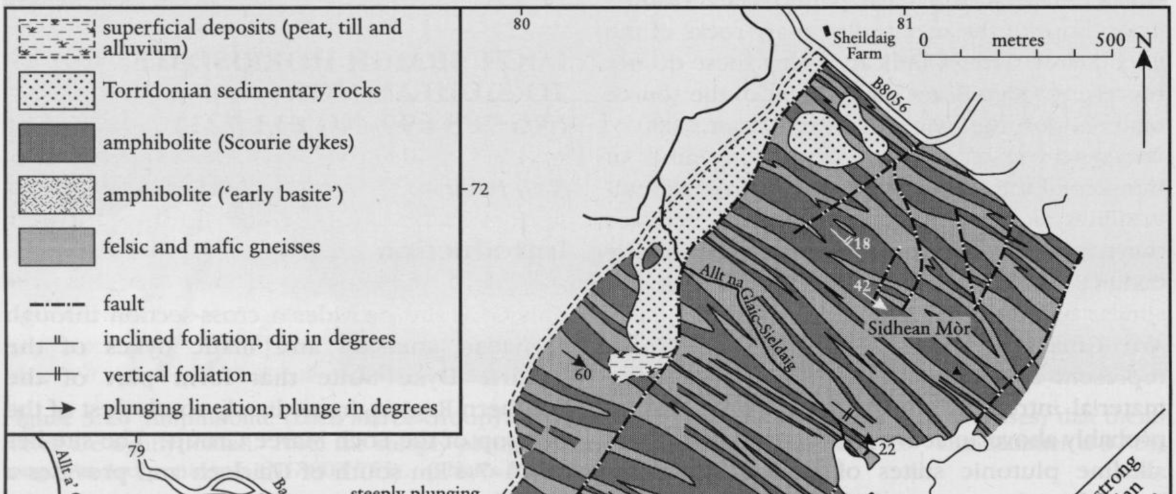


Figure 3.27 Map of the area between Loch Braìgh Horrisdale and Sidhean Mòr. After Park (2002).

3.27). The south-western area, west of Loch Braìgh Horrisdale and the Badachro River, lies within the northern part of the Badcallian enclave of An Ruadh Mheallan (NG 835 615) (see also **Alligin (Diabaig)** GCR site report, this chapter). Here centimetre- to metre-scale banded dominantly felsic (granodioritic) gneisses display Badcallian structure, and the banding/foliation trends generally north and dips moderately to steeply to the west. These coarse-grained Archaean gneisses are cut by sparse, narrow, Inverian shear-zones with a steep NW-trending foliation, and by NW-trending Scourie dykes, which are mostly undeformed, but a few show evidence of shearing in narrow marginal zones. The relationships between the Scourie dykes and the Badcallian banding are best displayed on the crags of Meallain an Uillt-ghiubhais (NG 790 700) (Figure 3.27). The dykes here are clearly discordant to the gneissose banding. A thicker dyke on the north-east side of this hill is undeformed, but several thinner dykes farther to the south-west contain narrow marginal shear-zones. The orientation of the fabric in these shear zones implies a sinistral, oblique (south-side-up) sense of shear has occurred.

The central part of the site extends from the north-east shore of Loch Braìgh Horrisdale to a small stream (Allt na Glaic–Sieldaig) that flows north-westwards from the un-named loch immediately south of Sidhean Mòr. The geology is best examined by making a traverse north-eastwards from Loch Braìgh Horrisdale. On the crags immediately north of the track at NG 803 708, a 50 m-wide amphibolite dyke displaying only marginal deformation cuts banded felsic gneisses; the gneisses display typical Inverian open to tight folding with steep NW-trending axial planes and foliation. The Inverian structures are clearly cross-cut by the dyke margin, showing that they pre-date mafic dyke emplacement. From here north-eastwards to the Allt na Glaic–Sieldaig, NW-trending structures of Inverian age are ubiquitous. There are many thin dykes, typically deformed only in marginal shear-zones. The sense of shear on these thin zones is again sinistral, south-up, and locally a faint, steeply SE-plunging intersection lineation may be observed.

There is an unusually high concentration of mafic dykes of the Scourie Dyke Suite in both the central and northern parts of the GCR site, where the dykes make up about one-third of the outcrop, the highest concentration seen anywhere in the Lewisian Gneiss Complex. Although up to 100 m wide, there are numerous smaller dykes between 1 m and 10 m wide. The dykes often form branching networks, and many of the thin dykes probably join at depth (Park, 2002).

