Lewisian, Torridonian and Moine Rocks of Scotland

J.R. Mendum,

A.J. Barber,

R.W.H. Butler,

D. Flinn,

K.M. Goodenough,

M. Krabbendam,

R.G. Park

and

A.D. Stewart

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British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Chapter 7

Moine (Central)

INTRODUCTION

J.R. Mendum

The Moine (Central) area lies between the Moine Thrust to the west and the Great Glen to the ESE, and extends from the Inverness–Ullapool line in the north to the Loch Hourn–Glen Garry line and onto Skye in the south (Figure 7.1). It encompasses most of the mountainous parts of Ross and Cromarty and the northern part of Inverness-shire. It stretches from the Fannich Mountains, south to the mountains of Kintail, the Glenelg area and onto the Sleat peninsula. The highest point is Carn Eighe (1183 m), but there are numerous peaks over 1000 m, particularly in the Kintail and Affric areas. Somewhat lower, less-rugged, but hilly ground occurs in the east around Strath Glass, Glen Urquhart, Glen Moriston and Glen Garry.

Geologically the Moine (Central) area comprises the Moine succession and Lewisianoid inliers, including the large Glenelg–Attadale Inlier. This inlier has experienced Grenvillian (*c.* 1000 Ma) high-pressure metamorphism. These elements are all affected by various deformational and metamorphic phases that have been dated from 873 Ma up to 420 Ma. The Grampian (*c.* 470–455 Ma) and Scandian (435–425 Ma) phases of this orogenic activity constitute the Caledonian Orogeny. The role of the Caledonian deformation is reasonably well understood, although new data as to the relative importance of the two different phases is still being produced. The character of the Neoproterozoic tectonic activity, including the so-called 'Knoydartian Orogeny', is less clear.

Suites of Neoproterozoic intrusive rocks are found in the Moine area, notably the West Highland Granite Gneiss Suite and metagabbros. The critical GCR sites occur within the Moine (South) and Moine (North) areas respectively, and the details of these igneous suites are described in the relevant chapters (Chapters 6 and 8). During the waning phases of the Caledonian Orogeny, the Cluanie and Ratagain plutons, the Glen Orrin intrusion, and several suites of minor intrusions were intruded into the Moine (Central) area. Post-orogenic Old Red Sandstone unconformably overlie the Moine succession in the east. Although distinctive elements of the Moine (Central) area are featured in GCR sites, there is a marked concentration in the Glenelg–Attadale Inlier and its immediate envelope.

History of geological work

Detailed work in much of the Moine (Central) area has been inhibited by the somewhat forbidding nature of the terrain, poor exposure, the high rainfall, and the complex geology. Following a brief reconnaissance traverse across the area, Murchison and Geikie (1861) showed considerable perception when they referred to the Moine and Lewisianoid rocks of Kintail as 'gneiss, mica-schist and micaceous quartz rocks, re-duplicated by folding'. Although some parts of the Fannich Forest were surveyed in the early 1890s, the bulk of the original survey mapping in the area took place between 1898 and 1903 by C.T. Clough, J. Horne, L.W. Hinxman and others. The geology was summarized in a series of memoirs (Peach *et al.*, 1910, 1913; Horne and Hinxman, 1914). Parts of the southern part of the area, including Kintail, Glen Affric and Invermoriston were mapped by the Geological Survey during the 1960s, 1970s and even the 1980s (Peacock *et al.*, 1992; May *et al.*, 1993; May and Highton, 1997). Academic mapping and other studies have had a similarly punctuated history of geological work in the Moine (Central) area. The area has proved to be a testing ground for significant geological theories and techniques.

The original surveyors recognized that the Lewisianoid gneisses and Moine metasedimentary rocks were distinct units showing evidence of different geological histories. They discovered rare occurrences of deformed conglomerate in the basal parts of the Moine succession (see **Allt Cracaig Coast** GCR site report, this chapter), and postulated an unconformable relationship between the two rock units. In the 1950s a series of structural studies of the Scardroy, Fannich and Monar Lewisianoid inliers (Figure 7.1) led some workers to put forward a contrary interpretation (Sutton and Watson, 1953, 1954; Ramsay, 1954). These studies emphasized the 'stratigraphical', structural and metamorphic concordance between the gneissose rocks of the inliers and the surrounding Moine metasedimentary succession. The deformed 'conglomerates' were ascribed to purely tectonic processes of segregation and deformation. The hornblendic felsic and mafic gneisses were regarded as possible metavolcanic units within the Moine stratigraphy. Such ideas were an extension of the 'Durcha-type-Moines' advocated by Read *et*

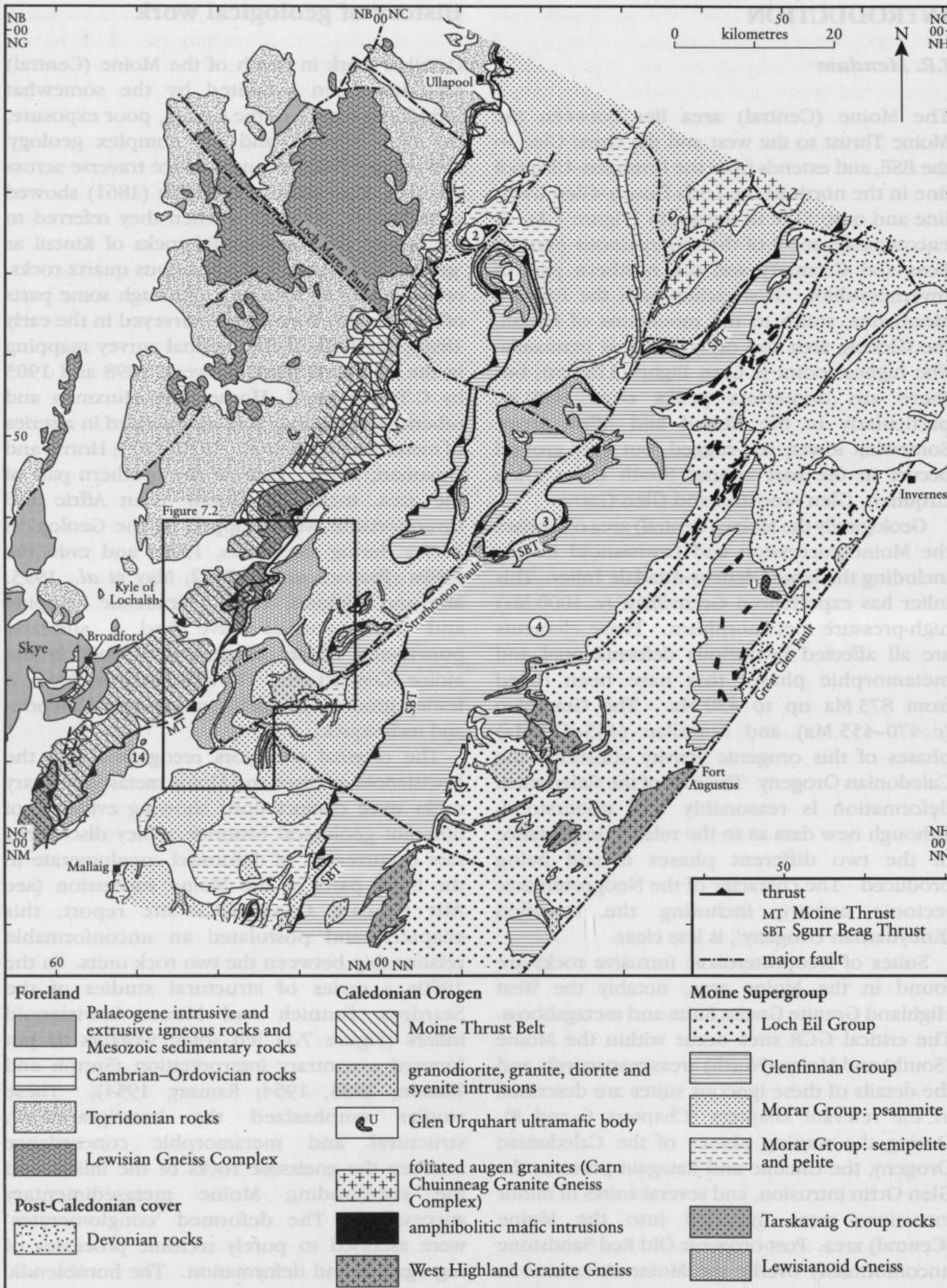


Figure 7.1 Geological map of the Moine (Central) area, with the location of the GCR sites: 1 – **Fannich**; 2 – **Meall an t-Sithe and Creag Rainich**; 3 – **Loch Monar**; 4 – **Abhainn Gleann nam Fiadh**; 14 – **Ard Ghunel**. GCR sites 5–13 are located within or marginal to the Glenelg–Attadale Inlier and are shown on Figure 7.2.

al. (1926) farther north (see **Allt Doir' a' Chatha** GCR site report, Chapter 6).

The dispute was resolved following Ramsay's (1957b) work in and around the Glenelg–Attadale Lewisianoid Inlier, where he became convinced of the unconformable nature of the Lewisianoid–Moine contact. He affirmed the local presence of basal conglomerate, and showed that cross-bedding in the inverted Moine rocks implied that the sequence younged away from the contact. These results supported Clough's early survey work. Subsequently Winchester (1971, 1973) used geochemistry in the Fannich Mountains to demonstrate the Lewisianoid affinity of the gneissose rocks in the succession. Moorbath and Taylor (1974) obtained a whole-rock Rb-Sr age of 2810 ± 120 Ma on the Lewisianoid gneisses of the Scardroy Inlier, again demonstrating a much older age for the Lewisianoid inliers.

Much of the work carried out by PhD students in the late 1950s and 1960s in the Moine (Central) area involved detailed mapping and structural analysis of parts of the Moine succession (Clifford, 1957; Ramsay, 1957a,b; Dhonau, 1960; Tanner, 1965; Tobisch *et al.*, 1970; Simony, 1973). Other workers concentrated on the Lewisianoid rocks of the Glenelg–Attadale Inlier (Ramsay, 1957b; May, 1959; Barber, 1968; Sanders, 1972; Barber and May, 1976; May *et al.*, 1993). Temperley and Windley (1997) suggested that much of the tectonic evolution of the Glenleg–Attadale Inlier involved post-Grenvillian extension. However, a detailed structural and geochronological study (Storey, 2002) argued for a combined extensional and contractional evolutionary history.

New methods of rigorous geometrical analysis were developed. Ramsay (1957a) analysed superimposed fold patterns in finely interbedded Moine metasediments near Loch Monar (see **Loch Monar** GCR site report, this chapter). The fold patterns are now regarded as type examples of the different geometries that result when two or more phases of folding affect an interbedded rock sequence (Ramsay, 1962, 1967; Ramsay and Huber, 1987).

Other workers attempted to define the Moine Supergroup stratigraphy and link it to the documented succession in the Morar and Glenfinnan areas farther south. Ramsay and Spring (1962) and Tanner *et al.* (1970) defined the Moine succession in the Loch Hourn area. However, later British Geological Survey mapping in Kintail (May *et al.*, 1993) and Glen Affric (Peacock *et al.*, 1992) resulted in definition of distinctive lithological units, but no coherent overall stratigraphy was presented owing to the structural and stratigraphical complexities. Holdsworth *et al.* (1994) presented an overall synthesis of the Moine stratigraphy, including the Moine (Central) region. They noted that local correlation was possible between successions, and formations could be broadly assigned to the Morar, Glenfinnan and Loch Eil groups. However, the presence of the Knoydart and Sgurr Beag thrusts and probable regional lateral facies variations made meaningful regional correlations difficult.

Tanner *et al.* (1970) and Tanner (1971) defined the trace of the Sgurr Beag Thrust in Ross-shire and part of Inverness-shire (see Chapter 8). They recognized that it was a major thrust that controlled the occurrence of Lewisianoid inliers, but was also the site of apparent stratigraphical excision. Rathbone and Harris (1977) documented the strain variations adjacent to the Sgurr Beag Thrust and confirmed that its trace separated Morar Group and Glenfinnan Group rocks. Kelley and Powell (1985) discussed the movement history of the Sgurr Beag Thrust relative to that of the Moine Thrust Belt in the Fannich Mountains (see **Fannich** and **Meall an t-Sithe and Creag Rannich** GCR site reports, this chapter).

Age dating of the original rock units and tectonometamorphic events in the area has served to highlight problems since isotopic techniques were first employed in the 1960s. For instance, with regard to the Caledonian metamorphism and deformation, syn-F3 pegmatites at Loch Monar have been dated by several workers using different methods. A K-Ar muscovite age of 413 ± 15 Ma was obtained by Brown *et al.* (1965), and Rb-Sr muscovite ages gave an average value of 447 ± 6 Ma (van Breemen *et al.*, 1974). The *c.* 450 Ma age is compatible with monazite U-Pb ages of 455 ± 3 Ma from Ardgour Granite Gneiss near Glenfinnan (Aftalion and van Breemen, 1980) and appears to date the main Caledonian metamorphic event in the central part of the North-west Highlands. Although documented Knoydartian-age (750–850 Ma) pegmatite and metamorphic mineral localities all lie outwith the Moine (Central) area, there is little doubt that similar-age pegmatites are also present in this area.

Geological history

As in the Moine (North) area, Lewisianoid gneisses record a complex Archaean and Proterozoic history. A *c.* 2700 Ma granulite-facies metamorphic event has been reported from the orthogneisses of the Scardroy and Glenelg–Attadale inliers (Moorbath and Taylor, 1974; Storey, 2002). However, the age of the metasedimentary elements, such as the meta-limestones, calc-silicate rocks and graphitic and aluminium-rich pelites, remains unclear. The Lewisianoid rocks of the Eastern Unit of the Glenelg–Attadale Inlier were deformed and affected by high-pressure eclogite-facies metamorphism during the Grenvillian Orogeny at around 1050 Ma (Sanders *et al.*, 1984; Storey, 2002), and underwent rapid exhumation at *c.* 995 Ma (Brewer *et al.*, 2003).

The Grenvillian Orogeny was followed by the formation of a large shallow-marine basin in which the Moine sequence was deposited. This succession of sandstone, siltstone and mudstone with local basal conglomerate was deposited after *c.* 950 Ma, based on ages of the youngest detrital zircon, but prior to 875 Ma, when the West Highland Granite Gneiss Suite was intruded farther south (Friend *et al.*, 1997, 2003).

By analogy with Moine rocks to the north and south, these elements were deformed and metamorphosed during Knoydartian events, possibly at *c.* 820–780 Ma and/or around 740 Ma. It is still unclear whether these events related to overall compressional or extensional tectonic movements, and within the Moine (Central) area only limited evidence for such events has been found.

Isotopic ages from Moine rocks to the south suggest that Caledonian orogenic events, marked by penetrative folding, dominantly WNW-directed thrusting and amphibolite-facies metamorphism, peaked at around 455 Ma. The Glendessarry Syenite, whose intrusion was dated by U-Pb bulk zircon methods at *c.* 456 Ma (van Breemen *et al.*, 1979b), was emplaced around the time of peak metamorphism. It is unclear whether the main penetrative (D2) fabric and related folds and shear zones were formed during an early Caledonian event, or whether they are a product of an earlier, Neoproterozoic event. It is possible that the Glen Urquhart serpentinite was also intruded at this time, but its age of emplacement relative to the deformation sequence remains unknown. The generation of mylonites close to the western edge of the orogen and the thrusting in the Moine Thrust Belt is mainly of Scandian age, between 435 Ma and 400 Ma (Kelley, 1988; Freeman *et al.*, 1998).

In the later stages of the Caledonian Orogeny the Cluanie and Ratagain plutons were emplaced at *c.* 425 Ma (Rogers and Dunning, 1991). Suites of Late Caledonian minor intrusions were also widely developed during the Late Silurian to Early Devonian; these include pegmatitic granites (notably common in Kintail), micro-diorite sheets and dykes, lamprophyres and the late-stage Glen Garry Vein-Complex.

Sinistral transcurrent movements have occurred along the Great Glen and Strathconon faults in Silurian and Devonian times, post-dating the Late Caledonian minor intrusions. Since Late Devonian times the Moine (Central) area has been an area of erosion. The roughly E-trending Killilan–Monar swarm of camptonite and monchiquite dykes was intruded during the Late Carboniferous. Palaeocene NW-trending basalt dykes belonging to the Skye swarm are abundant on the Sleat peninsula but only a few occur on the mainland in the Moine (Central) area.

Main lithologies

Lewisianoid gneiss inliers

The Lewisianoid gneiss inliers of the Moine (Central) area occur in two structurally different situations (Figure 7.1). Above and east of the Moine Thrust, and separated from it by a thin unit of Moine psammites, is the large Glenelg–Attadale Inlier, stretching from the Sleat peninsula on Skye north-east to Loch Carron. It is separated into a Western Unit and an Eastern Unit, which show very different lithologies and geological evolution. The Ross-shire Lewisianoid inliers lie farther east at higher structural levels commonly above the Sgurr Beag Thrust at the Morar Group–Glenfinnan Group boundary. They represent basement to the overlying Moine metasedimentary sequence, at least locally. The most prominent are Scardroy, Monar, Strathfarrar, Orrin and Fannich. In Kintail, and farther north in Ross-shire, Lewisianoid lenses are found within Morar Group psammites, whereas in Fannich, Lewisianoid rocks are interleaved with Glenfinnan Group pelites (Clifford, 1957; Kelley, 1988; May *et al.*, 1993).

The Glenelg–Attadale Inlier

The Glenelg–Attadale Inlier is the best exposed and most studied of the Lewisianoid inliers in the Moine succession and this is reflected in the number of GCR sites (9 sites – Figure 7.2). This basement inlier extends for some 30 km along the western margin of the Caledonian Orogen in the Glenelg, Kintail and Lochalsh areas, and for a farther 20 km in Sleat on Skye. At its southern end the Strathconon Fault displaces the inlier sinistrally, and its continuation is found again around Arnisdale. On the mainland, a mylonite zone containing highly deformed Moine and Lewisianoid rocks transects the inlier, dividing it into two distinctly different parts, termed the 'Western Unit' and the 'Eastern Unit' (Figure 7.2). The Western Unit shows affinities with the foreland Lewisian Gneiss Complex but the Eastern Unit shows distinctly different lithologies and isotopic signatures. The Glenelg–Attadale Inlier is unique in terms of its rock types, structural history and position in the orogen.

The Western Unit consists predominantly of layered granodioritic and tonalitic gneisses that are locally migmatitic, and are similar to the Lewisian gneisses of the Foreland. Abundant layers and pods of amphibolite or metadolerite ('Older basic rocks') occur roughly parallel to the layering of the adjacent acid gneiss. In some low-strain zones in the central part of the Western Unit, cross-cutting relationships are preserved, suggesting intrusion after the event that produced the first gneissic layering (Barber and May, 1976; May *et al.*, 1993; Storey, 2002). Minor pods and lenses of anorthosite, and ultrabasic rocks, now mainly serpentinite, are also present. Layers of pink homogeneous granitic gneiss are devoid of basic material and were presumably intruded after the metadolerites.

