Chapter 3 Lewisian of the Scottish mainland

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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 metasedimentary 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 Taxfordian'. 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 tectonometamorphic 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 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 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 at.,* 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* ed., 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 magma-tism 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 geo-chemically 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 under-plating. 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 under-plating 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 southwest 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 southwest side (Crane, 1978; Park *et al.,* 1987). A third major shear-zone is the 1–2km-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* ed., 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 Braigh 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 Carrunore and Gairloch, and south of Loch Torridon (e.g. see Alligin (Diabaig) and

Creag Mhor Thollaidh GCR site reports, this chapter). Thorough reworking of the original gneiss produces a finely banded Taxfordian' 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 2–4km 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 Mhor 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.

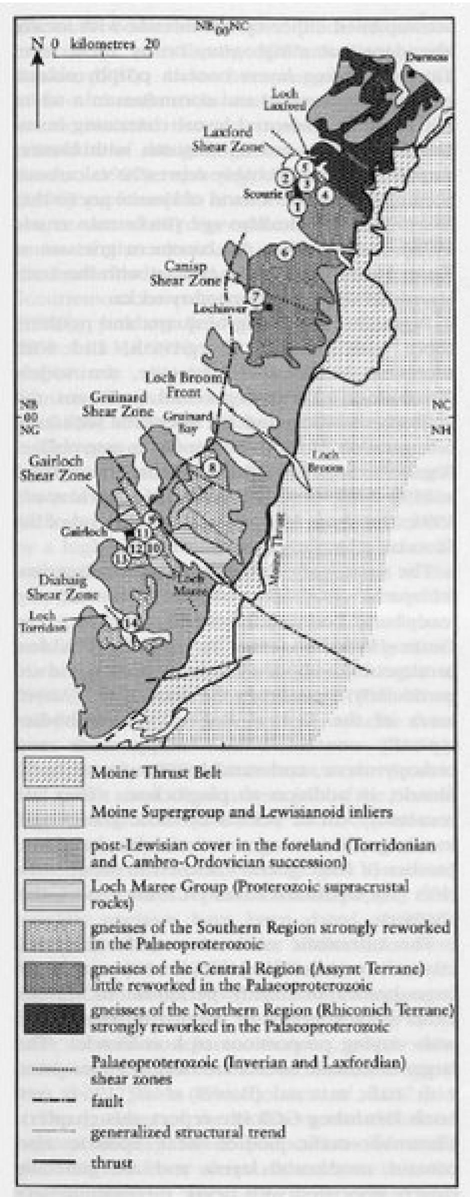
The regional D3 Laxfordian folds were superseded by later, more-localized structures of various styles and orientations, together with crush zones containing pseudotachylite (e.g. see Flowerdale, Kerrysdale and Creag Mhòr Thollaidh GCR site reports, this chapter). These later structures in the Gairloch 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).

References

1. Deposition of arenaceous and argillaceous Moine sediments unconformably upon Lewisianoid gneiss basement.
2. Emplacement of early tholeiitic igneous intrusives (now represented by the Bettyhill Suite amphibolites). These include the Ard Mor Amphibolite.
3. **D1**: Upper amphibolite-facies metamorphism producing gneissose layering (S1) and extensive lit-par-lit regional migmatization. Early mafic intrusives deformed and metamorphosed to foliated garnet amphibolites.
4. **D2**: Development of tight NW- and SE-plunging (F2) folds and associated strong mineral extension lineation L2. Some folds show extreme curvilinearity, associated with distinct zones of high strain. Retrogression of D1 mineral assemblages in some 'early' amphibolites and imposition of D2 fabric. Movement along Naver Thrust Zone. Partial melting of gneisses at the end of this event to produce foliated (G2) granite sheets (early phases of the Torrisdale Vein-Complex). U-Pb zircon dating suggests an Early Ordovician age (Kinny *et al.*, 1999).
5. **D3**: Upright, tight SE-plunging (F3) folds with steep E-dipping axial surfaces, largely coaxial with F2 folds. Associated extension, intersection and pronounced rodding lineation (L3). Coaxial F2–F3 refolds. Further retrogression and foliation of 'early' amphibolites.
6. Syn-D3 emplacement of the Clerkhill Intrusion followed by generation of foliation and folding of foliated appinitic amphibolite sheets. U-Pb zircon dating suggests Mid-Silurian age.
7. Emplacement of post-F3 microdiorites and unfoliated (G3) pegmatites and granites of the Torrisdale Vein-Complex.
8. **D4**: Localized brittle folding, faulting and development of en echelon tension gashes.
9. Emplacement of cross-cutting (G4) microgranites as well as porphyritic microgranite and lamprophyric sheets.

(Table 6.1) Sequence of tectonometamorphic events recognized in the Naver Nappe.



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