In the north-eastern area, from Allt na Glaic–Sieldaig to Sidhean Mòr, the effects of Laxfordian deformation become much more apparent. Most Scourie dykes are penetratively deformed and the felsic gneisses between the dykes also show evidence of the superimposition of a strong Laxfordian fabric. They are recrystallized to a finer grain-size and exhibit a marked grain-aggregate shape fabric, which shows a pronounced linear element with a moderate plunge to the south-east. Some of the coarser-grained dykes possess deformed felsic grain aggregates that have been used as strain markers; these also have a linear element plunging to the south-east. The prominent rocky ridge of Sidhean Mòr (NG 812 716) is formed by a *c.* 100 m-wide dyke, which forms part of a branching dyke system that extends down the north-east slopes of the hill. Parts of this dyke system are still undeformed and exhibit chilled margins against the host gneisses (Figure 3.28), even though thinner Scourie dykes to the south-west are foliated throughout.

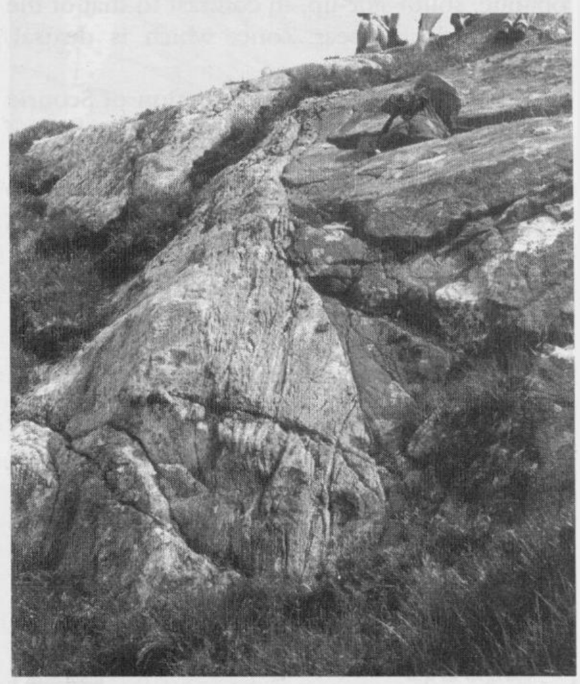


Figure 3.28 Undeformed Scourie dyke cutting steeply dipping Inverian foliation on the north-east slopes of Sidhean Mòr. (Photo: R.G. Park.)

Interpretation

From the traverse described above, it is clear that there is a transitional south-western boundary to the major zone of Laxfordian deformation that occupies the Gairloch area. It is marked mainly by the development of penetrative Laxfordian planar and linear fabrics in the felsic gneisses, rather than by any abrupt change in the state of deformation of the dykes. The Laxfordian foliation trends north-west and dips steeply and the lineation plunges south-east. They were developed under amphibolite-facies conditions, which characterize the early-Laxfordian phase of deformation in the Gairloch Shear Zone. This Laxfordian deformation is superimposed upon the earlier NW-trending, steeply dipping, Inverian foliation, which can be seen affecting the N-trending Badcallian gneisses in the southern part of the site. Both the Inverian and Badcallian gneisses also contain amphibolite-facies assemblages and show no evidence of an earlier granulite-facies event. The south-west margin of the main zone of Inverian deformation lies about 1 km south-west of the main Laxfordian shear-zone, although localized Laxfordian effects are present throughout the site. The sense of movement on the narrow localized Laxfordian shears is typically sinistral, oblique, south-side-up, in contrast to that of the main Gairloch Shear Zone, which is dextral, oblique, north-side-up.

The unusually high concentration of Scourie dykes in this area, making up about one-third of the outcrop area, might suggest proximity to an early Palaeoproterozoic rift approximately coincident with the Loch Maree Group outcrop (see Johnson *et al.*, 1987).

Conclusions

The Loch Braìgh Horrisdale to Sidhean Mòr site provides a near-continuous 3 km-long traverse across the south-west margin of the regional Laxfordian Gairloch Shear Zone. A series of excellent exposures clearly demonstrate the following features:

- In the south-western part of the site, undeformed Scourie dykes cross-cut Badcallian banded gneisses that exhibit N-trending structures.
- In the central part of the site, the Badcallian gneissic banding is folded, and affected by steep NW-trending Inverian foliation; the dykes are subconcordant to this foliation but locally cross-cut it, thus establishing the pre-dyke age of the Inverian structure.
- In both the south-western and central areas, narrow Laxfordian shear-zones are common; they affect the margins of the dykes and typically have a sinistral, oblique, south-side-up sense of shear.
- In the north-eastern part of the site, Laxfordian deformation is more widespread; although its effects are still variable in the dykes, in the gneisses a pervasive new fabric and SE-plunging lineation are developed.