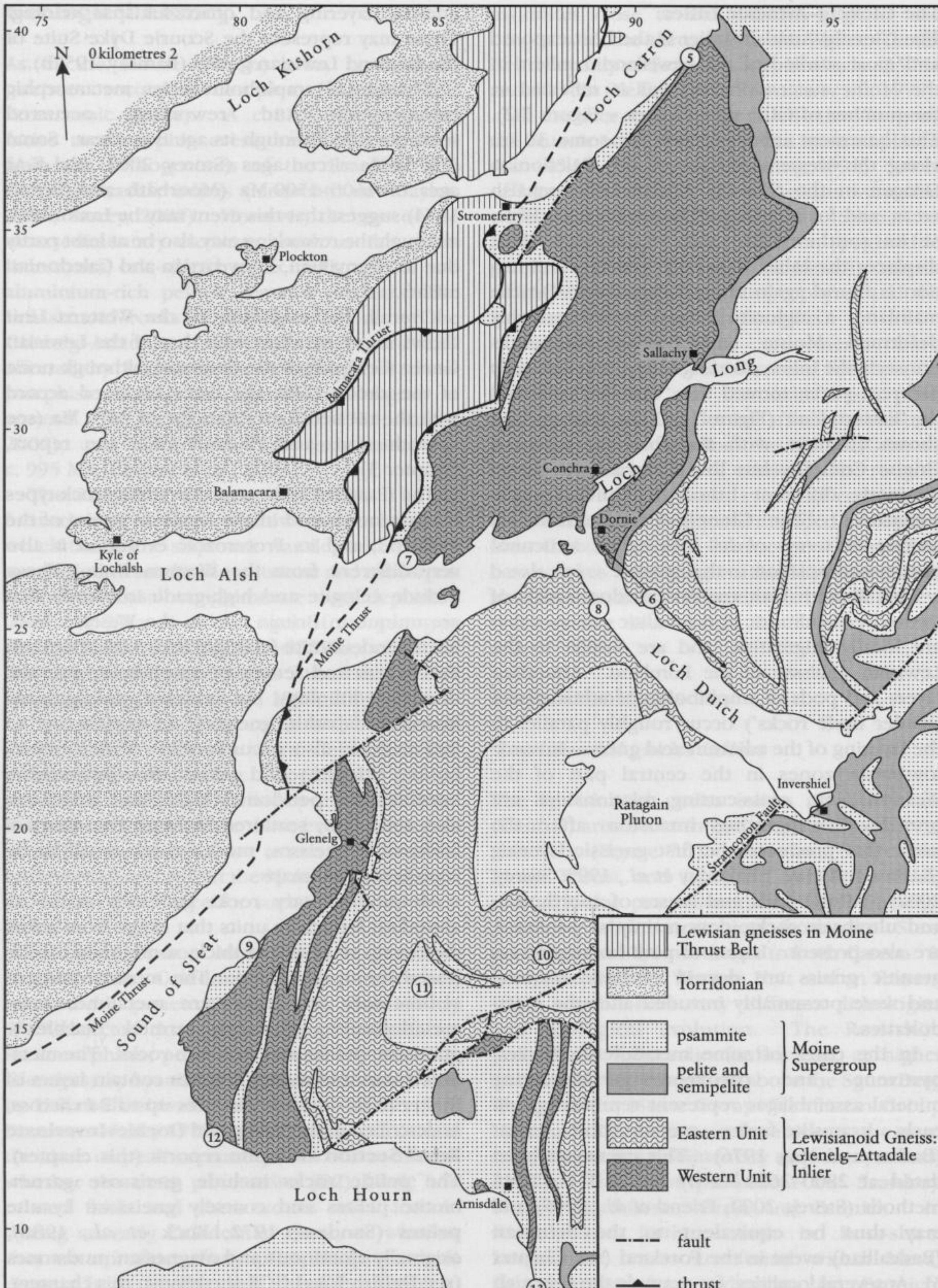
In the cores of some metadolerite bodies, pyroxene- and pyroxene + garnet-bearing mineral assemblages represent remnants of an early granulite-facies metamorphic event (Barber and May, 1976). This event has been dated at 2800–2600 Ma by zircon U-Pb TIMS methods (Storey, 2002; Friend *et al.*, 2008) and may thus be equivalent to the Scourian (Badcallian) event in the Foreland (see Chapter 3). At several localities, for example the **Avernish** and **Eilean Chlamail–Camas nan Ceann** GCR sites, amphibolite dykes, originally basalt or dolerite ('Newer basic rocks'), cut the earlier gneissic layering and quartz-feldspar veining. These may represent the Scourie Dyke Suite of the foreland Lewisian gneiss (Ramsay, 1957b).

Widespread amphibolite-facies metamorphic retrogression and reworking occurred subsequently, although its age is unclear. Some *c.* 1750 Ma zircon ages (Storey, 2002) and K-Ar ages of 1600–1500 Ma (Moorbath and Taylor, 1974) suggest that this event may be Laxfordian, although the reworking may also be at least partly due to Grenvillian, Knoydartian and Caledonian events.

Overall, the evolution of the Western Unit shows many parallels with that of the Lewisian Gneiss Complex of the Foreland, although none of the zircon U-Pb age dates obtained accord with the revised Badcallian age of 2470 Ma (see 'Introduction' and **Badcall** GCR site report, Chapter 3).

The Eastern Unit contains many rock-types that are not found in the Lewisian gneiss of the Foreland, and its Proterozoic evolution is also very different from the Western Unit. These include eclogite and high-grade ironstone that are unique in Britain. As in the Western Unit, hornblende-biotite-felsic gneisses with abundant thin layers and lenses of amphibolite are the dominant lithology, but uniform pink, granitic quartzofeldspathic gneisses, in bodies up to 200 m thick, also occur locally. Mafic (amphibolite, eclogite) and ultramafic (pyroxenite, hornblendite, peridotite) layers and lenses are also abundant, scattered through the quartzofeldspathic gneisses; most are too small to be represented on maps.

Metasedimentary rocks generally occur as abundant lenticular units that range from a few metres up to *c.* 450 m thick; some units can be traced for up to 20 km. The most prominent sedimentary lithologies are metalimestones/metadolomites (formerly termed 'marbles'), gneissose pelites and iron-rich rocks. The metalimestones and metadolomites contain layers of forsterite or diopside nodules up to 2 m across, as described in the **Totaig** and **Dornie–Inverinate Road Section** GCR site reports (this chapter). The pelitic rocks include gneissose garnet-biotite pelites and coarsely gneissose kyanite pelites (Sanders, 1972; Rock *et al.*, 1986), originally aluminous and magnesian mudstones (see **Druim Iosal** GCR site report, this chapter). More highly iron-rich mudstones or clays are represented by the rare garnet-magnetite eulysites, which contain iron-rich olivine (fayalite)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N
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Lochalsh
Loch Alsh
Moine Thrust
Loch Duich
Inversheil
Ratagain
Pluton
Strathconon Fault
Glenelg
Sound of Sleat
Moine Thrust
Loch Hourn
Arnisdale
Lewisian gneisses in Moine Thrust Belt
Torridonian
psammite
pelite and semipelite
Moine Supergroup
Eastern Unit
Western Unit
Lewisianoid Gneiss: Glenelg–Attadale Inlier
fault
thrust

◄**Figure7.2** Geological sketch map of the Glenelg–Attadale Inlier and surrounding area (after Barber and May, 1976), showing the location of the GCR sites within or marginal to the Glenelg–Attadale Inlier. 5 – **Attadale**; 6 – **Dornie–Inverinate Road Section**; 7 – **Avernish**; 8 – **Totaig**; 9 – **Allt Cracaig Coast**; 10 – **Druim Iosal**; 11 – **Beinn a' Chapuill**; 12 – **Eilean Chlamail–Camas nan Ceann**; 13 – **Rubha Camas na Cailinn**.

and iron-rich pyroxenes. They are seen around Totaig (Tilley, 1936) and in several other places (Barber, 1968; Sanders, 1972).

The Lewisianoid gneisses of the Eastern Unit are also host to pods of eclogite, a meta-igneous rock composed essentially of coarse green sodium-rich pyroxene (omphacite) and red pyrope garnet. The Glenelg eclogites are the only such rocks in Britain. High-pressure assemblages preserved in metacarbonate rocks, gneissose pelites, and in the eulysites (Sanders, 1972) probably also relate to the eclogite-facies metamorphic event. Eclogite pods occur widely and range in size from a few metres to *c*. 200 m across. Most of the rocks show evidence of pervasive retrogression, but eclogite-facies textures are retained in places, notably in the mafic lithologies. The metamorphic mineralogy enables peak pressure estimates of 16–20 kbar and temperature estimates of between 700° C and 750° C to be inferred (Sanders, 1972; Storey *et al*., 2005). This high-pressure metamorphism attests to burial of these rocks to some 50 km depth, followed by rapid exhumation. Sanders *et al*. (1984) obtained Sm-Nd ages of 1082 ± 24 Ma and 1010 ± 13 Ma from eclogite. These were interpreted as dating closure of the garnet-omphacite isotopic Sm-Nd system and hence uplift of the eclogite. Zircon and monazite U-Pb TIMS dates (Storey, 2002; Brewer *et al*., 2003) have confirmed this age of eclogite formation by dating the amphibolite-facies retrogression at *c*. 1000 Ma. Thus, Glenelg is one of the few places in the British Isles where evidence of Grenvillian metamorphism and deformation has been preserved. Eclogite-facies rocks of similar ages have also been found in the Grenville Province in Canada (Indares and Dunning, 1997) and in the Sveconorwegian Province in Sweden (Möller, 1998); the Glenelg–Attadale Inlier thus provides an apparent link between Laurentia and Baltica in Grenvillian times.

Ultramafic rocks generally occur as pods of serpentinized and altered peridotite up to tens of metres across. The best example is found in Sleat, where a 2 km-long serpentinized peridotite apparently cross-cuts the Lewisianoid gneiss layering and earlier folded amphibolites (Peach *et al*., 1910). In places where strong Caledonian deformation and greenschist-facies metamorphism are dominant, the ultramafic rocks are altered to talc, magnesite, chlorite, tremolite-bearing rocks (see **Ard Ghunel** GCR site report, this chapter).

Storey (2002) used zircon U-Pb TIMS data to show that the Western and Eastern units of the Glenelg–Attadale Inlier experienced different metamorphic histories prior to the Grenvillian event (*c*. 1000 Ma). For instance, complex zoned zircons from the gneisses of the Western Unit show evidence of a granulite-facies event at *c*. 2700 Ma and amphibolite-facies reworking at *c*. 1700 Ma, whereas the Eastern Unit shows evidence of reworking at *c*. 1450 Ma. Both parts of the inlier were affected locally by Grenvillian deformation and metamorphism, although only the Eastern Unit shows evidence of the high-pressure eclogite-facies metamorphism. The Eastern and Western units are separated by a zone of intense shearing, and mylonitization is assigned to the regional D2 event (see below). This amphibolite-facies mylonite zone comprises both Moine rocks and adjacent gneisses. Storey *et al*. (2004) inferred that this shear zone originated as a Grenvillian shear-zone, potentially facilitating the rapid uprise of the eclogite-facies Eastern Unit and juxtaposing it against or close to the Western Unit. However, later movement must have occurred to account for the shearing and mylonitization of the post-Grenvillian-age Moine psammites. U-Pb titanite dating from this zone (Storey *et al*., 2004) suggested that the reworking was possibly Knoydartian, but Caledonian reworking has also probably occurred.

Lewisianoid inliers of Ross-shire and other areas

The remaining Lewisianoid gneiss inliers of the Moine (Central) area lithologically resemble those found in the Moine (North) area. The large central Ross-shire inliers of Strathfarrar, Monar, Orrin and Scardroy, and the Coire nan Gall Inlier (Figure 7.1) all occur in the hanging-wall of the Sgurr Beag Thrust and are overlain by Glenfinnan Group rocks. The Lewisianoid gneisses of the Fannich Inlier lie within the basal Glenfinnan Group pelitic unit. The gneisses in these allochthonous lenticular basement sheets consist of granodioritic and tonalitic orthogneisses with abundant amphibolitic mafic bodies. Smaller lenses of ultrabasic rocks, and thin lenticular bands of metalimestones, calc-silicate rocks, and graphitic pelites are present locally. Deformed quartz-feldspar pegmatites are common. The inliers are variably deformed by Caledonian and probably earlier Knoydartian deformation, but the thicker Scardroy and Strathfarrar inliers do contain areas of relatively unmodified Lewisianoid gneisses. These contain middle amphibolite-facies assemblages with diopside-bearing calc-silicate rocks and brown hornblende in the amphibolite bodies (Sutton and Watson, 1953). In the smaller inliers and near the margins of the large inliers the Lewisianoid gneisses have been strongly reworked by Knoydartian and/or Caledonian deformation and pervasively metamorphosed under lower- to middle-amphibolite-facies conditions (Winchester, 1974).

Lewisianoid–Moine relationships

The relationships between the basement Lewisianoid gneiss and the Moine succession can be divided into three broad categories; unconformity, thrust slices, and infolds. Generally, the Lewisianoid–Moine boundaries have acted as a locus for faulting, shearing and fluid flow with associated metamorphism and metasomatism. As a result, many of these boundary zones are extremely complex, and in numerous areas even differentiation of the protoliths as Lewisianoid or Moine is problematic.

Moine psammites occur both structurally above and below the Glenelg–Attadale Inlier, with their contacts generally concordant to layering and foliation in both Moine and Lewisianoid rocks. However, along both the eastern and western contacts discordances and metaconglomerates have been recorded locally as described in the **Attadale** and **Allt Cracaig Coast** GCR site reports (this chapter) (Clough in Peach *et al.*, 1910; Ramsay, 1957b, 1963a,b). In addition, the Lewisianoid gneisses contain intrusions that are absent in the Moine succession. Hence, the Moine metasediments were deposited unconformably on a gneissose, crystalline Lewisianoid basement, which shows compelling evidence of an earlier complex tectonometamorphic history.

The Sgurr Beag Thrust is probably the best example of a tectonic contact between Lewisianoid and Moine rocks. This gently E-dipping, ductile shear-zone juxtaposes Glenfinnan Group Moine rocks over Morar Group rocks (see below). Along the length of the thrust, numerous Lewisianoid inliers lie directly in its hangingwall or within the thrust zone. Moine psammites also occur as thin highly deformed slivers within the Glenelg–Attadale Inlier either as attenuated thrust slices or tight infolds (e.g. Ramsay, 1957b). The best example of a Moine thrust slice is the shear zone that separates the Western and Eastern units of this inlier (see above). Lewisianoid inliers are also interleaved by thrusting with Morar Group rocks in upper Glen Strathfarrar (Monar Forest) and smaller-scale Lewisianoid–Moine imbrication has been documented in Kintail (May *et al.*, 1993).

Complex, large- and small-scale, close to tight interfolding of basement and cover are well seen along the eastern and southern margins of the Glenelg–Attadale Inlier; examples are described in the **Beinn a' Chapuill** and **Rubha Camas na Cailinn** GCR site reports (this chapter).

Moine Supergroup

The sediments that comprise the Moine Supergroup were deposited in a shallow-marine basin between about 950 Ma and 875 Ma (see 'Introduction', Chapter 6 and 'Introduction', Chapter 8 for details). The stratigraphy in the Moine (Central) area is less clearly defined than in the areas to the north and south, but the tripartite division into Morar (lowest), Glenfinnan, and Loch Eil (highest) groups can be applied generally (Figure 7.3). Resolution into formations and their lateral and vertical relationships is more problematic because of the structural complexity and the occurrence of major thrusts that disrupt the original stratigraphical template. The Geological Survey memoirs that describe Kintail (May *et al.*, 1993), Glen Affric (Peacock *et al.*, 1992) and Invermoriston (May and Highton, 1997) present local sequences, but do not define a coherent stratigraphy. The stratigraphical synthesis of Holdsworth *et al.* (1994) also relies on the patchy coverage and varied dates of mapping. Figure 7.3 shows the updated stratigraphy for the Moine (Central) area compiled from the various available sources.

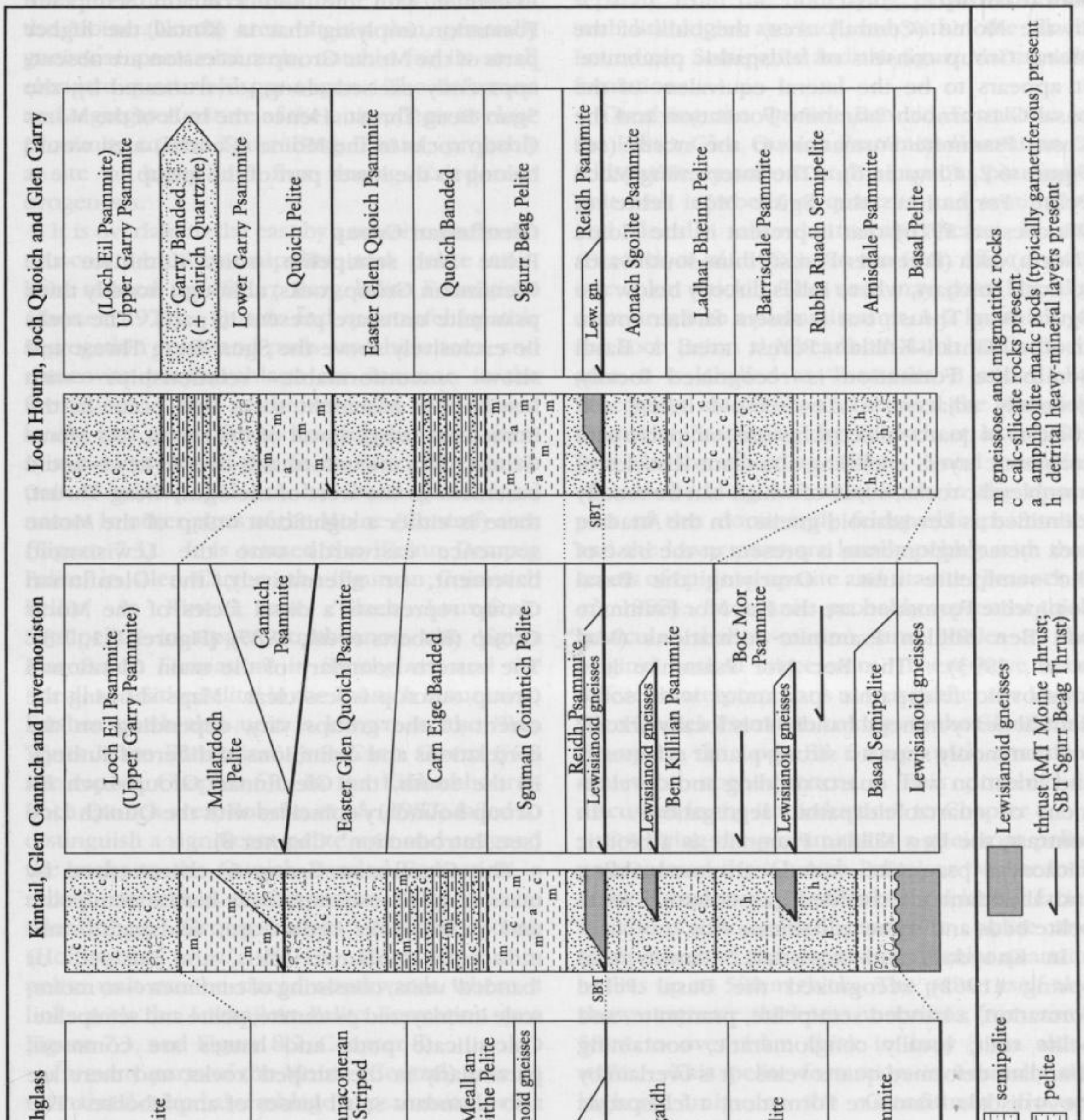


Figure 7.3 Tectonostratigraphy of the Moine succession within the Moine (Central) area.