These four observations help to reconstruct the sequence of Palaeoproterozoic events in the Southern Region of the Lewisian Gneiss Complex, and improve the understanding of the geometry and kinematics of the Gairloch Shear Zone. The site is of national importance in that it is one of the few places where the sequence of events involved in the Palaeoproterozoic reworking of the Archaean gneiss complex can be readily demonstrated.

ALLIGIN (DIABAIG) (NG 806 566–NG 830 620)

R.G. Park

Introduction

The Alligin GCR site area is one of the two areas where the original division of the Lewisian Gneiss Complex into the earlier Scourian and later Laxfordian components was described by Sutton and Watson (1951). It is therefore one of the most important sites in the Lewisian Gneiss Complex for demonstrating the evidence on which the stratigraphical and chronological framework of the Lewisian has been based. The other area is described in the **Tarbet to Rubha Ruadh** GCR site report (this chapter). In terms of quality of exposure, it is probably unrivalled; it is possible to walk for several kilometres across virtually uninterrupted rock in which some of the most remarkable petrological and structural features of the complex are clearly displayed. Hence, the Alligin area is one of the most frequently visited Lewisian sites, both by research workers and by student parties for teaching purposes.

The Alligin GCR site lies within the most southerly inlier of the Southern Region, and provides a complete and excellently exposed traverse from the granulite-facies Badcallian enclave of An Ruadh Mheallan in the north to the intensely deformed Laxfordian belt at Diabaig in the south (Figure 3.29). The latter forms the Diabaig Shear Zone at the north-east margin of a wide zone of Laxfordian deformation, extending across Loch Torridon and embracing the whole of the inlier to the south-west of the loch (Figure 3.1).

The area was first mapped and described by L.W. Hinxman (in Peach *et al.*, 1907) for the Geological Survey. A more-complete study was undertaken by Cresswell (1969, 1972), who mapped the elements of the Lewisian gneisses in detail; Figure 3.29 is based on Cresswell's map. More recently the area has been re-interpreted in terms of more-modern shear-zone theory by Wheeler *et al.* (1987) and Niamatullah and Park (1990), but this work has served to confirm the essential elements of Cresswell's structural mapping and interpretation.

Description

The Alligin GCR site forms a curved elongate area some 5.9 km long and 0.6–1.5 km wide that extends north-east from Loch Shieldaig to the slopes immediately west of An Ruadh Mheallan. The glacially scoured, craggy dissected ground rises rapidly from sea level to *c.* 300 m and then only rises slowly until at its northern extent it reaches *c.* 500 m above OD. Lochans, small burns and gullies are common, but the area is dominated by the abundant exposure of the Lewisian gneisses. Torridonian rocks extend down to Loch Diabaigas Airde immediately north-west of the site area, and they also form the prominent hill of An Ruadh Mheallan (671 m) that overlooks the area to the north (Figure 3.29). They are described in the **Diabaig** GCR site report (Chapter 4).

On the south-west slopes of An Ruadh Mheallan (NG 836 615), lithologies and structures of Scourian gneisses deformed during the Badcallian event are evident, whereas to the north and south these early-formed gneisses are strongly reworked by Inverian and Laxfordian deformational and metamorphic events. The Scourian rocks consist of a series of alternating banded and massive, granodioritic to tonalitic gneisses that represent for the most part an intrusive