Morar Group

In the Moine (Central) area, the bulk of the Morar Group consists of feldspathic psammite. It appears to be the lateral equivalent of the basal Glascarnoch Psammite Formation and the Crom Psammite Formation to the north (see Figure 6.2, Chapter 6). The intervening Vaich Pelite Formation (the Sgùrr Mòr Pelite of Winchester, 1976) that is present in the Moine (North) area (Freevater Forest) thins southwards to Loch Luichart, where it lies directly below the Sgurr Beag Thrust, but is absent farther south. In the Kintail–Killilan Forest area, a Basal Semipelite Formation is recognized locally, generally adjacent to Lewisianoid inliers. It consists of quartz-veined schistose semipelite with psammitic layers enclosing abundant lenticles of hornblendic rocks, some of which can be readily identified as Lewisianoid gneiss. In the Attadale area metaconglomerate is present at the base of the semipelite unit. Overlying the Basal Semipelite Formation are the Boc Mor Psammite and Ben Killilan Psammite formations (May *et al*., 1993). The Boc Mor Psammite is a muscovitic feldspathic psammite with some detrital heavy-mineral bands. It is locally arkosic but commonly shows a strong planar schistosity and lineation with quartz rodding and development of quartzofeldspathic segregations. In contrast, the Ben Killilan Psammite is a biotitic micaceous psammite, with local cross-bedding and abundant interbedded garnetiferous semipelite beds and some calc-silicate ribs.

In Knoydart and Arnisdale, Ramsay and Spring (1962) recognized the Basal Pelite Formation, a banded semipelite, psammite, and pelite unit, locally conglomeratic, containing abundant deformed quartz veins. It is overlain by the Arnisdale Psammite Formation, a feldspathic psammite unit containing epidotic magnetite-ilmenite heavy-mineral bands, which passes transitionally upwards into the Rubha Ruadh Semipelite Formation, an interlayered sequence of semipelites, pelites and psammites. The overlying Barrisdale Psammite Formation shows abundant cross-bedding. The succeeding Ladhar Bheinn Pelite Formation and Aonach Sgoilte Psammite Formation only crop out in Knoydart and farther south. The Ladhar Bheinn Pelite Formation consists of schistose pelite and semipelite, with abundant calc-silicate ribs in its central and upper part. It correlates with the Morar Pelite Formation in the Moine (South) area. May *et al*. (1993) correlate the Ben Killilan Psammite with the Rubha Ruadh Semipelite Formation implying that in Kintail the higher parts of the Morar Group succession are absent; apparently excised along, or truncated by, the Sgurr Beag Thrust. Hence, the bulk of the Morar Group rocks in the Moine (Central) area would belong to the lower part of the group.

Glenfinnan Group

Pelite and semipelite units dominate the Glenfinnan Group rocks, although notably thick psammite units are present in parts. The rocks lie exclusively above the Sgurr Beag Thrust and show unconformable relationships with Lewisianoid basement slices that occur in the immediate hangingwall of the thrust. As Morar Group rocks unconformably overlie Lewisianoid basement to the west of the Sgurr Beag Thrust, there is either a significant onlap of the Moine sequence eastwards onto the Lewisianoid basement, or alternatively, the Glenfinnan Group represents a distal facies of the Morar Group (Roberts *et al*., 1987) (Figures 7.1, 7.3). The eastern boundary of the main Glenfinnan Group outcrop is less clear. Maps showing the extent of the groups vary, depending on the correlations and definitions of different authors. In the south, the Glenfinnan Group–Loch Eil Group boundary coincides with the Quoich Line (see 'Introduction', Chapter 8).

The Glenfinnan Group is characterized by massive gneissose muscovite-biotite semipelite and pelite units, quartzose, feldspathic and micaceous psammite units, and 'striped' or 'banded' units, consisting of centimetre- to metre-scale interlayered psammite, pelite and semipelite. Calc-silicate pods and lenses are common, particularly in the 'striped' rocks, and there are also abundant small lenses of amphibolite. The semipelitic units are normally garnetiferous with abundant quartz-feldspar segregations and veins. The psammites commonly show excellent examples of cross-bedding and, more rarely, convolute bedding (see **Abhainn Gleann nam Fiadh** GCR site report, this chapter). Rarely pebbly lenses are present.

The lowest exposed formation in the Glenfinnan Group is the Reidh Psammite Formation, which occurs between Kinloch Hourn and the Strathconon Fault (Tanner, 1971), and in the Coire Nan Gall structural outlier (May *et al*., 1993) (Figures 7.1, 7.3). It is absent in central Ross-shire, but present again farther north around Loch Luichart where it links to the Garve Psammite Formation of the Moine (North) area. It is a thin, generally gneissose psammite unit, notable for its small elongate quartz-feldspar augen. The deformed and segregated nature of the unit reflects its close proximity to the Sgurr Beag Thrust, probably a site of high fluid flux during Caledonian orogenesis.

It is overlain to the east by a massive gneissose muscovite-biotite-semipelite and pelite unit, here termed the 'Sgurr Beag Pelite Formation' (Tanner, 1971). Quartz and quartzofeldspathic segregation veins and pods are ubiquitous, and muscovite porphyroblasts are common in the formation. Thin psammite units, calc-silicate lenses and garnetiferous amphibolite pods form minor elements of the formation. The pelite unit is widespread but has been given local names in other parts of the Moine (Central) area (Figure 7.3). It is termed the 'Beinn Dronaig Pelite' in Glen Carron, the 'Sguman Coinntich Pelite' in Kintail, the 'Clach Loundrain Semipelite' in upper Strathconon, the 'Sgurr Marcasaidh Formation' in Strathglass, and the 'Meall an t-Sithe Pelite' in the Fannich Mountains. Farther north this unit is known as the 'Ben Wyvis Pelite Formation' (see **Carn Gorm** GCR site report, Chapter 6). In the Kinlochhourn–Loch Quoich area, Roberts *et al.* (1987) failed to distinguish a significant pelite unit and assigned the rocks to the Quoich Banded Formation, a mixed unit that encompasses much of the Glenfinnan Group rocks farther south (Holdsworth *et al.*, 1994). However, a thin pelite unit can be traced southwards where it links with the Lochailort Pelite Formation (see Figure 7.3, and Figure 8.2, Chapter 8).

In many parts of the Moine (Central) area an un-named mixed assemblage of psammite, pelite and semipelite overlies the semipelite–pelite unit (May *et al.*, 1993). These lithologically diverse Glenfinnan Group rocks are structurally and stratigraphically complex. In the Glen Affric–Glen Cannich area a Carn Eige Banded Formation is recognized that lies in an approximately equivalent position to the Quoich Banded Formation. However, it is bounded by a slide on its eastern side, and its stratigraphical position can be variously interpreted as either high or low in the Glenfinnan Group succession (e.g. see Holdsworth *et al.*, 1994). To the north in Ross-shire (Glen Strathfarrar to Strathconon) the more-mixed Glenfinnan Group psammite, semi-pelite and pelite lithologies are difficult to separate from the underlying pelite unit, and such lithologies are included within the Clach Loundrain Semipelite and the Sgurr Marcasaidh formations.

Overlying the Quoich Banded Formation is the Easter Glen Quoich Psammite Formation, a feldspathic, quartzose and micaceous psammite unit with interbeds of quartzite and semipelite and locally abundant calc-silicate lenses (Peacock *et al.*, 1992). In the Glen Affric area it is *c.* 1 km thick. The unit may pass laterally eastwards into a psammite unit, 1–2 km thick, in the Loch Beinn a' Mheadhoin–Loch Mullardoch area; it is labelled as 'Psammite B and C' by Peacock *et al.* (1992) and termed the 'Cannich Psammite Formation' by Tobisch *et al.* (1970) (see Holdsworth *et al.*, 1994). Good examples of cross-bedding are ubiquitous in the upper part of this dominantly feldspathic psammite, and the lower parts are locally pebbly with thin seams of epidote, apatite and titanite (Peacock *et al.*, 1992). Such units probably represent thick lenticular shallow-marine sand bodies in the original basinal succession. There have been different interpretations as to whether the Easter Glen Quoich Psammite belongs to the Glenfinnan Group or the Loch Eil Group, with attendant structural consequences. This problem is discussed in the 'Introduction' to Chapter 8.

Overlying the psammites is a gneissose pelite unit, termed the 'Quoich Pelite' or 'Mullardoch Pelite Formation'. It exhibits local lateral facies variations into mixed psammite, pelite and semipelite, and encompasses lenticular quartzite bodies up to 500 m thick. The pelite itself also shows extreme thickness variations from some 50 m to over 1 km thick in only 3 km along strike. This pelite formation is normally the highest unit in the Glenfinnan Group. Transitional lithologies into the overlying Loch Eil Group succession occur around Loch Cluanie (Peacock *et al.*, 1992) and farther south (see 'Introduction', Chapter 8).

The Achnaconeran Striped Formation is a thick (> 3 km) rhythmically interlayered psammite and semipelite unit that crops out east of the main Loch Eil Group psammite outcrop over a wide swathe from north of the River Glass south through to beyond Invermoriston. Minor calc-silicate lenses occur in its northern part where it is known as the 'Drumonreoch Striped Formation'. It is attributed to the Glenfinnan Group on lithological and structural grounds. May and Highton (1997) show that the

Achnaconeran Striped Formation has a transitional contact with the overlying Loch Eil Group (Upper Garry Psammite Formation) but also postulate lateral facies variation.

Loch Eil Group

The predominantly psammitic Loch Eil Group rocks overlie the Glenfinnan Group with general conformity; contacts are normally rapid transitions from the uppermost Glenfinnan Group pelitic units to feldspathic psammites. Typically, a single psammite unit represents the group in the Moine (Central) area. This is termed the 'Loch Eil Psammite Formation' or the 'Upper Garry Psammite Formation' in the south (Roberts and Harris, 1983), and the 'Cluanie Psammite Formation' or 'Tarvie Psammite Formation' farther north (Figure 7.3). It consists of fine- to medium-grained feldspathic and micaceous psammite with semipelite and quartzose psammite units and abundant calc-silicate lenses. Cross-bedding is locally abundant and ripple-drift lamination is seen in places. Semipelitic units can be distinguished in the upper parts of the succession around Loch ma Stac (NH 34 22) and east and north of Loch a' Chràthaich (NH 36 21). Loch Eil Group rocks lie in a broad asymmetrical syncline with regional dips of 20°–60° on its western limb and up to 85° on its eastern limb (May and Highton, 1997). The rocks are generally less deformed than the Glenfinnan Group rocks to the west and east. In their northern outcrop the Achnaconeran Striped Formation bounds the Loch Eil Group rocks to the east. However, at the south-west end of Loch Ness the Great Glen Fault truncates the Loch Eil Group rocks to the south-east, but farther south-west the West Highland Granite Gneiss Suite intervenes.

Igneous rocks

Neoproterozoic metadolerite

Throughout the Moine (Central) area mafic dykes or sheets are locally common. They were originally mainly dolerite sills or dykes, intruded prior to any deformation and metamorphism, but now form amphibolite bodies from a few centimetres up to 20 m thick. Rarely small metagabbro bodies are present. Particular concentrations occur in the transition zone between the Glenfinnan and Loch Eil groups. The amphibolites contain hornblende, plagioclase, quartz and a range of accessory minerals (Peacock *et al.*, 1992; May and Highton, 1997). More-detailed descriptions are found in the **Comrie** (Chapter 6) and **Glen Doe** (Chapter 8) GCR site reports.

Caledonian igneous rocks

Major Caledonian intrusions within the Moine (Central) area are limited to the Cluanie Granodiorite Pluton, the Ratagain Dioritic-syenitic Pluton and the smaller Glen Orrin and Abriachan intrusions. Emplacement of the Cluanie and Ratagain plutons has been dated around 425 Ma (Brook in Powell, 1983; Rogers and Dunning, 1991), coeval with the Strontian Pluton. All belong to the Argyll and Northern Highlands Suite, which is described in GCR Volume 17 (Highton, 1999).

There are numerous swarms of Late Caledonian dykes and sheets in the Moine (Central) area, ranging from quartz-feldspar pegmatites, lamprophyres, microgranodiorites and microgranite ('felsite'), to microdiorites, appinitic diorites, and sodic metasomatite pods. These minor intrusions range in age from Ordovician to Silurian for the Caledonian swarms, to the younger Permo–Carboniferous camptonite and Palaeocene basalt/dolerite dyke-swarms. The Late Caledonian intrusions provide a record of the waning phases of the Caledonian Orogeny and bracket the timing of uplift and faulting. The most widespread and abundant rock-types relate to the Late Silurian calc-alkaline plutonic granitic bodies of the Argyll and Northern Highlands Suite. The swarms extend into the Moine (South) area and are listed in Table 7.1. Only brief comments are appended below.

Swarms of granitic intrusions and quartz-feldspar pegmatites are common and normally lie sub-parallel to the host layering and foliation and are variably foliated. Locally they show folding, necking and boudinage. Where deformed they are thought to be Ordovician in age if the deformation is ductile. They are pre- or syn-F3 (Kelley, 1988 – see also **Meall an t-Sithe and Creag Rainich** GCR site report, this chapter). As the intrusions are cross-cut by undeformed Late Silurian to Early Devonian major and minor intrusions, they appear to relate to the later stages of the Grampian Event. However, they appear to have been emplaced under amphibolite- to greenschist-facies metamorphic conditions.

Intrusions of the Microdiorite Sub-suite are wide ranging in the Cluanie and Glen Moriston area and farther south (see Figure 8.4, Chapter 8). Locally they exhibit metamorphic mineralogies characteristic of greenschist- and even lower-amphibolite-facies. They cross-cut the Cluanie Pluton, but are locally sheared and carry a strong marginal, or at times penetrative, schistosity or foliation. May and Highton (1997) recognized an earlier foliated and later non-foliated swarm of microdiorites, but showed that their geochemistry is similar. The porphyritic microgranodiorites (formerly 'Felsic Porphyrites') show a similar pattern but are restricted to a central 7–20 km-wide zone that stretches south-west from the Cluanie Pluton (Figure 8.4, Chapter 8; Johnstone and Mykura, 1989).

In contrast to the microdiorites, the Lamprophyre Sub-suite (formerly 'Minette Suite') is generally widely distributed, but only form a major swarm in the Glenelg district and east from the Ratagain Pluton (Loch Duich). They are mainly pyroxene-minettes but also include vogesites in which hornblende is the dominant ferromagnesian mineral. The lamprophyres are an important marker in the structural sequence. The main swarm cross-cuts the Ratagain Pluton, and individual dykes intrude indurated breccias and cataclasites linked to early movements on the Strathconon Fault. However, the swarm itself is displaced some 6 km sinistrally across this fault (Smith, 1979). They also occur in various parts of the foreland.

The Appinite Suite has affinities with the microdiorites but the main concentrations of intrusions do not particularly accord with the microdiorites and they are texturally distinct. Fowler and Henney (1996) suggested the intrusions are representatives of a primary shoshonitic magma of mantle derivation that links closely to the calc-alkaline plutonic intrusions. In places appinites cluster near major faults, and they are locally associated with breccia pipes, for example in Glen Garry (May and Highton, 1997).

Structure, metamorphism and Neoproterozoic and Caledonian orogenic evolution

The Lewisianoid and Moine rocks of the Moine (Central) area pose a number of structural problems. It is unclear as to the number, age and relative importance of orogenic events that have affected the Moine succession. The Glenelg–Attadale Inlier provides evidence of Grenvillian orogenic activity that is unique on the Scottish mainland (see 'The Glenelg–Attadale Inlier', this chapter), but its wider context is unclear. Lewisianoid gneiss inliers commonly show sheared margins and were strongly reworked by the orogenic events that also deformed the Moine succession. However, in their central parts the inliers often preserve evidence of complex sequences of intrusion and earlier high-grade metamorphic events, implying the rocks have undergone an extended tectonometamorphic history prior to deposition of the Moine succession at *c.* 950 Ma.

The overall structural succession in the Moine (Central) area can be divided into two major thrust nappes, the Moine and Sgurr Beag nappes, with a third intervening nappe, the Knoydart Nappe, occurring farther south (Kelley and Powell, 1985; Barr *et al.*, 1986; Johnstone and Mykura, 1989). The Moine Nappe is underlain by the Moine Thrust, a mainly Scandian (Silurian age) thrust structure (see Chapter 5). However, the Grampian (Ordovician) and possibly Knoydartian (Neoproterozoic) events recorded within Moine rocks must also relate to orogenic fronts. These fronts must lie either beneath the present Moine outcrop, or be coincident with the Scandian Front; at present their position is not known.

Structural sequence in the Moine succession

In much of the Moine succession in this central area, three main penetrative deformational and metamorphic events can be readily distinguished (see Table 7.2). In that respect there is a similarity to the Moine (North) area, but it is unclear whether the deformation phases are direct correlatives. In north Sutherland, west of the Naver Thrust Zone, Sm-Nd ages on metamorphic garnet and hornblende suggest that the earliest fabric-forming event (D1) occurred around 800–830 Ma (Strachan *et al.*, 2002b), but Ar-Ar and Rb-Sr mica and hornblende dating implies that the main fabrics (? 'D2') formed during the Scandian Event (Dallmeyer *et al.*, 2001). East of the Naver Thrust Zone U-Pb zircon age dating suggests that the main 'D2' fabrics and mineralogy result from the Grampian Event (see Chapter 6). In contrast, in the Moine (South) area, available geochronological evidence suggests the main 'D2' deformation

Table 7.1 Caledonian and later minor intrusions – Moine (Central) and Moine (South) areas. *Continued opposite.*

Name of swarm/ sub-suite/suite	Age	Area of occurrence	Abundance	Rock types
Quartzose Amphibolite	Upper Ordovician	Near Fort Augustus.	Local	Quartzose amphibolite, tonalite
Glen Moriston Vein-Complex	Upper Ordovician	In Glen Moriston, extending north to Strathglass.	Abundant	Muscovite-biotite granite, aplitic and pegmatitic granite
Loch Eil Granite Vein-Complex	Late Silurian	West end of Loch Eil, Glen Fionnlighe.	Abundant	Granite, including aplitic and pegmatitic granite
Loch Arkaig Granite Vein-Complex	Late Silurian	Centred on Meall Blair north of Loch Arkaig.	Abundant	Granite, including aplitic and pegmatitic granite
Mallie Granite Vein-Complex	Late Silurian	In Glen Mallie, south of Loch Arkaig.	Abundant	Granite, including aplitic and pegmatitic granite. Includes small granodiorite body
porphyritic microgranodiorite ('Felsic Porphyrites')	Late Silurian	Cluanie area, upper Glen Moriston.	Moderately abundant	Porphyritic microgranodiorite
Microdiorite Sub-suite	Late Silurian	Widespread across Moine outcrop south of Glen Moriston to the Sound of Mull. Also present in Ross-shire.	Very abundant, reaching maximum concentration in central zone between Cluanie and Salen	Range from microgranodiorite to melamicrodiorite
Appinite Suite	Late Silurian	Widespread across the Moine outcrop but concentrated in Strontian–Sunart–Moidart area and in Glen Garry. Associated with the Strontian Pluton. Sparse to north of Glen Affric and Glen Shiel.	Abundant within clusters	Mainly coarse-grained hornblende-diorite but range from monzonite to pyroxene- and olivine-bearing hornblende-rich ultramafic rocks
porphyritic microgranodiorite ('Main Felsic Porphyrites')	Late Silurian	From Glen Affric south-west via Cluanie, Loch Arkaig and Loch Shiel down to Loch Aline on the Sound of Mull.	Abundant	Porphyritic microgranodiorite ranging to quartz microdiorites
Banavie Vein-Complex	Late Silurian	Adjacent to the Great Glen south of Loch Lochy. Extends up to 5 km north-west of Great Glen Fault.	Abundant	Granite and subsidiary aplitic granite and quartz feldspar pegmatite veins
Glen Garry Vein-Complex	Late Silurian	From Cluanie south-east to Loch Lochy, centred on Glen Garry.	Abundant	Mostly medium- to coarse-grained granodiorite, but ranging from quartz diorite to monzogranite
microgranite swarm ('felsites')	Early Devonian	Widespread but only abundant in swarm east of Ratagain Pluton.	Not abundant except in Ratagain swarm	Microgranite and microgranodiorite, locally porphyritic
Lamprophyre Sub-suite	Early Devonian	Widespread but concentrated in Ratagain swarm stretching from Loch Hourn north-east through Kintail to Glen Affric and Glen Cannich. Dykes extend west of Moine Thrust on Skye and in Applecross area.	Not abundant except in Ratagain swarm	Pyroxene minette, but some vogesite and rare kersantite
camptonite-monchiquite suite	Permo–Carboniferous	Widespread but concentrated in swarms – Monar, Killilan, Morar, Eil–Arkaig, Ardgour and Iona–Ross of Mull.	Locally abundant	Camptonite and camptonitic basalt mainly, rare monchiquite
Palaeogene dykes, mainly of the Skye, Mull, and Ardnamurchan swarms	Palaeocene to Early Eocene	Widespead on Sleat and west coast south of Loch Nevis.	Locally abundant	Dolerite, basalt

Table 7.1 – *continued*. Caledonian and later minor intrusions – Moine (Central) and Moine (South) areas.

Nature and trend of intrusion	Thickness of intrusion	Deformation	Reference
Elliptical masses, elongated north-east, rarely dykes. Found within Fort Augustus Granite Gneiss.	Bodies up to 1 km long but also as smaller pods. Rare dykes *c*. 3 m thick.	Low.	May and Highton, 1997
Lenticular sheets, veins, mainly concordant. Thicker sheets trend north-east.	From a few cm up to 40 m thick, but typically < 2 m thick.	Foliated, folded, boudined.	May and Highton, 1997
Ramifying network, no preferred orientation.	Seldom > 2 m thick, rarely larger bodies.	Only minor deformation.	Fettes and Macdonald, 1978
Ramifying network, no preferred orientation.	Seldom > 2 m thick, rarely larger bodies.	Only minor deformation.	Fettes and Macdonald, 1978
Ramifying network, no preferred orientation.	Seldom > 2 m thick, rarely larger bodies.	Only minor deformation.	Fettes and Macdonald, 1978
Dykes and sheets, trending approximately east. Some irregular bodies.	Typically *c*. 2 m thick but up to 5 m recorded.	Weakly schistose and recrystallized.	Peacock *et al*., 1992; May and Highton, 1997
Sheets and dykes with chilled margins. Mineral assemblages altered and in part recrystallized under greenschist- or epidote-amphibolite-facies conditions. Some irregular sheets in west coastal area exhibit largely unmodified igneous textures and mineralogies. Most sheets dip moderately south-east, but swarms of NNE- and E–W-trending sheets can be distinguished locally.	Up to 10 m thick but typically *c*. 1 m thick. Variable thickness along length of intrusion.	In parts show flow foliation in chilled zones. Locally cleaved, both in marginal zones and throughout whole intrusion.	Smith, 1979; May and Highton, 1997; Peacock *et al*., 1993; May *et al*., 1992
Small bosses and pods. Also thick sheets.	Bosses typically 20 m to 50 m across. Sheets mainly in range 2 m to 10 m across.	Foliated in part, particularly at margins.	Smith, 1979; May and Highton, 1997
Dykes and sheets, mainly dipping moderately to the south-east and steeply to north-west.	Dykes typically < 1 m thick, sheets commonly around 5 m thick , but up to 15 m.	Oblique internal schistosity common. Recrystallized to greenschist.	Smith, 1979; Peacock *et al*., 1992; May and Highton, 1997
Veins and vein networks. No obvious preferred orientation.	Typically up to 1 m in width but locally thicker.	Not foliated.	Johnstone and Mykura, 1989
Discrete veins, sheets and larger bodies, which show a general north-east alignment.	Veins from a few centimetres up to tens of metres thick. Larger masses up to several hundred metres across.	Not foliated.	Fettes and Macdonald, 1978
Dykes commonly aligned east–west.	1 m to 10 m wide (average 4 m) in Kintail swarm.	Not foliated.	May *et al*., 1992
Dykes with chilled margins. Commonly altered mineralogy.	Range from 0.2 m to 6 m. Average thickness *c*. 3 m.	Not foliated.	Smith, 1979
Dykes with chilled margins. Dykes subvertical. Trend east–west in north and ENE in Ardgour swarm and south-east in Ross of Mull.	Average thickness *c*. 1 m.	Not foliated.	Rock, 1983
Dykes with chilled margins, commonly vesicular.	Commonly 0.3 m to 2 m thick but averages 4.5 m in Morar and can be 10 m or more.	Not foliated.	Speight *et al*., 1982

Table 7.2 Deformation sequences in the Moine (Central) area. Note that structural events do not correlate simply across different areas.

Ramsay, 1960, 1963		**Barber and May, 1976**		**May *et al.*, 1993**		**Tobisch *et al.*, 1970**	
Moine & Lewisianoid rocks: Glenelg–Arnisdale area		**Western unit of Glenelg–Attadale Lewisianoid inlier**		**Moine rocks of Killilan Forest (Sheet 72W, Kintail)**		**Moine rocks:– Glen Affric to Strathconon**	
		$D6_L$	Monoclinal folding.			Affric	Open to close, minor and medium-scale folding. Axial planes swing in strike from east in Glen Strathfarrar to NNE in Glen Affric and are subvertical or dip steeply south.
D4	Conjugate minor folds adjacent to Moine Thrust.	$D5_L$	Minor folding in Thrust Belt and Moine succession.				
		$D4_L$	Mylonitization and ESE-plunging lineation.				
D3	Open to tight major and minor folding. N-trending axial planes. Low plunge. Coaxial crenulations.			$D3_M$	Major folding with SE-plunging axes.	Monar	Open to tight major and minor folding on NE-trending axial planes. Related schistosity and crenulation cleavage. Axial plunge commonly to the south-west but locally variable.
						Orrin	Open to tight, rarely isoclinal, major and minor folding. Local axial-plane schistosity and segregations. Gently to steeply W- and SW-plunging axes and lineation. Confined to upper parts of Glens Cannich, Strathfarrar and Orrin.
			Growth of hornblende porphyroblasts.			Strathfarrar	Tight to isoclinal major folds. Axial planes strike north to north-west and axes dip steeply north and south. Confined to middle part of Glen Strathfarrar.
D2	Tight major and minor folding and penetrative axial-plane schistosity.	$D3_L$	SE-plunging folds and rodding.	$D2_M$	Reclined folding with ESE- to SE-trending mineral lineation and rodding. Major sliding and stacking of thrust sheets. Development of flaggy zones and mylonites in the west. Migmatization of the Boc Mor Psammite and formation of the quartz-biotite rock in some slide zones. Amphibolite-facies metamorphism.	Cannich	Tight to isoclinal major and minor folding. Penetrative axial-planar schistosity trends north-east and dips south-east. Axial plunges tend to be steep but are rather variable in orientation. Moderate south-west plunge is common. Amphibolite-facies metamorphism.
D1	Tight to isoclinal, major and minor folds. Interleaving of Lewisianoid and Moine rocks.	$D2_L$	NE-plunging minor folds and rodding abundant. Moderately SE-dipping axial-plane foliation.				
		$D1_L$	Interbanding of Moine and Lewisian.	$D1_M$	Minor isoclinal folding with axial-plane schistosity and rodding lineation. Amphibolite-facies metamorphism.	Pre-Cannich	Tight to isoclinal minor folding. Bedding-parallel schistosity. Intersection lineation. Amphibolite-facies metamorphism.

may well be Knoydartian (Neoproterozoic). The recognition and dating of at least four separate phases of metamorphism based on detailed garnet studies in the Moine (South) area (Zeh and Millar, 2001 – see below) suggests that the metamorphic evolution of the Moine spanned some 450 million years. However, little direct dating evidence from the tectonic fabrics or metamorphic assemblages is available for the Moine (Central) area. Emery *et al.* (2004) obtained a U-Pb SHRIMP zircon age of 727 ± 6 Ma from kyanite-bearing migmatitic semipelite from the Achnaconeran Striped Formation in Glen Urquhart. They interpreted this age as dating anatexis and hence Neoproterozoic high-grade metamorphism.

Table 7.2 gives the documented structural sequences from different areas in the Moine (Central) area, and shows there is not yet a coherent model for the evolution of the area as a whole. It is unclear how far eastwards the Scandian deformation effects extend into the orogen from the Moine Thrust Belt; it may be only a few kilometres as implied in the **Meall an t-Sithe and Creag Rainich** GCR site report (this chapter). Currently, it is not possible to unravel the structural history of this complex multi-phase orogenic belt by local studies alone.

D1 deformation

This episode is manifest as a bedding-parallel cleavage or schistosity in the Moine succession. Tight to isoclinal minor F1 folds can only be confirmed where they occur in F2 fold hinges. D1 is also deemed responsible for interleaving of Lewisianoid basement and Moine cover rocks in the Glenelg–Attadale Inlier, as described in the **Rubha Camas na Cailinn** and **Beinn a' Chapuill** GCR site reports (this chapter) (Ramsay, 1957b; May *et al.*, 1993). Ramsay's (1957b) mapping showed that F1 folds dominate in the Glenelg–Attadale Inlier and record an early deformation and folding event that appears to be lacking farther east. In other areas, D1 does not seem to have resulted in major folding, but may have resulted in movement along some of the main slides in the succession. The accompanying metamorphic conditions are also difficult to ascertain. Tobisch *et al.* (1970) noted quartzofeldspathic segregations and a rodding lineation and mica schistosity that they attributed to D1, and inferred that amphibolite-facies metamorphism accompanied the event. Although D1 duplicates the succession in the Glenelg–Attadale area, it is unclear as to whether D1 was an overall compressional or extensional tectonic event.

D2 deformation

As in the Moine (North) area the deformation phase termed 'D2' has resulted in the most pervasive structures in the Moine and reworked Lewisianoid rocks. Minor and major folds, related rodding lineations, and a prominent cleavage/schistosity are all common. The structures and related mineralogy are indicative of lower- and middle-amphibolite-facies metamorphic conditions. Movement on the main thrusts ('slides'), such as the Sgurr Beag Thrust, is also attributed primarily to this phase. Generally, folds attributed to F2 are reclined, and their axes and related lineations plunge moderately steeply to the south-east (Ramsay, 1957b; May *et al.*, 1993), probably related to overall top-to-the-NW tectonic movements.

D2 slides and the Sgurr Beag Thrust

The Sgurr Beag Thrust in the Moine (Central) area is one of the best examples of a 'slide' and the dominant discontinuity in the Moine succession. 'Slides' are ductile shear-zones, generally at a shallow angle to the regional bedding, that mark an overall discontinuity in the succession (e.g. Bailey, 1922; Hutton, 1979; Mendum, 1979). They commonly occur at major lithological boundaries and may have either a compressional geometry, duplicating the succession, or an extensional geometry, excising or attenuating parts of the succession. Major 'slides' that duplicate the succession, i.e. those with a demonstrably compressional character, have been subsequently renamed 'thrusts'. Most 'slides'/thrusts within the Moine succession have a pervasive platy S2 schistosity, and some carry a strong L2 rodding lineation; their main ductile movements are attributed to the D2 deformation event. Almost all the 'slides'/thrusts dip eastwards except where folded by later deformation episodes.

The Sgurr Beag Thrust can be traced from Kinlochhourn, north to Glen Shiel, and via the central Ross-shire Lewisianoid inliers to Garve. In the Fannich–Beinn Dronaig area of Wester Ross, the Sgurr Beag Thrust occurs in a large structural outlier. The thrust generally dips moderately to steeply east to south-east. It separates Morar Group rocks in the footwall from Glenfinnan Group rocks in the hangingwall. The Sgurr Beag Thrust itself is not a sharp, distinct plane, but a ductile shear-zone up to several hundred metres thick, as described in the **Kinloch Hourn** GCR site report (Chapter 8) and the **Fannich** GCR site report (this chapter). Numerous Lewisianoid inliers occur within the shear zone and directly in its hangingwall.

The Sgurr Beag Thrust is folded by major Caledonian (F3) antiforms and synforms, the most notable example forming a large outlier that stretches *c.* 70 km south from the Fannich Forest, to Achnasheen, as far as the West Monar Forest (see **Fannich** GCR site, report, this chapter). In the Sgùman Còinntich area (NG 977 303), a closed kilometre-sized outcrop of Glenfinnan Group pelite, surrounded by the Sgurr Beag Thrust, is interpreted as a synformal, steeply E-plunging sheath-fold (May *et al.*, 1993).

Although upper parts of the Morar Group succession appear to be missing in the Moine (Central) area, the Sgurr Beag Thrust transports Lewisianoid basement up-section. This geometry and other features suggest that it acted as a WNW-directed ductile thrust zone at least during D2, with a minimum displacement of 15–30 km (Rathbone and Harris, 1979; Powell *et al.*, 1981; Kelley and Powell, 1985; Barr *et al.*, 1986). Powell *et al.* (1981) presented evidence of metamorphic steps across the Sgurr Beag Thrust and other 'slides' and argued for a multi-stage tectonic history.

D3 deformation

F3 structures are typically centimetre- to kilometre-scale, open to tight folds that control much of the overall outcrop pattern of the Moine succession. They have a locally developed penetrative or crenulation cleavage, S3, best seen in F3 hinge zones, dependent on the degree of D3 strain and the lithology. They formed under lower- to middle-amphibolite-facies conditions with quartz-feldspar pegmatite segregations developed preferentially along F3 axial planes. Muscovites from a post-F3 pegmatite at Loch Monar have been dated by van Breemen *et al.* (1974) using Rb-Sr techniques at 447 ± 6 Ma, in accord with similar ages for D3-related pegmatites and metamorphic fabrics in the Moine (South) area. 'Slide' zones are locally associated with major F3 folds, but in many areas the F3 structures fold the major D2 'slide'/thrust zones.

Examples of D2 structures, refolded by F3 folds, are very abundant throughout the area. Classic outcrop-scale F2–F3 fold interference patterns in Glenfinnan Group rocks are described in the **Loch Monar** GCR site report (this chapter), whereas the **Beinn a' Chapuill** GCR site represents a large-scale F2–F3 refold. F3 fold axes are locally curvilinear on a small- to medium-scale, as a result of D3 strain variations and the complex F2 and earlier geometry (Ramsay, 1957a).

D4 and later phases

Within the Moine succession are variably developed, identifiable phases of later open to close folds. In Glenfinnan Group rocks of the Glen Strathfarrar–Glen Affric area, Tobisch *et al.* (1970) document a coherent late deformation phase characterized by steep, open folds and an associated crenulation cleavage. Similar late open folds are also developed in the Kintail area (May *et al.*, 1993, table 11 and fig. 16). In semipelitic and pelitic units, related crenulation cleavages are locally developed. Biotite has recrystallized in many of the related cleavages, suggesting that metamorphic conditions were at least at greenschist facies.

Metamorphism

The overall pattern of metamorphism in the Moine (Central) area is one of increasing metamorphic grade from west to east. Plagioclase compositions in calc-silicate rocks have been used to show the rise from greenschist facies ($< An_{20}$) on Sleat in the west, to lower- and middle-amphibolite-facies assemblages ($> An_{60}$) in the Glenfinnan Group rocks in the east (Winchester, 1972; Tanner, 1976; Fettes *et al.*, 1985). Diopside occurs in only a few of the highest-grade calc-silicate pods. Loch Eil Group calc-silicate rocks show evidence of hornblende replacement of pyroxene and development of two-stage garnets. Later retrograde actinolite, biotite and clinozoisite are also commonly developed in many of these calcareous rocks (May and Highton, 1997). Index minerals relating to pelitic rocks are not abundant, and although kyanite does occur in some of the pelitic units, for example in Glen Cannich (Tobisch, 1963; Peacock *et al.*, 1992) and around Loch a' Chràthaich (May and Highton, 1997), normally it is partly or wholly pseudomorphed by muscovite. Muscovite also occurs abundantly as shimmer aggregate in the higher-grade areas, probably after fibrolite and sillimanite. Garnet, muscovite and biotite porphyroblasts are also common. Garnets show flat compositional profiles in the higher-grade areas, but zoning profiles are present farther east where retrogression has reduced the grade to lower-amphibolite facies. Relict staurolites have been reported in some muscovite porphyroblasts in the south-west part of the Invermoriston district (May and Highton, 1997).

The age of the main metamorphic minerals is unclear and may differ from place to place. In Kintail and Glen Affric the peak metamorphic mineralogy appears to be wrapped by the dominant S2 foliation. The micas have grown or recrystallized during D2 and in parts during the later D3 or D4 events, and effectively define the S2, S3 and S4 fabrics (Peacock *et al.*, 1992; May and Highton, 1997). Amphibolite-facies fabrics and mineralogies developed widely during D2 deformation, resulting in growth of garnet, kyanite and rarely sillimanite in the pelitic lithologies, and hornblende, pyroxene and anorthite-rich plagioclase in the calc-silicate rocks. These minerals commonly define an L2 lineation, which is generally orientated parallel to F2 minor fold axes. Quartz and quartzo-feldspathic veins were also generated widely during D2 deformation. However, in most areas metamorphic conditions also attained amphibolite facies during the D3 deformation, and locally the peak mineral assemblages reflect this later event. The peak metamorphic assemblages are commonly retrograded in the Moine rocks. Patchy retrogression is well documented in the Loch Eil Group rocks of Glen Urquhart and Glen Moriston (May and Highton, 1997). The greenschist-facies overprint found in the western part of the Moine outcrop is linked to movements on the Moine Thrust Belt, and is likely to be Silurian (Scandian) in age (Kelley, 1988). In the central Moine area the Grampian Event was undoubtedly important (see also Chapter 6), but age dating of metamorphic minerals farther south suggests that Knoydartian (Neoproterozoic) events may also have been very significant.

Devonian and later faulting

The dominant fault trend in the Moine (Central) area is north-east–south-west, with the Great Glen, Strathconon and Strathglass faults being the major structures. These faults were generated or strongly reactivated at the close of the Caledonian Orogeny, when they were the sites of significant sinistral movements. Subsidiary WNW-trending dextral faults occur in Kintail and at Kinloch Hourn. Carboniferous and Mesozoic reactivation of the larger structures has occurred (Roberts and Holdsworth, 1999).