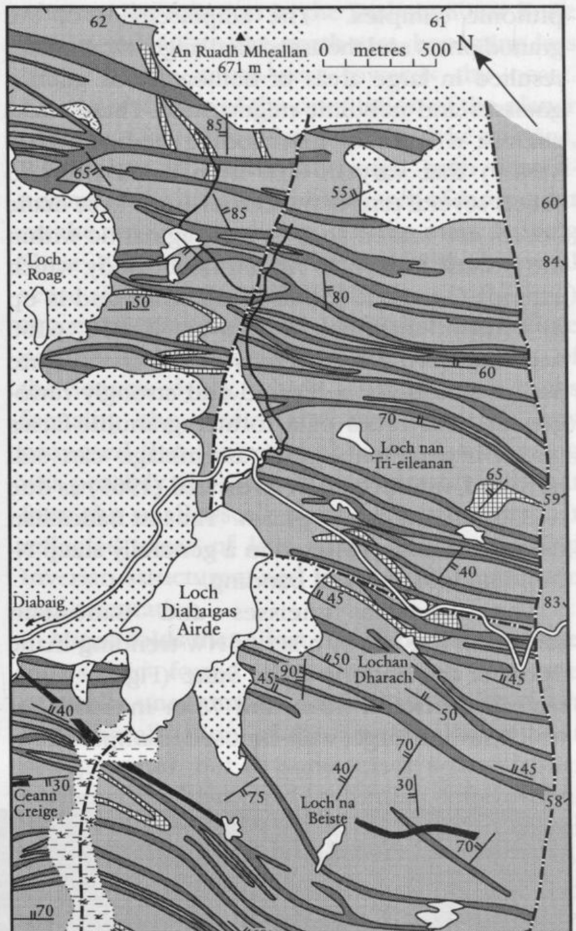


Figure 3.29 Map of the Alligin (Diabaig) GCR site. After Cresswell (1972).

plutonic complex. The emplacement of the granodiorites and the associated migmatization has resulted in large areas of homogeneous granitic gneisses and nebulitic migmatites. These rocks enclose a suite of amphibolite bodies ('early basics') that vary in size from small pods to sheets several tens of metres across. These mafic bodies are veined and, in part, agmatitic within the granitic host rock. An ultramafic body, which extends for about 350 m along strike and is up to 40 m in thickness, occurs at NG 8367 6160 near the northern extremity of the site (Figure 3.29). The body is layered and strongly retrogressed, but relics of a former granulite-facies olivine-hypersthene-spinel assemblage can still be found, interpreted by Cresswell (1969) as due to Badcallian metamorphism. The last Badcallian deformation has resulted in a generally steep N-trending foliation and banding.

The Scourian gneisses and Badcallian structures are cut by a set of NW-trending mafic dykes of the Scourie Dyke Suite (Figure 3.30), typically between 30 m and 75 m in width, of which several large, well-exposed examples form prominent ridges south-west of the summit of An Ruadh Mheallan (Figure 3.29). These dykes are undeformed except for small (millimetre- to centimetre-wide) shear-zones, but have been metamorphosed and are now all amphibolites. Most of the dykes are metadolerites, and exhibit sub-ophitic textures in their undeformed state. However, a few ultramafic dykes are also present, for example 150 m east of Loch na Beiste where an ultramafic dyke cross-cuts a metadolerite dyke. These later dykes are also amphibolitized, but their geochemistry is similar to that of picrites.

Towards the south-west margin of the An Ruadh Mheallan enclave (Figure 3.29) the gneisses become progressively deformed by folds with steeply dipping, NW-trending axial planes. A new related penetrative amphibolite-facies metamorphic planar fabric is also developed. The mafic dykes also become deformed; thicker dykes possess marginal foliated zones whereas thinner dykes are deformed throughout. Careful examination of the relationships between the new foliation in the gneisses and