The Great Glen Fault is the most important fault, and its linear trace and deep valley are one of the most prominent structures of the Scottish Highlands. It is manifest as a *c.* 300 m-wide fault-zone that separates the Northern and Grampian Highlands. To the north-east its trace lies immediately offshore in the Inner Moray Firth and it is integral to the Cromarty and Rosemarkie inliers (see **Cromarty and Rosemarkie Inliers** GCR site report, Chapter 6). In much of the Moine (Central) area the fault trace lies beneath Loch Ness, and even south-west from Fort Augustus thick till and sands and gravels obscure most of its outcrop. In the fault zone are mylonites, breccias, cataclasites and gouge zones that represent the differing pressure, temperature and fluid conditions prevailing at the time of movement, and a complex and lengthy movement history. The fault rocks reflect both frictional brittle and ductile viscous creep mechanisms and those presently seen in the restricted surface outcrops developed at different crustal levels estimated to be between 9 km and 16 km deep (Stewart *et al.*, 1999). Although movement has largely focused on a central fault-zone, fracturing, brittle folding, cataclastic bands, and fluid-related alteration extend for up to 3 km from main fault trace. The early Devonian (Emsian) outlier of Meall Fuar-mhonaidh is fault-bounded on its western side and shows folding and local thrusting related to Acadian transpression that accompanied sinistral movements on the Great Glen Fault.

The Strathconon Fault is a complex fault-zone marked by cataclasite, breccia and soft gouge. The overall fractured zone is up to 1.5 km wide. The net sinistral displacement of *c.* 6 km is shown by displacement of the microdiorite, andesitic and microgranite (felsite) dykes related to the Ratagain Pluton as well as the offset of the Sgurr Beag Thrust and other Caledonian structures. However, Permo–Carboniferous camptonite dykes cross-cut the fault without deflection. Roberts and Holdsworth (1999) postulate that the Strathconon Fault was re-activated in the Mesozoic as a normal fault, arguing that it linked the offshore basins in the Moray Firth to those in the Sea of the Hebrides.

The Kinlochhourn Fault forms a well-defined narrow linear gully feature ('slack') in which gouge and fine breccia are reported (May *et al.*, 1993). It offsets the Sgurr Beag Thrust trace dextrally by *c.* 1 km and has been suggested by Ringrose (1989) as the site of post-glacial movement on the basis of stream offsets. However, a comprehensive study of the fault zone and features by Stewart *et al.* (2001) has seriously questioned the evidence for its post-glacial movement history.

FANNICH (NH 150 742–NH 171 712, NH 185 708–NH 205 659)

S.P. Kelley

Introduction

The Moine and Lewisianoid rocks of the Fannich Mountains are folded into the Fannich Synform, a large-scale Caledonian structure which also folds the earlier Sgurr Beag Thrust (Figure 7.1). The Sgurr Beag Thrust juxtaposes middle amphibolite-facies pelitic and semipelitic rocks of the Glenfinnan Group, interleaved with felsic and mafic gneiss inliers of probable Lewisianoid origin, against lower amphibolite-facies psammites and pelites of the Morar Group.

The area was first mapped by J. Horne for the Geological Survey and described in the memoir for the Fannich Mountains (Sheet 92) (Geological Survey of Scotland, 1913a; Peach *et al.*, 1913). Horne recognized the importance of the difference between the two pelites of the area, the Meall an t-Sithe Pelite and Sgùrr Mòr Pelite formations, describing the former pelite as a gneiss. Even at this early stage there was controversy concerning the mainly felsic gneisses at the core of the Fannich Mountains. The high structural level of the gneisses in the succession (Figures 7.3, 7.4) implied some sort of stratigraphical or structural break, but the lithologies of the area seemed to form a simple syncline with the gneisses apparently overlain and underlain by Moine lithologies. In 1898, W. Gunn and J. Horne postulated a thrust relationship between the Lewisianoid gneisses and the Meall an t-Sithe Pelite, but in the memoir (Peach *et al.*, 1913), a 'fan shaped anticlinorium' of nappes was preferred. Later published work on the Fannich Mountains generally placed stratigraphical breaks in the succession in order to explain the presence of the Lewisianoid gneisses (Rutledge, 1952). However, Sutton and Watson (1954) used 'way-up' criteria from the metasedimentary succession to suggest that the supposed Lewisianoid inliers lay at the top of a continuous sequence. They rejected the notion of Lewisianoid parentage and interpreted them as an integral part of the Moine succession, preferring the name 'Fannich Gneisses'. It was not until 1962 that Sutton and Watson accepted a Lewisianoid origin for the Fannich gneisses, following detailed work on the Glenelg–Attadale Inlier by Ramsay (1957b – see also **Allt Cracaig Coast** GCR site report, this chapter).

Winchester (1971, 1973) studied essentially the same area as Sutton and Watson (1954), and demonstrated geochemical differences between the Moine and felsic gneiss lithologies. He deduced that the gneisses were most likely of Lewisanoid origin, interleaved with the Moine metasedimentary succession. Winchester (1973) refined the Sutton and Watson (1954) stratigraphy, and extended the outcrop of the Lewisianoid 'Fannich Gneisses' south of Loch Fannich. He also interpreted spindle-shaped quartzofeldspathic pods as a basal metaconglomerate between the Meall an t-Sithe Pelite Formation and the Lewisianoid felsic gneisses. He considered, but eventually rejected, the presence of the Sgurr Beag Thrust at the boundary between the Meall a' Chrasgaidh Psammite Formation and the Meall an t-Sithe Pelite Formation.

Kelley and Powell (1985) established the presence of the Sgurr Beag Thrust at the boundary between the Meall a' Chrasgaidh Psammite and the Meall an t-Sithe Pelite around the northern end of the main Fannich Synform and in a small structural outlier immediately north-west of Loch a' Bhraoin (Figure 7.4), which is described in the **Meall an t-Sithe and Creag Rainich** GCR site report (this chapter).

The importance of the Fannich Mountains lies in their unique position between the type area for the Sgurr Beag Thrust in the Kinlochhourn area (Tanner 1971) (see **Kinloch Hourn** GCR site report, Chapter 8), where it juxtaposes Morar Group and Glenfinnan Group rocks, and the Moine rocks of Sutherland, to where the Sgurr Beag Thrust has been traced (see Chapter 6). The Fannich Mountains represent the northernmost closure of a structural outlier that

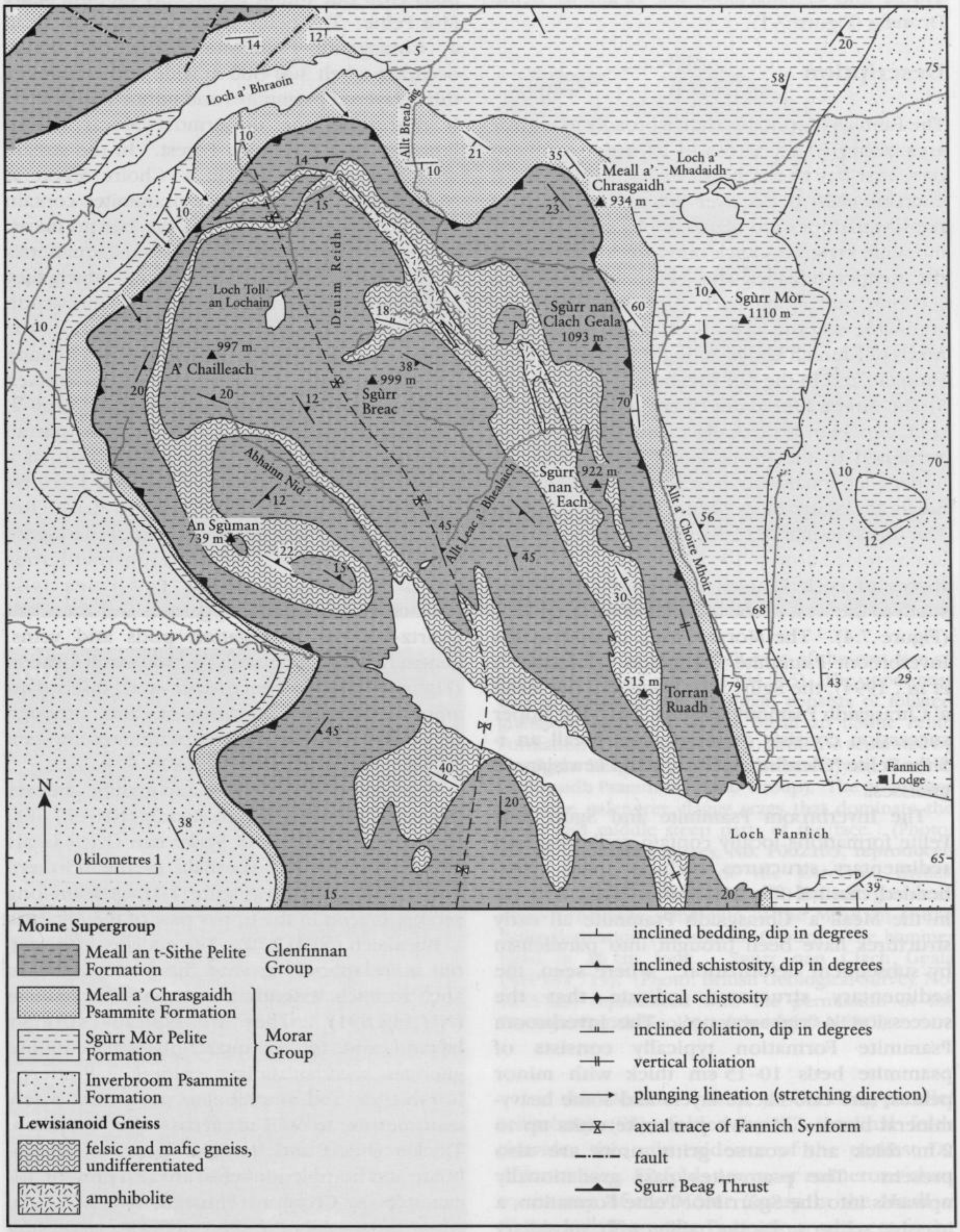


Figure 7.4 Geological map of the Fannich Mountains. Based on Geological Survey of Scotland (1913a) (Sheet 92), and Kelley and Powell (1985).

lies west of the main outcrop of the Sgurr Beag Thrust and extends SSW for 42 km to Beinn Dronaig (Figure 7.1).

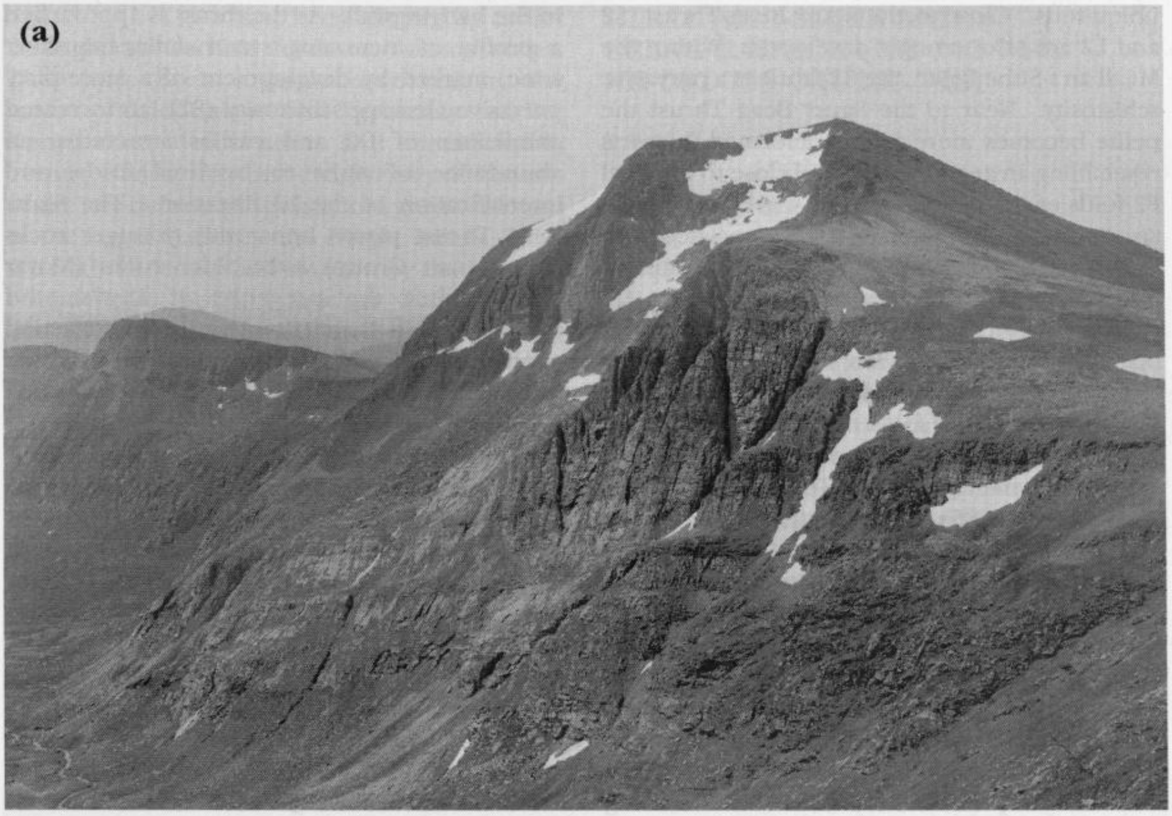
Description

The Fannich Mountains form a broadly triangular area, some 10 km across in its wider southern part, that lies to the north of Loch Fannich. It contains eight peaks over 900 m, but much of the lower slopes are blanketed by peat, till and morainic material. Rock outcrops are found on the steeper hillsides and cliffs, in the stream sections, and along Loch Fannich. The most accessible sections are in the hills and streams north of Fannich Lodge, along the shore of Loch Fannich, and in the Allt Breabaig.

The Moine lithologies of the area are readily split into two structurally distinct successions, attributed to the lower Morar Group and the upper Glenfinnan Group, separated by a tectonic break, the Sgurr Beag Thrust (Figures 7.3, 7.4). The thrust is marked by a high-strain zone that can be traced around the later synform from the shores of Loch Fannich northwards, returning south to the west of the loch in the flat-lying limb (Figure 7.4). The Morar Group comprises the Inverbroom Psammite Formation (Holdsworth *et al.*, 1994), the Sgùrr Mòr Pelite and the Meall a' Chrasgaidh Psammite (Figure 7.3). The upper succession consists of intercalated Meall an t-Sithe Pelite (Glenfinnan Group) and Lewisianoid gneisses.

The Inverbroom Psammite and Sgùrr Mòr Pelite formations locally contain well-preserved sedimentary structures such as small cross-bedded channel fills and slump-folds, whereas in the Meall a' Chrasgaidh Psammite all early structures have been brought into parallelism by subsequent deformation. Where seen, the sedimentary structures indicate that the succession is 'right-way-up'. The Inverbroom Psammite Formation typically consists of psammite beds 10–15 cm thick with minor pelites, rare calc-silicate layers and some heavy-mineral bands. Massive psammite units up to 2 m thick and coarse gritty units are also present. The psammites pass gradationally upwards into the Sgùrr Mòr Pelite Formation, a massive schistose biotite pelite with subsidiary interbedded semipelites. Calc-silicate rock lenses are common and concordant amphibolites are recorded in parts. North of Loch Fannich, around NH 207 667, several massive psammite beds crop out within the steeply dipping Sgùrr Mòr Pelite. The pelite grades up into the Meall a' Chrasgaidh Psammite Formation, which occupies a belt 100–300 m wide and consists of thinly layered psammites and minor semipelites. It represents the uppermost Morar Group lithology in the Fannich Forest. In the stream section south-west of Allt a' Choire Mhòir at NH 198 675, thin dark-grey psammites contain hornblende, sphene and epidote but no micas. Sutton and Watson (1953) found similar minerals in psammites of the Scardroy area, which they correlated with the Meall a' Chrasgaidh Psammite. Above the Sgurr Beag Thrust, the Meall an t-Sithe Pelite Formation (Glenfinnan Group) occupies the major part of the Fannich Synform, resting everywhere upon the Meall a' Chrasgaidh Psammite. It forms the upper part of Sgùrr nan Clach Geala (Figure 7.5a) and has a wide outcrop across Sgùrr Mòr (NH 176 689) and Sgùrr Breac (NH 158 711) to Loch Toll an Lochain. This pelitic unit is a dark-grey, gneissose, locally migmatitic, garnetiferous muscovite-biotite semipelite and pelite with distinctive claret-coloured garnets and abundant quartz-feldspar segregation pods and veins, generally orientated parallel to the overall foliation (Figure 7.5b). Concordant and discordant amphibolite pods are present, and although pelitic lithologies dominate, psammites are seen on Sgùrr nan Each (NH 185 697).

Lewisianoid granodioritic and granitic gneisses extend NNW from Torran Ruadh (NH 190 671) to the western flank of Sgùrr nan Clach Geala and across the Allt Breabaig to the northern end of Druim Reidh (Figure 7.4). A 1 km-long section is seen in the upper part of the Allt Leac a' Bhealaich (NH 17 70). The gneisses also crop out more sparsely around the western part of Loch Fannich, extending west onto An Sgùman (NH 138 691). They are typically strongly layered and folded quartz-plagioclase-biotite gneisses with subsidiary epidote. Scattered hornblende and amphibolite pods from a few centimetres to *c.* 1 m across are common. Thicker sheets and irregular lenses of amphibolite and hornblende schist are also present, for example on Creag an Fhuarain (NH 177 713), where an amphibolite sheet defines a large, very tight, reclined fold and attains a thickness of 250 m in its hinge zone (Peach *et al.*, 1913, p. 67).



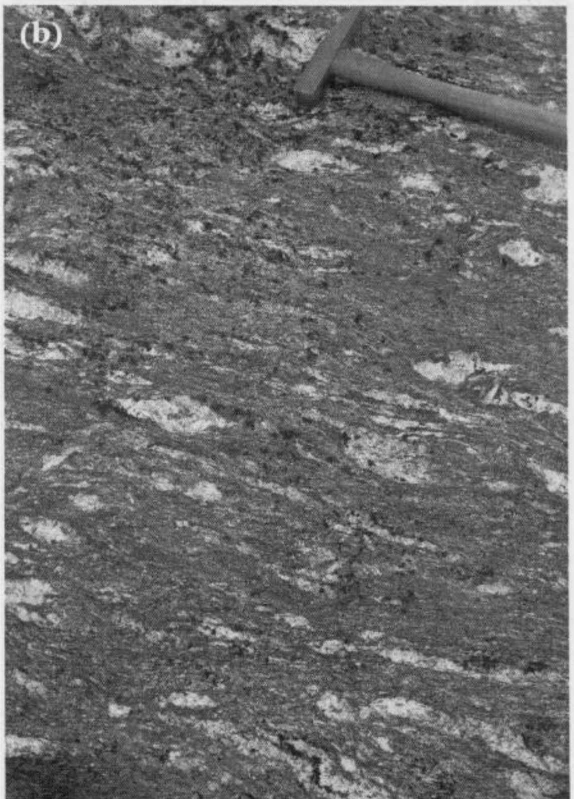


Figure 7.5 ▲(a) View south-west of the east face of Sgùrr nan Clach Geala (NH 184 715). The uppermost dark-grey part of the mountain consists of foliated gneissose semipelite of the Meall an t-Sithe Pelite Formation (Glenfinnan Group), which is separated by the Sgurr Beag Thrust from the underlying Meall a' Chrasgaidh Psammite (Morar Group). The psammites form the paler-grey, flaggy crags that dominate the lower and middle steep parts of the face. (Photo: British Geological Survey, No. P002105, reproduced with the permission of the Director, British Geological Survey, © NERC.) ◄(b) Foliated gneissose muscovite-biotite semipelite of the Meall an t-Sithe Pelite Formation (Glenfinnan Group). The hammer head is 16 cm long. Sgùrr nan Clach Geala (NH 184 715). (Photo: British Geological Survey, No. P215729, reproduced with the permission of the Director, British Geological Survey, © NERC.)

In the Moine rocks a bedding-parallel schistosity (S1), folded by F2 isoclinal folds provides the only evidence of the earliest D1 deformation. F2 folds are most numerous close to the top of the Morar Group in the Meall a' Chrasgaidh Psammite Formation, adjacent to the Sgurr Beag Thrust. No large-scale F2 folds are seen in the Morar Group in the Fannich area, although the associated S2 schistosity is ubiquitous. Close to the Sgurr Beag Thrust, S2 and L2 are also strongly developed. Within the Meall an t-Sithe Pelite, the S2 fabric is a pervasive schistosity. Near to the Sgurr Beag Thrust the pelite becomes more highly deformed, in parts resembling an augen gneiss, and close to isoclinal F2 folds of the quartz-feldspar segregation veins are common. The later F3 folds associated with the broad Fannich Synform are the most common folds throughout the area and crenulate the D2 foliation/schistosity in the pelitic units. The open asymmetrical F3 Fannich Synform has an E-dipping axial plane and controls the regional outcrop pattern. It folds the interleaved Moine and Lewisianoid rocks, the S2 structures and fabrics, and the Sgurr Beag Thrust itself (Kelley and Powell, 1985). The eastern limb of the synform is characterized by moderate to steep westerly dips and is best exposed in streams flowing south from the Fannich Mountains to Loch Fannich. The gently E-dipping western limb is exposed close to the A832 road between Braemore Junction (NH 209 777) and Dundonnell (Figure 7.4).

A section through the gently dipping western limb is exposed in the Allt Breabaig (NH 174 707–NH 163 751). In the northern part of the burn section, highly strained Meall a' Chrasgaidh Psammite is exposed until the Sgurr Beag Thrust is reached. The thrust is well exposed in the stream and on the surrounding slopes, where tight to isoclinal F2 folding is seen. Farther upstream, Lewisianoid felsic gneisses are characterized by coarser textures and a strong stretching lineation. Tight to isoclinal folds are very abundant. Winchester (1971) showed that the gneisses could be distinguished readily from the surrounding Moine rocks on the basis of their whole-rock geochemistry.

Interpretation

The structural sequence in the Fannich Mountains has been folded by the Caledonian-age F3 Fannich Synform. This synform folds the Sgurr Beag Thrust and related D2 structures, and forms part of a large structural outlier of Glenfinnan Group rocks. The thrust marks the position of the Morar Group–Glenfinnan Group boundary and also coincides with a metamorphic break between the lower-grade Sgùrr Mòr Pelite (Morar Group) in the footwall and the higher-grade Meall an t-Sithe Pelite (Glenfinnan Group) in the hangingwall. As the thrust is approached a profile of increasing strain defines a shear zone, marked by development of a more-platy pervasive cleavage/schistosity (S2), an increased parallelism of D2 and earlier structures, an abundance of tight to isoclinal folds, and intensification of the L2 lineation. The Sgurr Beag Thrust places apparently younger rocks (Glenfinnan Group) over older rocks (Morar Group), but the presence of Lewisianoid gneisses and its correlation to a similar structural geometry to the south has resulted in its interpretation as a thrust.

Although peak metamorphic ages have not been determined directly from the Fannich area, they are most probably around 450 million years old, similar to ages derived farther south (Brewer *et al.*, 1979). However, Tanner and Evans (2003) showed that the Sgurr Beag Thrust near Lochailort may have an important component of Knoydartian (*c.* 740 Ma) movement.

The Fannich Synform is thought to pre-date the early Scandian development of mylonites along the Moine Thrust Belt. D2 and D3 macro- and micro-deformational textures in the Fannich area can be traced along Loch a' Bhraoin towards the Moine Thrust Belt where they are overprinted by mylonitic fabrics (Kelley and Powell, 1985; see **Meall an t-Sithe and Creag Rainich** GCR site report, this chapter). Hence, the Fannich Synform probably formed prior to the time indicated by the K-Ar cooling ages obtained by Kelley (1988). Kelley showed that mica K-Ar ages varied with grain size, implying that the grains were partially reset during late Caledonian dynamic recrystallization, probably during D3, when the Fannich Synform was formed. The mean cooling ages in Fannich for 250–500 μm grain-sizes were 434 ± 9 Ma for muscovite and 434 ± 8 Ma for biotite (Kelley, 1988). Muscovite ages of 440–435 Ma were obtained close to the Moine Thrust Belt (see also Freeman *et al.*, 1998). These Scandian ages suggest that pervasive deformation and fluid effects related to the ductile movements on the Moine Thrust penetrated the hangingwall Moine and Lewisianoid succession for several kilometres above the thrust. The effects can be traced laterally some 18 km east of the Moine Thrust trace.

The Lewisianoid felsic gneisses have been variously interpreted as Moine lithologies (Sutton and Watson, 1954) and Lewisianoid inliers (Peach *et al.*, 1913; Winchester, 1971, 1973). The gneisses are repeated across F3 open to tight folds but also have been affected by earlier D2 tight to isoclinal folds on various scales. They have been strongly reworked by the various Caledonian and probably earlier Knoydartian deformation and metamorphic events. Hence, they lack the diversity of features of the less-deformed Lewisianoid gneisses found in the larger Scardroy and Borgie inliers. They are both underlain and overlain by the Meall an t-Sithe Pelite, but it is unclear whether these boundaries represent modified unconformities (i.e. they are tight to isoclinal folds) or are the site of D1 or D2 slides or thrusts.

The gneisses have been correlated with the foreland Lewisian Gneiss Complex to the west, as this is the closest Archaean/Proterozoic gneiss terrain, but a strict Lewisian parentage is not fully proven. They retain enough features to allow their complex pre-Caledonian Lewisianoid parentage to be recognized, although their highly deformed nature and limited outcrop inhibit further investigation.

Conclusions

In the Fannich Forest area Moine rocks of the Glenfinnan Group and Lewisianoid felsic gneisses form a structural outlier west of the main outcrop. These distinctive units were intercalated early in the tectonic history of the area, and subsequently the composite succession has been thrust to the WNW over Morar Group rocks along the Sgurr Beag Thrust. The later asymmetrical open to close F3 Fannich Synform has folded the main penetrative Caledonian and earlier structures, the metamorphic fabrics and the Sgurr Beag Thrust. This F3 deformation in turn pre-dated the formation of the Moine mylonites during the mid-Silurian-age Scandian Event. The Fannich site contains one of the northernmost and structurally simplest exposures of the Sgurr Beag Thrust, yet the thrust can still be correlated southwards to the type area (see **Kinloch Hourn** GCR site report, Chapter 8). Earlier studies in the Fannich area presented radically different interpretations of the Lewisianoid gneiss inliers. The site is nationally important from the historical aspect, and because its geology links folding, thrusting and metamorphic fabrics and mineralogies in the internal part of the Caledonian Orogen with those in the nearby Moine Thrust Belt. It retains the potential for further detailed studies of the relationships between its different geological elements.

MEALL AN T-SITHE AND CREAG RAINICH (NH 142 764, NH 081 755–NH 108 748)

S.P. Kelley

Introduction

The Moine rocks of the Meall an t-Sithe and Creag Rainich GCR site in Ross-shire represent the closest approach of the Sgurr Beag Thrust, a ductile D2 structure, to the later Moine Thrust Belt. The site affords an excellent opportunity to study the interaction of Scandian mylonitization and thrusting of the Moine Thrust Belt with earlier Caledonian structures and metamorphic fabrics associated with the Sgurr Beag Thrust.

In the Fannich Mountains, middle amphibolite-facies gneissose semipelites and pelites of the Glenfinnan Group lie structurally above lower amphibolite-facies psammitic and pelitic rocks of the Morar Group, separated by a major tectonic break, the Sgurr Beag Thrust. The area was originally mapped by J. Horne for the Geological Survey and described in the memoir for the Fannich Mountains (Sheet 92) (Peach *et al.*, 1913; Geological Survey of Scotland, 1913a). Horne selected Meall an t-Sithe as the type area for the gneissose, partly migmatitic semipelite and pelite which forms the bulk of the Glenfinnan Group rocks in this area. The early descriptions of the site (Peach *et al.*, 1913) emphasize the high metamorphic grade of the Meall an t-Sithe Pelite, although Winchester (1973) thought the grade was similar in the underlying Sgùrr Mòr Pelite of the Morar Group (see Figure 7.3). The importance of the Meall an t-Sithe–Creag Rainich area in terms of the relationship between the early and later Caledonian deformations was first recognized by Kelley and Powell (1985).

The area lies at the northern end of the F3 Fannich Synform, which post-dates the Sgurr Beag Thrust, and bedding and S2 cleavage orientations generally dip gently to the south. D3 deformation effects are restricted to minor folds, which fold the earlier penetrative S2 cleavage and D2 structures. Westwards, towards the Moine Thrust Belt, the D3 deformation features become more strongly developed, with F3 folds becoming tight and even locally isoclinal, and a penetrative, composite S2–S3 cleavage is present. Lewisianoid gneisses are interfolded with the Meall an t-Sithe Pelite Formation in the

Fannich Mountains to the south-east (see **Fannich** GCR site report, this chapter), but are absent in the Meall an t-Sithe and Creag Rainich GCR site.

Description

The site encompasses two sections at either end of the broad, rocky, partly peat-covered, WSW-trending ridge between Meall an t-Sithe and Creag Rainich. The western section stretches from Abhainn Loch an Nid to Creag Rainich and Meall Dubh and includes the Moine Thrust. The eastern section is focused on Meall an t-Sithe, and lies some 6 km east of the Moine Thrust. The structurally highest unit is the coarsely foliated gneissose semipelite and pelite of the Meall an t-Sithe Pelite Formation, assigned to the Glenfinnan Group. This formation lies in a structural outlier or klippe, surrounded by the Sgurr Beag Thrust (Figure 7.6). It is preserved owing to a NE-trending normal fault that passes through part of Loch a' Bhraoin and throws the succession down to the north-west. The main synformal outlier of the Sgurr Beag Thrust and Glenfinnan Group rocks lies to the south and is described in the **Fannich** GCR site report (this chapter).

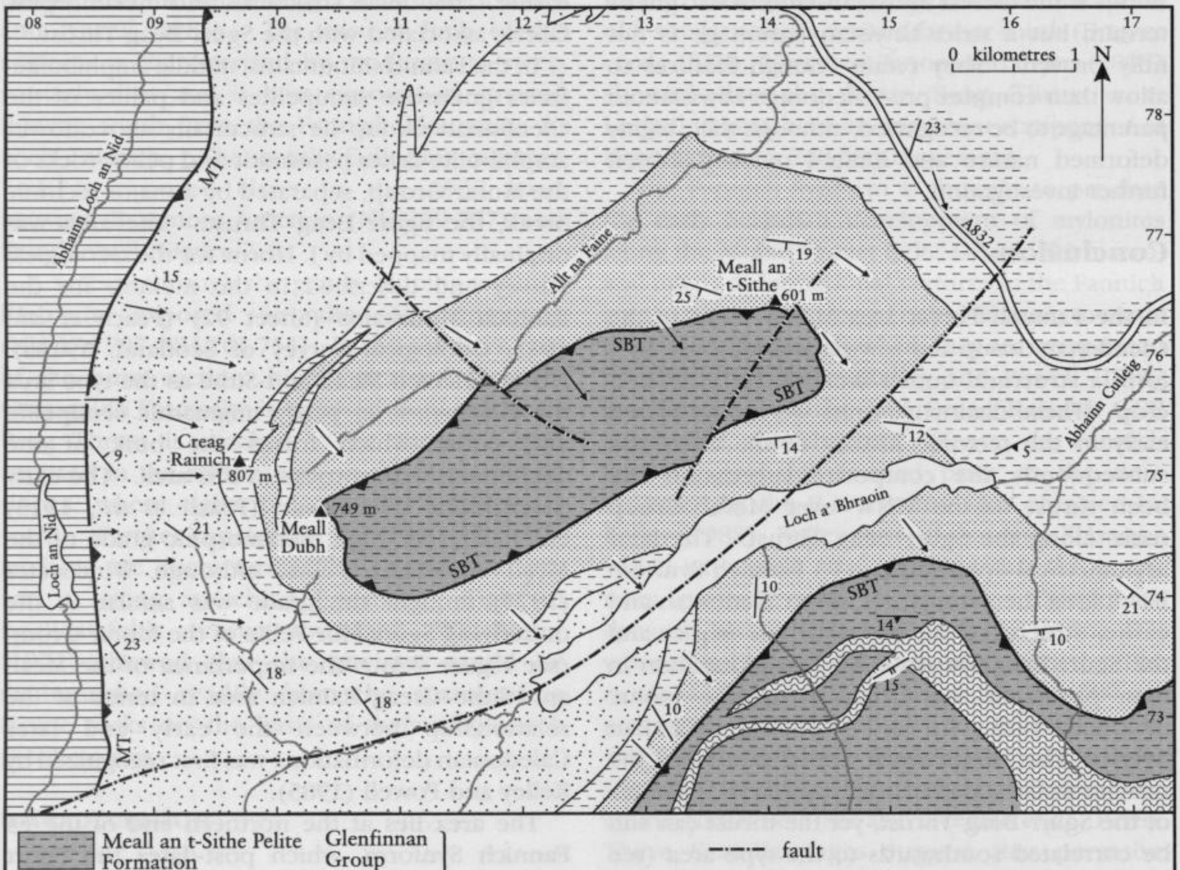


Figure 7.6 Geological map of the Meall an t-Sithe and Creag Rainich area. Based on Geological Survey of Scotland (1913a) (Sheet 92) and Kelley and Powell (1985).

The gneissose semipelite of the Meall an t-Sithe Pelite Formation consists of biotite, muscovite, garnet, quartz and plagioclase feldspar with abundant coarse-grained plagioclase-quartz segregations that in part define the foliation. Claret-coloured garnets are locally very abundant. The unit is locally layered and migmatitic. It crops out on the ridge running from Meall Dubh (NH 103 747) to Meall an t-Sithe (NH 140 764) and underlies much of the peat-covered southern slopes of the ridge towards Loch a' Bhraoin. The gneissose semipelite contrasts strongly with the schistose pelites and flaggy psammites of the Morar Group on the summit of Creag Rainich and on the lower slopes north of Meall an t-Sithe, towards the A832 road.

In the eastern part of the structural outlier, the peak metamorphic D2 structures associated with the Sgurr Beag Thrust are preserved. These include: L2 stretching lineations in both the gneissose semipelites and pelites and underlying psammites that plunge towards 160°; a suite of discordant pegmatitic granites that cross-cut the D2/Sgurr Beag Thrust fabrics and post-date peak metamorphism; and quartz c-axis preferred orientations associated with the Sgurr Beag Thrust that are little modified by later deformation (Kelley and Powell, 1985). Farther west, the L2 lineations swing gradually towards 110° and 090°, to accord with stretching lineations developed within the later Moine Thrust mylonites. The undeformed pegmatites found in the east become progressively rotated into parallelism with the composite fabric, and the Sgurr Beag Thrust fabrics in both psammites and pelites become deformed by S–C-type fabrics on all scales, implying a top-to-the-WNW sense of movement. Finally, exposures of the Meall a' Chrasgaidh Psammite close to the Moine Thrust exhibit some brittle deformation features, including cataclastic zones and thin pseudotachylyte veins. At its most westerly exposure in the site area, on Meall Dubh (NH 103 747), the Sgurr Beag Thrust lies only 2 km east of the brittle Moine Thrust and only 400 m structurally above it.

Interpretation

The close proximity of the Sgurr Beag Thrust to the Moine Thrust Belt in the Meall an t-Sithe and Creag Rainich area demonstrates the relative ages of the Moine mylonites and the D2 movements on the Sgurr Beag Thrust. D2 movements along the Sgurr Beag Thrust in the area are generally considered to have occurred mainly during the Grampian Event (Early Ordovician), although farther south Knoydartian (Neoproterozoic) movement has been documented (Tanner and Evans, 2003). Near Creag Rainich, the Sgurr Beag Thrust and Moine Thrust are exposed less than 2 km apart. The increasing deformation that has resulted in formation of the Moine Thrust Belt mylonites has progressively rotated the earlier L2 linear and S2 planar fabrics into parallelism. The peak metamorphic amphibolite-facies textures associated with the Sgurr Beag Thrust have been deformed under greenschist-facies conditions, with the earlier coarse-grained fabrics recrystallized into finer-grained mylonites. Hence, movements on the Sgurr Beag Thrust had ceased and the rocks had been uplifted and cooled substantially prior to the formation of the Moine mylonites. This is in contrast to earlier syntheses of the Moine Thrust Belt, which correlated mylonite formation with the peak of metamorphism in the Moine rocks farther east (Johnson, 1957, 1960; Barber, 1965). In the adjoining Fannich area to the south-east of the site (see **Fannich** GCR site report, this chapter), the Sgurr Beag Thrust is folded in a large F3 synform, but it appears that the mylonitic fabrics also overprint these D3 structures. Although it is not possible to determine the length of time between formation of the Fannich Synform and formation of the Moine mylonites, there is some continuity of minor F3 folds and microtextures from the synform into the mylonites (Kelley and Powell, 1985). This may indicate a possible progressive link between F3 and the Scandian-age mylonitization. However, if the Fannich Synform links to the F3 Monar Synform farther to the south-east there seems to be an age disparity, as *c.* 450 Ma pegmatites are related to the minor F3 folds at Monar (van Breemen *et al.*, 1974). In contrast, the K-Ar mica ages from the Fannich and Creag Rainich areas imply that mylonitization of the Moine Thrust Belt occurred later at around 440–430 Ma (Kelley, 1988; Freeman *et al.*, 1998).

Conclusions

The Meall an t-Sithe and Creag Rainich GCR site is unique within the Northern Highlands in that it illustrates the relationship between probable Grampian (Early Ordovician age) D2 thrusting, peak metamorphism, later D3 folding, and the main period of Scandian mylonitization associated with the Moine Thrust Belt. As such it is of national importance as it enables the orogenic history of the more-internal, once deeper-level parts of the Caledonian mountain belt to be related to that of the external Moine Thrust Belt. The Sgurr Beag Thrust, a composite D2 + D3 structure in the type area to the south (see **Kinloch Hourn** and **Lochailort** GCR site reports, Chapter 8), is here folded by the asymmetrical large-scale F3 Fannich Synform along gently S-plunging axes. Quartz-feldspar pegmatites that discordantly cross-cut the Sgurr Beag Thrust and its related fabrics are progressively deformed and re-orientated as the mylonite zone of the Moine Thrust Belt is approached. The site allows for further detailed studies to be made of the relationship between the Ordovician-age Grampian D2 and D3 deformation events and the later mid-Silurian-age Scandian thrusting and deformation events.