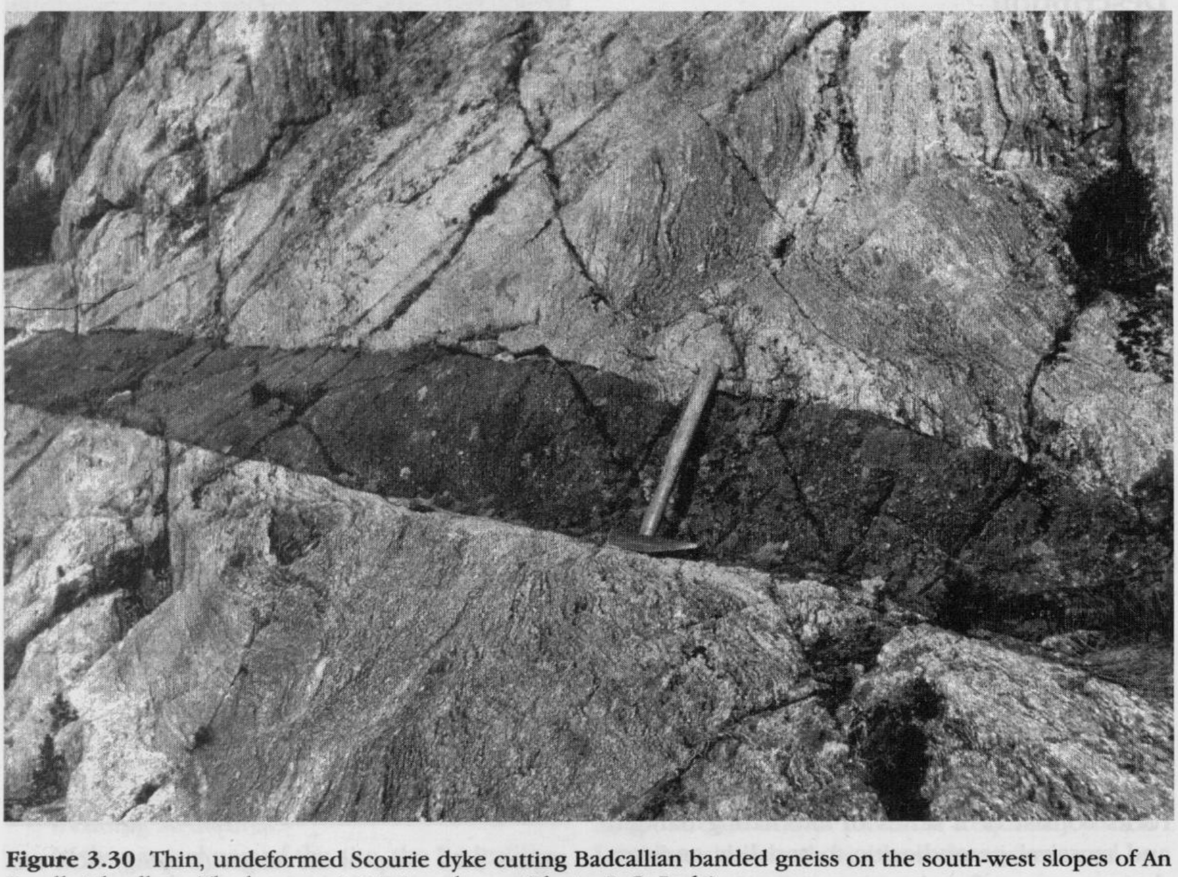


Figure 3.30 Thin, undeformed Scourie dyke cutting Badcallian banded gneiss on the south-west slopes of An Ruadh Mheallan. The hammer is 37.5 cm long. (Photo: R.G. Park.)

the margins of the dykes shows that some of the NW-trending structures in the gneisses are cut by and thus pre-date the dykes. Cresswell (1972) hence assigned these structures to the Inverian episode, whereas the later NW-trending structures, which do affect the dykes, were assigned to the Laxfordian. This relationship between the dykes and the Inverian and Laxfordian structures is particularly clear south of the road near Loch na Beiste (Figure 3.29). Here the Inverian foliation has an easterly trend and moderate northward dip, and is clearly cross-cut by steep NW-trending dykes.

Cresswell (1972) concluded from his study of the relationships between the Scourie dykes and the earlier structures in the host gneisses that the latter had exerted a significant control over the size, orientation and spacing of the dykes. In areas of strongly developed, steep, NW-trending, Inverian foliation, the dykes are concordant, thinner and more closely spaced than in areas where the pre-existing foliation has a different orientation. This can be demonstrated by comparing the area immediately south of An Ruadh Mheallan, where the pre-dyke foliation has a northerly trend, with the two NW-trending belts lying respectively 1.5 km and 2 km farther to the south-west (Figure 3.29).

The nature of the Laxfordian deformation is strongly reflected by the deformation state of the Scourie dykes, which are numerous in the Alligin site area. Although the dykes are universally amphibolitized, there are great variations in their deformation state. Several distinct shear-zones of differing width and intensity can be recognized between the south-west edge of the An Ruadh Mheallan enclave and the north-east edge of the main Diabaig Shear Zone, which is situated just south-west of Loch na Beiste (Figure 3.29). A crude estimate of the amount of strain in the dykes can be obtained from the ellipsoidal shapes of the grain aggregates making up the deformed ophitic texture. Niamatullah and Park (1990) used these aggregates as strain markers to map the Laxfordian strain variations across the area. The orientation of the lineation, which at high strains lies close to the shear direction, can also be used to indicate the shear direction within the shear zones. This elongation lineation varies across the area but typically plunges at moderate angles towards the east or ENE, obliquely down the dip of the foliation. The narrow shear-zones generally dip at moderate to steep angles to the north-east, whereas the foliation in the Diabaig Shear Zone dips at 40°–50° to the north-east, becoming less steep to the south-west towards the coast. Based on studies of the orientation of the planar and linear fabrics in relation to the dyke margins, Wheeler *et al.* (1987) recorded both dextral-normal and sinistral-reverse senses of movement on the small shear-zones, but the main Diabaig Shear Zone appears to have a dextral-normal sense (Park *et al.*, 1987). Wheeler *et al.* (1987) suggested that the local Laxfordian shear-zone pattern was influenced by the orientation of the Scourie dykes, which acted as weak zones focusing the strain and movement. They proposed that the regional Laxfordian shearing was possibly top-to-the-W, considerably different from the smaller-scale shear-zone geometry that reflected areas of low strain, the pre-existing Inverian structures, and mafic dyke abundance and orientation.