LOCH MONAR (NH 197 389)

J.R. Mendum

Introduction

Smooth glaciated slabs by Loch Monar in Glen Strathfarrar show excellent examples of minor folding and fold interference patterns in thinly bedded psammites and semipelites of the Morar Group. J.G. Ramsay (1957a) carried out what is now recognized as a classic detailed structural synthesis of this area. This was one of the first geometrically rigorous studies of a complex folded area to be undertaken; similar work has since been done by many workers, but the original examples are featured in numerous structural geology textbooks. The dominant small-scale early folds form part of the kilometre-scale Monar Synform, which has been refolded by later upright structures (Figures 7.7, 7.8).

To the south and east of the site lies the thick Strathfarrar Lewisianoid Inlier, separated from the underlying Morar Group metasedimentary rocks by the Sgurr Beag Thrust, a major ductile shear-zone that dips steeply east in this area. South and east of the Lewisianoid inlier are Glenfinnan Group rocks. The Monar Synform folds all the units and appears to fold the Sgurr Beag Thrust. An early D1 deformation phase is present in the area, but generally only results in a bedding-parallel foliation, S1. Two subsequent major deformation phases, D2 and D3, are responsible for the spectacular interference pattern. The F2 Monar Synform is a large, gently W-plunging structure, which has been refolded by steeply plunging NE-trending F3 folds (Figure 7.8). Ramsay (1957a) originally referred to the two fold phases as 'F1' and 'F2' as he did not recognize the earlier S1 foliation and rare related minor structures. Tobisch *et al.* (1970) confused the terminology further by allocating the Monar Synform to a locally developed fold phase, the Orrin Phase, and the later folds to a Monar Phase (see Table 7.2.)

Officers of the Geological Survey mapped the area in 1905 (Peach *et al.*, 1913), but it was not until J.G. Ramsay remapped the upper part of Glen Strathfarrar in detail with particular regard to the complex structural pattern that the full picture emerged. Ramsay collected large amounts of structural data and used it to illustrate the three-dimensional geometry of the fold pattern and the complex fold interference patterns. He synthesized the results in a series of seminal papers (Ramsay, 1957a, 1960, 1962), and the material has been used subsequently in textbooks on structural geology (Ramsay, 1967; Ramsay and Huber, 1987).

Description

The GCR site lies at the southern end of Loch Monar, with the best exposures being a series of gently sloping glaciated slabs immediately below the road between the cut-off dam and the Loichel Tunnel Intake. Although once clean, the glacial slabs are now considerably vegetated, but some clean sections are still present, particularly at the north-west end of the section. The sections are typically not submerged, as the Loch Monar reservoir rarely attains its top water level. The mapping of J.G. Ramsay was done prior to the construction of the Monar Dam, and hence some localities now lie beneath the waters of the reservoir.

The exposures show excellent small-scale fold patterns in a sequence of thinly bedded, Moine psammites and subsidiary semipelites (Figure 7.9a,b,c). Minor thin pelite beds and amphibolite layers are also present. The psammites vary from quartzose to feldspathic and micaceous. The deformation occurred under amphibolite-facies conditions and a prominent S2 cleavage is

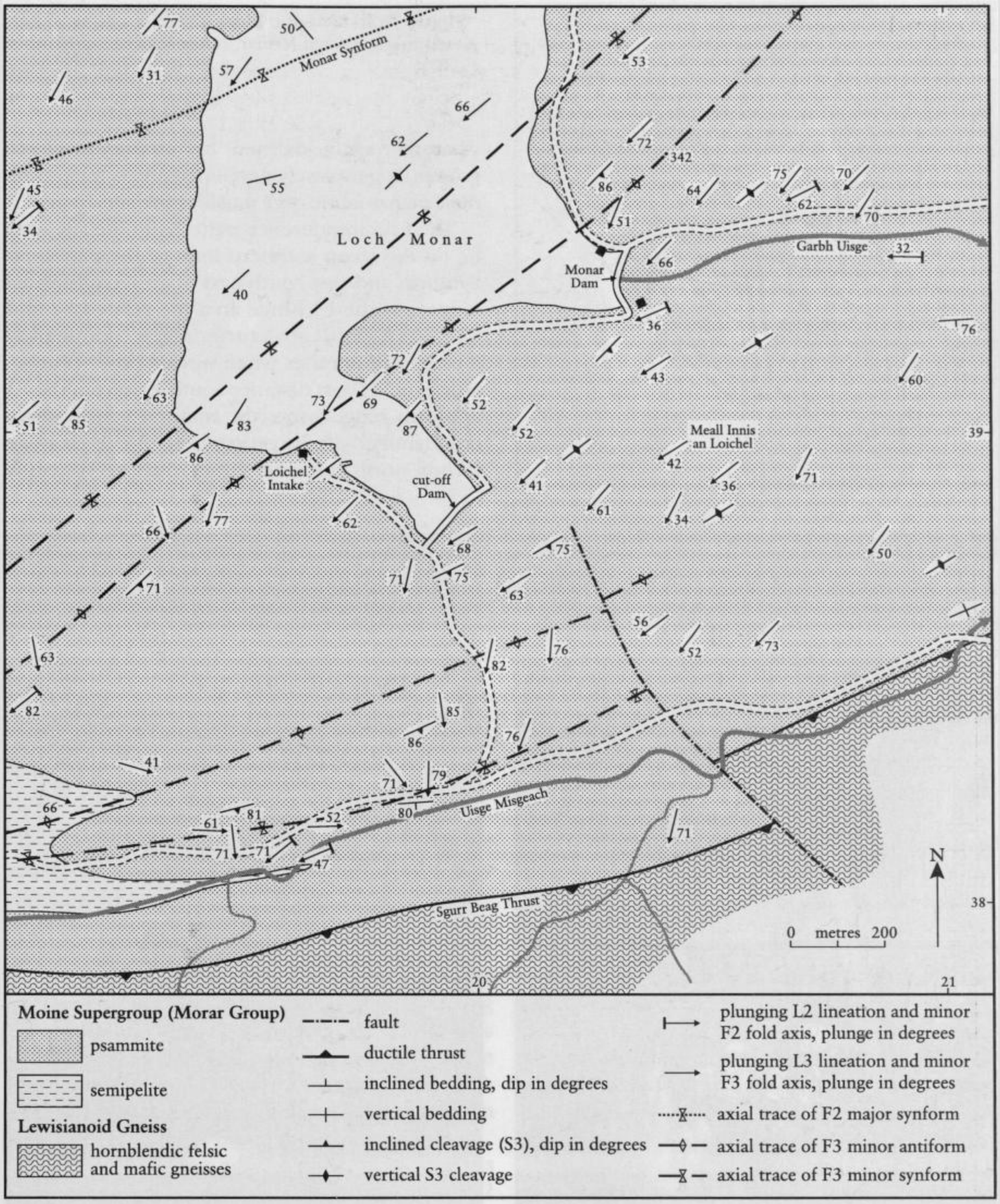
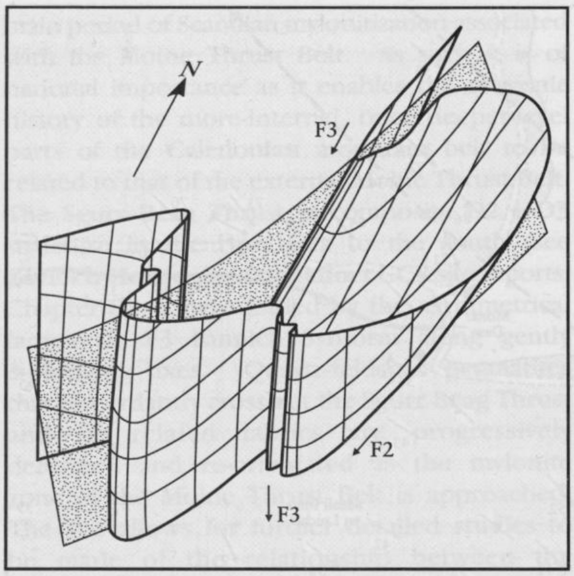


Figure 7.7 Map of the Loch Monar GCR site and immediate surrounding area.

developed, defined by biotite and muscovite. Garnet is developed in the pelitic units, and locally the rocks are gneissose, and quartz and quartz-feldspar pegmatite segregations are present.

In general, the beds dip very steeply to the south and SSE. Minor F2 folds are found on the limbs of the Monar Synform and show S-profiles on the steep southern limb of the synform and Z-profiles on the shallower-dipping northern limb. The F2 folds are refolded by later open to tight, small- to medium-scale, F3 folds whose axial planes strike north-east. A new S3 axial-planar



◂**Figure 7.8** Synoptic block diagram of the superposed folds at Loch Monar. After Ramsay and Huber (1987).

cleavage, again defined by biotite/muscovite growth, is pervasively developed and is the prominent planar fabric over much of the site area.

The fold interference patterns in the site area lie on the steep southern limb of the F2 Monar Synform and just south-east of an F3 antiformal hinge. In the F3 hinge area the related F2 and F3 minor fold structures show dominantly S-profile geometries when viewed down-plunge. However, a short distance south-east from the F3 antiform hinge zone, the minor F3 folds show dominantly Z-profile geometries. The S3 cleavage trends north-east and either dips very steeply

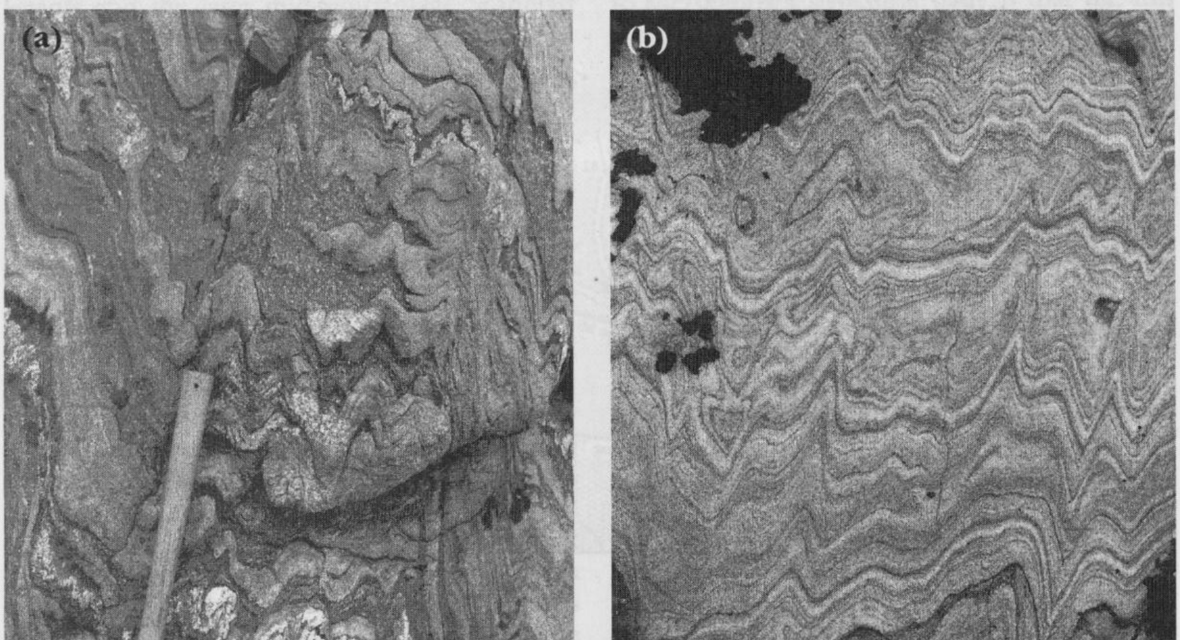


Figure 7.9 (a) Interference fold patterns (F2 + F3) in thinly bedded Morar Group psammites, semipelites and pelites. Pegmatite veins are also present. Type-3 structures dominate here. The hammer is 37 cm long. Low-water exposure at Loch Monar, 300 m north-west of the cut-off dam. (Photo: J.R. Mendum, BGS No. P552321, reproduced with the permission of the Director, British Geological Survey, © NERC.) (b) Interference fold patterns (F2 + F3) in thinly bedded Morar Group psammites and subsidiary semipelites. Type-1, Type-2 and Type-3 interference patterns are all represented here. The hand lens is 6 cm long. Low-water exposure at Loch Monar, 270 m north-west of the cut-off dam. (Photo: J.R. Mendum, BGS No. P552324, reproduced with the permission of the Director, British Geological Survey, © NERC.) *Continued opposite.*

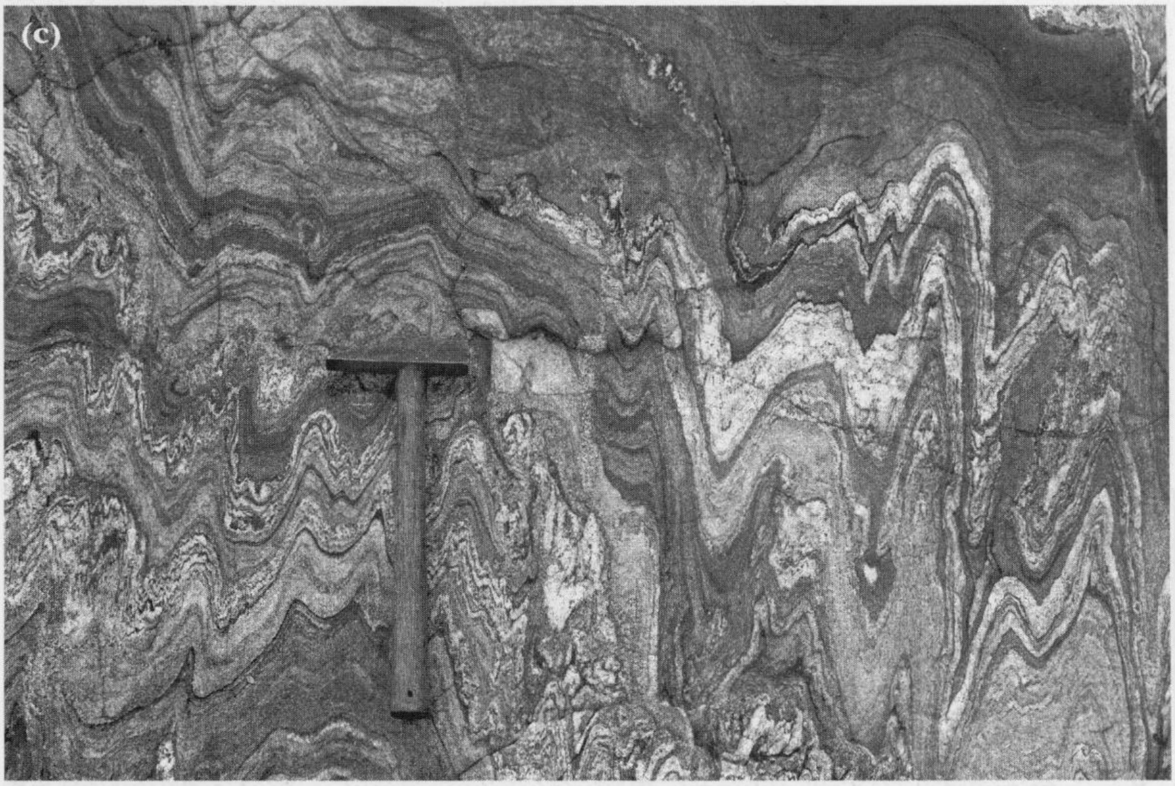


Figure 7.9 – *continued*. (c) Interference fold patterns (F2 + F3) in thinly bedded Morar Group psammites and semipelites with early pegmatite veins. Type-2 and Type-3 interference patterns are represented here. The hammer is 37 cm long. Low-water exposure at Loch Monar, 220 m north-west of the cut-off dam. (Photo: J.R. Mendum, No. P552325, reproduced with the permission of the Director, British Geological Survey, © NERC.)

south-east or is vertical. F2 fold axes plunge moderately to the WSW but locally where they have been re-orientated by D3 structures they plunge steeply south-west. F3 fold axes show a more-consistent direction of plunge, here typically 50°–65° to the south-west, but the amount varies dependent on the orientation of the bedding and earlier F2 folding effects. Ramsay (1967) has shown that there is more variation in the amount and direction of plunge of F3 axes on the steep southern limb of the Monar Synform than on the gentler dipping northern limb.

The combination of minor F2 S-profile folds and minor F3 Z-profile folds results in type-2 'mushroom' fold interference patterns. These occur when the fold axes and axial planes of the two fold phases are at high angle to each other, but the second fold-axis lies more-or-less within the first axial plane (Ramsay, 1967; Ramsay and Huber, 1987). Numerous examples of type-1 'dome and basin' interference patterns also occur, particularly in the south-east part of the section. These form when the axial planes and folds axes of the two fold phases lie at right angles to each other. Close to the hinge area of a minor F3 antiform, both type-2 'mushroom' and type-3 'crooked finger' fold interference patterns occur (Figure 7.9a,b). The latter occur when the fold axes are sub-parallel, but the axial planes are at high angles to each other.

Quartz, quartz-feldspar and granitic pegmatite veins and pods generally post-date the F2 folds and are folded by F3. At the north-west end of the section near the F3 antiformal hinge, these syn- to post-D2 pegmatitic pods and veins are well seen (Figure 7.9a,c). Later syn-F3, near-planar, thin pegmatite veins with diffuse boundaries, which lie sub-parallel to the S3 cleavage, are also developed here. More-extensive migmatization and pegmatite veining occur to the north-west of the site area.

Interpretation

Fold interference structures are common in many parts of the Moine succession of the

North-west Highlands. They are particularly well developed in lithologically varied, thinly layered rocks, typified by the Glenfinnan Group rocks (e.g. above Loch Eilt: see **Fassfern to Lochailort Road Cuttings** GCR site report, Chapter 8). They are also common in Morar Group rocks that lie adjacent to Lewisianoid inliers, such as in upper Glen Strathfarrar (this site), and in the Arnisdale–Loch Hourn area. The Loch Monar site exposes excellent F2 + F3 interference structures of three different types that are geometrically well constrained. Their interpretation by Ramsay (1957a, 1960, 1962) laid the groundwork for subsequent detailed structural studies both in the Moine outcrop and elsewhere in the world, and attempted to explain the mechanisms and constraints on the generation of such complex folding patterns. Ramsay (1957a) recognized the D2 and D3 phases (although referring to them as 'D1' and 'D2') as discrete deformation episodes, but envisaged them as part of the same orogenic movements. The early F2 folds originally had gentle W-plunging axes and formed part of a regional set of major antiformal and synformal structures with an overall northerly vergence. These imply that in this area there was at least a locally northward component of compression responsible for the D2 structures. Regional amphibolite-grade metamorphism, local migmatization, and the development of a penetrative cleavage all accompanied the generation of the folds.

Ramsay (1957a) noted that the geometry and orientation of the F3 folds are controlled by the orientation of the limbs of the F2 folds upon which they are superimposed. He did consider that during D3 there appears to have been some regeneration of F2 folding. The F2 folds appear to have tightened up and in the process the superimposed F3 structures were slightly deformed. The D3 deformation was probably responsible for inverting the steep southern limb of the Monar Synform.