Minor folds that affect the planar fabric in the dykes are found in some areas, but are generally uncommon. Laxfordian fabrics result in recrystallization of the amphibolite without retrogression, but in some cases a new fabric, attributed to the second Laxfordian deformation, is developed. Younger folds, generally with steep axial planes, are accompanied by retrogressive effects and are attributed to the third Laxfordian deformation.

Interpretation

The structural relationships of the gneisses and dykes seen on a traverse between An Ruadh Mheallan in the north-east and Loch Shieldaig in the south-west allow a sequence of metamorphic events to be established. The earlier part of this sequence can be seen near An Ruadh Mheallan. Here, the oldest rocks are mafic sheets and lenses, generally composed of amphibolite, but including the northerly Loch na h-Uamhaig metaperidotite. The mafic and ultramafic rocks are enclosed in, and veined by, tonalitic and granodioritic material, which is deformed by a steep, N-trending foliation. The events leading up to this Badcallian deformation and metamorphism are attributed to the Scourian.

To the south-west the Badcallian foliation is deformed, resulting in folding and a steep, NW-trending foliation, attributed to the Inverian event. However, over much of the area, the intensity of the later Laxfordian deformation, and its similarity in trend to the Inverian structures, make distinction between Inverian and Laxfordian structures difficult. Nevertheless, from scattered observations across the Laxfordian belt, Park *et al.* (1987) concluded that the whole area south-west of An Ruadh Mheallan had been affected by Inverian deformation and lay within a wide Inverian shear-zone that extended to the present limit of the Lewisian Gneiss Complex outcrop south of Loch Torridon.

The Inverian structures are cut in turn by the Scourie dykes, which provide the clearest record of the effects of Laxfordian deformation. Indeed, Wheeler *et al.* (1987) show that the Laxfordian deformation is focused along the dykes, which act as weak roughly planar zones in the banded felsic and mafic gneisses. All the dykes are now amphibolite, indicating that the main (first) Laxfordian event took place under amphibolite-facies metamorphic conditions, but there are major variations in the degree of deformation/reworking. Several distinct Laxfordian shear-zones of variable width, intensity and sense of movement can be recognized, but the dextral-normal sense of the main Diabaig Shear Zone implies that the zone is extensional in its present orientation.

Two subsequent sets of minor folds that affect the planar fabric in the mafic dykes have been correlated with the second and third Laxfordian deformations, the last of which is responsible for major upright NW-trending folds south of Loch Torridon and farther north, in the Gairloch–Loch Maree district.

Conclusions

The Alligin GCR site is one of the two classic areas where the original orogenic classification of the Lewisian Gneiss Complex into Scourian and Laxfordian components was formulated by Sutton and Watson (1951). It lies astride the road from Torridon to Diabaig and provides a complete and excellently exposed *c.* 6 km-long traverse from the An Ruadh Mheallan enclave in the north-east, where the Scourian gneisses show only the effects of the Badcallian tectonothermal event, to the strongly deformed Laxfordian belt of Diabaig (part of the major Diabaig or Torridon Shear Zone) in the south-west. In the An Ruadh Mheallan enclave, the pre-dyke structural history has been established, leading to the recognition of a sequence of Badcallian and Inverian events prior to Scourie dyke emplacement. By noting the deformation patterns of the Scourie dykes and in the Scourian gneisses south of An Ruadh Mheallan, the effects of the Laxfordian event can be demonstrated. Several narrow Laxfordian shear-zones of varying width and intensity can be studied in the transitional zone between An Ruadh Mheallan and the main Diabaig Shear Zone and their sense of movement can be worked out. This area contains some of the best localities in Britain for the study of ductile shear-zones.

The Alligin site is of international importance, both in terms of the quality of exposure, its geological features, historical significance and its suitability for teaching and further research.