Tobisch *et al.* (1970) assessed the regional structural pattern from Glen Affric to Glen Cannich to Glen Strathfarrar. They allocated the Monar Synform and related minor structures to a locally developed Orrin Phase, which they interpreted as preceded by a Strathfarrar, Cannich and pre-Cannich phase. The Cannich phase gave rise to the main early folds and related schistosity. Monar and Affric phases were also recognized as post-dating the Monar Synform. Powell (1974) rationalized these many fold phases, allocating them to two major penetrative deformation events, D2 and D3. Powell attributed D2 deformation (mainly Cannich Phase) to a Neoproterozoic event, and D3 (mainly Monar Phase) to a Grampian Event. Similar ductile fold and related structures do occur in much of the North-west Highlands, and commonly have been correlated. The F3 event is dated by U-Pb monazite ages of 455 ± 3 Ma from the Glenfinnan area (Aftalion and van Breemen, 1980). If the two fold phases both relate to the Caledonian Orogeny then the D2 event probably occurred in the early Ordovician (*c.* 470–490 Ma) during the Grampian Event. However, fold chronologies are undoubtedly complex, and numerous geochronological studies suggest that pegmatite intrusion and D2-related metamorphism in the Moine rocks occurred during a Knoydartian orogenic event at around 750–800 Ma (e.g. van Breemen *et al.*, 1978; Rogers and Pankhurst, 1993; Tanner and Evans, 2003). In addition, the age of the D3 deformation has been questioned recently: it has been attributed to either the Grampian Event or the Scandian Event (Strachan *et al.*, 2002a).

Conclusions

The small-scale fold interference patterns involving thinly bedded Moine psammites and semipelites at the Loch Monar GCR site are among the best examples found in Britain. The three principal types of interference patterns, 'mushroom', 'crooked finger' and 'dome and basin', all can be seen at the site. Their geometry and mechanisms of formation have been rigorously studied (Ramsay, 1957a, 1960, 1962) and form a classic foundation on which subsequent work on structurally complex folded rocks has been based. Hence the site is of both national and international importance. The fold patterns result from the interaction of two distinct fold phases. The earlier phase resulted in a W-plunging major synform, the Monar Synform, and associated minor folds all with S- to SSE-dipping axial planes. The later phase is manifest as medium- to small-scale folds that plunge moderately steeply south-west with NE-trending near-vertical axial planes. Both fold phases were accompanied by amphibolite-facies metamorphism and developed penetrative axial-planar cleavages.

ABHAINN GLEANN NAM FIADH (GLEN AFFRIC) (NH 194 259)

J.R. Mendum

Introduction

The Abhainn Gleann nam Fiadh GCR site provides clean-washed sections through psammites of the Glenfinnan Group in which sedimentary structures are well seen. Cross-bedding and convolute bedding are locally common within psammite lithologies in the Moine Supergroup, and this GCR site is representative of the style and nature of these sedimentary structures. Although the Moine rocks in the Glen Affric area have been highly deformed and metamorphosed by both Neoproterozoic and Caledonian tectonic events, original sedimentary features are locally preserved, particularly in low-strain areas, albeit in a considerably modified state. In the Glen Affric region, metamorphism attained lower-amphibolite facies.

The Abhainn Gleann nam Fiadh section lies immediately west of the hinge zone of a sideways closing, tight F3 antiform whose axial plane here trends north–south (Figure 7.10). The well-defined sedimentary structures lie within

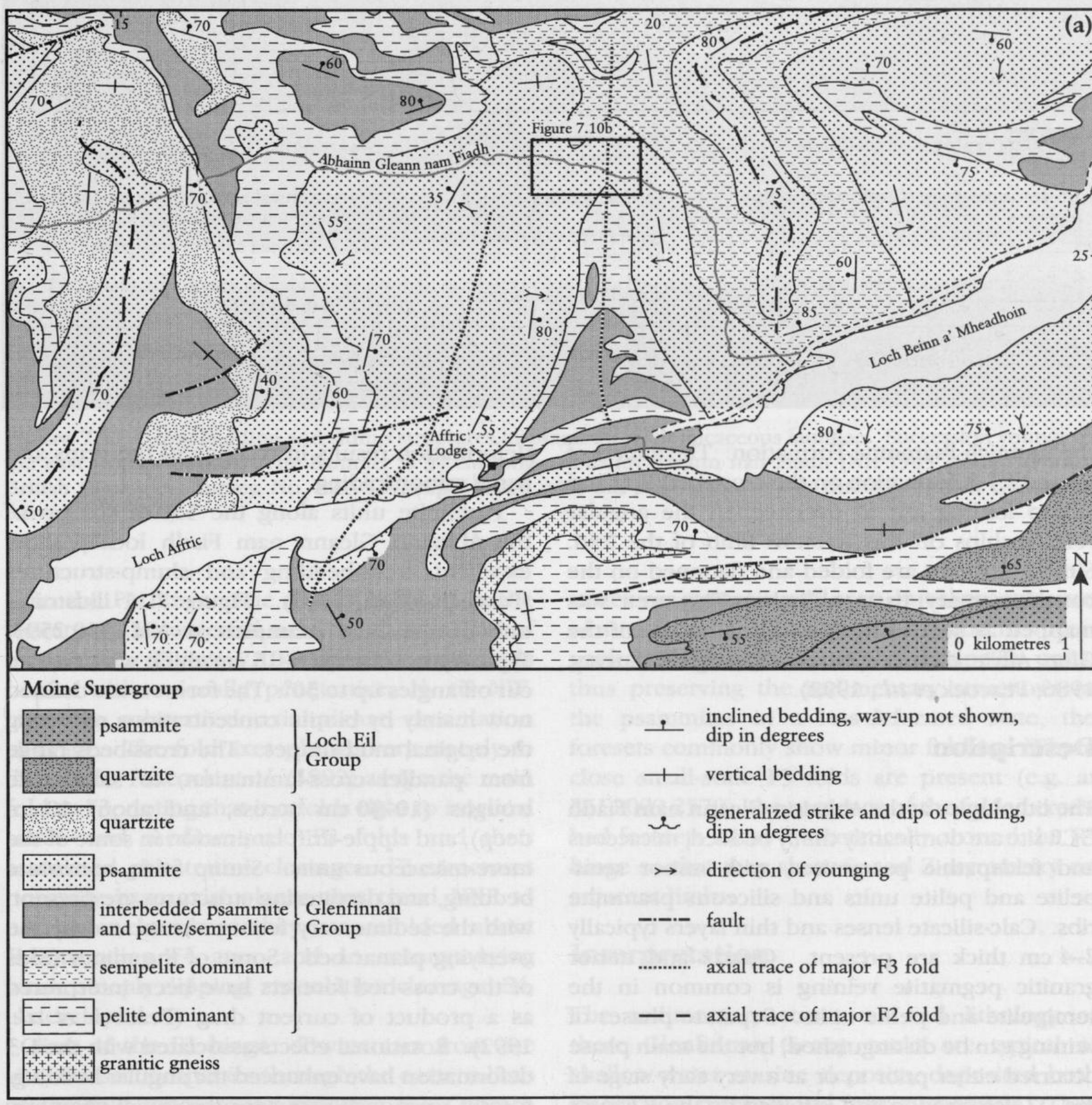


Figure 7.10 (a) Map of the Abhainn Gleann nam Fiadh site area and surrounding geology. *Continued overleaf.*

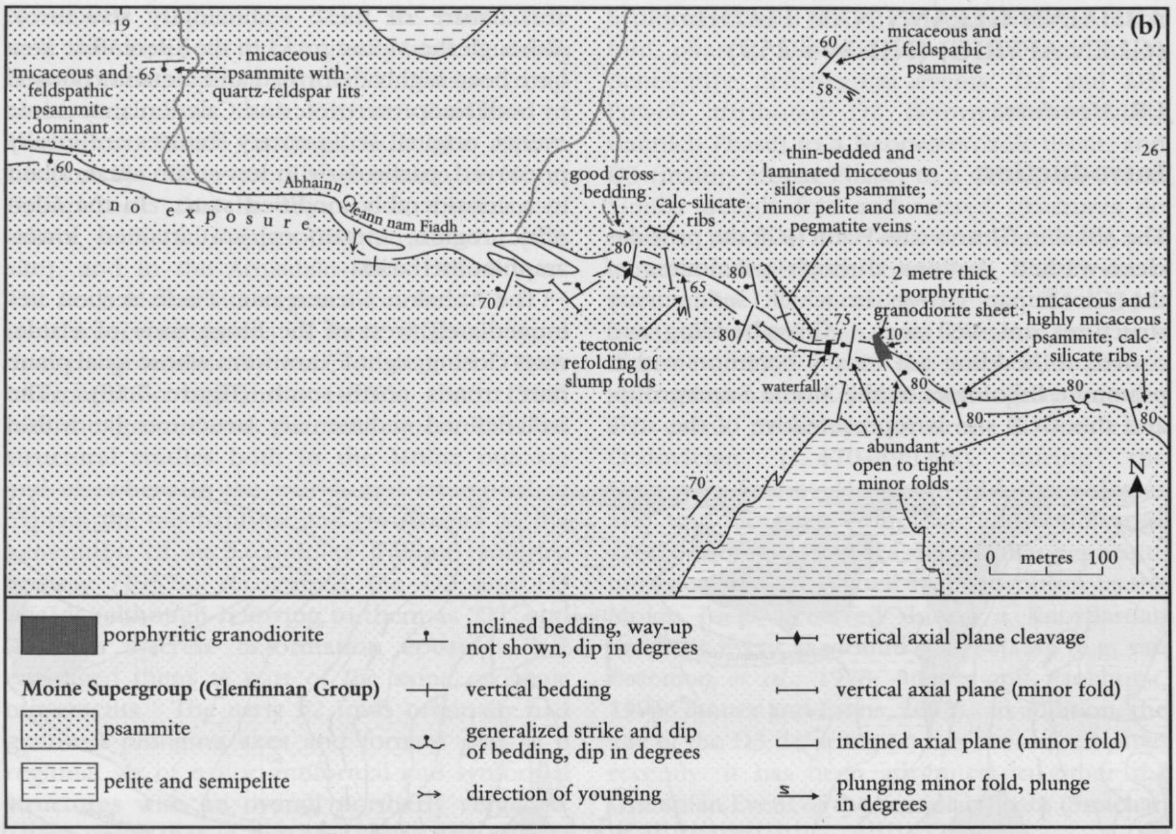


Figure 7.10 – ***continued*****.** **(b) Detailed map of the Abhainn Gleann nam Fiadh site area and surrounding geology.**

the Cannich Psammite Formation. The effects of F2 and F3 deformation on the cross-bedding and slump folding are to oversteepen the angular relationships on this western limb of the fold. Similar features are folded and flattened on the complementary eastern limb. The area was mapped as part of the geological survey of the Glen Affric district (British Geological Survey, 1986; Peacock *et al.*, 1992).

Description

The lithologies at the Abhainn Gleann nam Fiadh GCR site are dominantly thinly bedded, micaceous and feldspathic psammites, with minor semi-pelite and pelite units and siliceous psammite ribs. Calc-silicate lenses and thin layers typically 2–4 cm thick are present. Quartz and minor granitic pegmatite veining is common in the semipelite and pelite units. Separate phases of veining can be distinguished, but the main phase occurred either prior to or at a very early stage of the D2 deformation and is folded by the F2 folds and boudinaged in the S2 cleavage. The later D3 deformation results in rodding of the veins and some minor folding.

Psammite units along the 550 m section of the Abhainn Gleann nam Fiadh locally show excellent cross-bedding and slump-structures (Peacock *et al.*, 1992). Figure 7.11 illustrates one of the best examples at NH 1950 2593. Typically cosets are 5–15 cm thick with foreset cut-off angles up to 30°. The foresets are defined now mainly by biotite concentrations reflecting the original mud drapes. The cross-beds range from parallel cross-lamination, to small-scale troughs (10–30 cm across, and about 10 cm deep), and ripple-drift lamination in some of the more-micaceous units. Slump folds, convolute bedding, and dewatering structures are present, with the sedimentary features truncated by the overlying planar bed. Some of the minor folds of the cross-bed foresets have been interpreted as a product of current drag (Peacock *et al.*, 1992). Rotational effects associated with the D3 deformation have enhanced the angular bedding-foreset relationships where the initial geometry has been favourably orientated.

Figure 7.11 Cross-bedding and slump structures in psammite with micaceous laminae. Succession youngs to the east (top of photo). The hammer is 37 cm long. Abhainn Gleann nan Fiadh (NH 1945 2591). (Photo: British Geological Survey, No. P219449, reproduced with the permission of the Director, British Geological Survey, © NERC.)

In the F3 hinge zone that is exposed in the vicinity of the waterfall near the eastern end of the section (Figure 7.10), open to tight folds occur, with a locally penetrative, N- to NW-trending subvertical axial-planar crenulation cleavage. The fold axes plunge very steeply to the north. Peacock *et al.* (1992) assign the main fold to F3, noting that it refolds tight to isoclinal small- and medium-scale F2 folds and their associated penetrative cleavage. F3 structures normally have axial planes that trend NNE to north-east, but here they are refolded about E–W-trending F4 axes, and an accompanying weak, steeply dipping, crenulation cleavage, S4, is developed.

East of the F3 hinge, downstream from the site, the section passes through the eastern limb of the fold, once more exposing the Cannich Psammite Formation. Cross-beds and slump structures are again well seen, but show evidence of attenuation. Although deformation has been preferentially taken up in the semipelite units, thus preserving the sedimentary structures in the psammites in a less-deformed state, the foresets commonly show minor folding. Where close small-scale F3 folds are present (e.g. at NH 2009 2570), the vergence of the folded cross-bed foresets varies systematically around the F3 hinge so that they show S- and Z-asymmetry on adjacent limbs.

Interpretation

The sedimentary structures and lithology of these Glenfinnan Group rocks are typical of shallow-water marine deposits, deposited both by traction currents and from suspension. They imply that the beds young towards the F3 antiformal hinge, i.e. towards the east along the stream section west of the hinge, and regionally towards the south and south-east. The detailed mapping of the area (British Geological Survey, 1986; Peacock *et al.*, 1992) shows that the psammite–pelite–semipelite sequence is folded into large-scale, tight to isoclinal F2 folds, refolded by the F3 structures. Ductile thrusts are also present. South-west from the site area the Cannich Psammite Formation defines a tight and near-vertically plunging F2 fold, whose hinge lies just south of the eastern part of Loch Affric. Hence the Abhainn Gleann nam Fiadh section lies on the eastern limb of a regional F2 fold but a western limb of an F3 antiform. Undoubtedly D3 deformation has tightened the earlier F2 fold but it seems that the cross-bedding and slump structures have avoided substantial tectonic modification owing to their initial geometry and fortuitous position relative to the F2 and F3 hinge zones. On the eastern limb of the F3 structure some D3 flattening effects are evident.

Ramsay (1967) documented the variations in angle between truncated foresets and bedding around a tight fold in psammite from the Northern Highlands of Scotland. He showed that the maximum angle is not found along the axial trace of the fold (i.e. in the hinge zone), but on one of the fold limbs where the bedding lies at 45°–55° to the axial trace. Dependent on the original geometry of the foresets, they may be flattened or oversteepened on opposite limbs. This is in line with theoretical predictions for the deformation of pre-existing angular structures around tight folds formed by a combination of simple shear followed by pure shear. Internal rotation of sedimentary features within individual psammite units can modify this geometry dependent on the local strain pattern and the variations in lithology of the folded sequence.

Conclusions

Within the well-exposed and clean-washed section of the Abhainn Gleann nam Fiadh, cross-bedding, convolute bedding and slump structures are preserved in the Cannich Psammite Formation. The psammite unit lies within a strongly deformed and metamorphosed sequence of Neoproterozoic Glenfinnan Group psammites, semipelites, pelites and subsidiary quartzite units. The sediments were originally part of a shallow-marine, possibly tidally influenced, succession of sands, silts and muds with some thin reworked clean-washed sand lenses. Despite the strong deformation and lower amphibolite-grade metamorphism, the sedimentary structures are clear and eminently recognizable, and unequivocally show the direction of younging. They are by no means unique in the Moine Supergroup, but the Abhainn Gleann nam Fiadh section is of regional importance and shows an excellent representative example of these features.

The sedimentary structures owe their preservation to a combination of favourable circumstances. The psammite occurs on the limb of a major F2 fold in a position where original bedding-foreset angles were preserved or possibly rotated to slightly steeper angles during D2 deformation. Subsequently, a near-vertically plunging F3 major fold developed. The sedimentary structures on both the western and eastern limbs of this F3 fold have been affected differently. Those on the western limb are little deformed, with their original angles slightly oversteepened, whereas those on the eastern limb have been flattened and locally folded by the D3 deformation.

ATTADALE (NG 913 377)

A.J. Barber

Introduction

Deformed basal metaconglomerate of the Moine succession is exposed over a distance of 100 m along the A890 road section adjacent to the avalanche shelter south-west of Attadale. The metaconglomerate underlies the Western Unit of the Lewisianoid Glenelg–Attadale Inlier on its western margin and the section represents an inverted unconformity. The discovery of this outcrop contributed to the resolution of the controversy concerning the status of the Lewisianoid inliers in the Moine. The section also clearly demonstrates the different sequence of structural and metamorphic events that have affected the Lewisianoid gneiss basement and its Moine metasedimentary cover during the Caledonian and possibly earlier Knoydartian orogenic events.

The Glenelg–Attadale Inlier is the largest and most westerly of the Lewisianoid basement inliers within the Moine outcrop (Figure 7.2) and the Attadale GCR site lies close to its northern tip. The general dip of the foliation in both Moine and Lewisianoid rocks is gently or moderately eastwards, and hence the Lewisianoid inlier structurally overlies the Moine rocks to the west, which are themselves locally interleaved with further Lewisianoid gneiss sheets. This structural succession rests in turn on the Moine Thrust.

The Attadale area was mapped by L.W. Hinxman in 1902–1903 as part of the primary geological survey of the Lochcarron (Sheet 82) (Geological Survey of Scotland, 1913b) and was described in the Central Ross-shire memoir (Peach *et al.*, 1913). A detailed study by May (1959) focused on the structural and metamorphic evolution of the Lewisianoid and Moine rocks. May (1959) suggested that the 'conglomeratic' rocks were produced tectonically by the disruption of layered gneiss and folded quartz veins during deformation, but new exposures created by the construction of the A890 pointed to a sedimentary origin for the metaconglomerate. A brief description of this locality was published in a field meeting report (Barber and Soper, 1973, p. 227, plate 10). Unfortunately, recent landslips and remedial work have combined to destroy or conceal many of the exposures originally described. The reader is referred to the less-accessible but better exposed localities on the craggy spur above.

Description

Moine rocks forming the western margin of the Glenelg–Attadale Inlier outcrop on hill-slopes along the southern shores of Loch Carron between Attadale and Ardnarff (Figure 7.12). Moine psammites form the core of the complex, NE-plunging Ardnarff Antiform, whose axial plane dips south-east. The fold closes in poorly exposed ground to the south of Ardnarff. On the south-eastern limb, Moine psammites are overlain by semipelites, exposed in the road section south-west of the avalanche shelter, and then by deformed metaconglomerate, which is exposed on both sides of the shelter. Exposures of metaconglomerate can be traced across the hillside to the south-west of the road section for a distance of 500 m. Lewisianoid gneisses with interlayered amphibolitic mafic and ultramafic bodies, and cross-cutting amphibolite mafic dykes, overlie the metaconglomerate to the north of the shelter and also on the hillsides above the road section. The gneisses are similar to those as described in the **Avernish** GCR site report (this chapter). The Moine and Lewisianoid sequence is patently inverted.

The A890 road section along the south-east shore of Loch Carron, between Attadale and Ardnarff, is cut into steep and unstable hill-slopes. The railway between Kyle of Lochalsh and Dingwall runs parallel to the road. In the early 1970s an extensive landslip blocked the railway for several months. As a protection from further falls an avalanche shelter was built over both the road and railway. The road section on either side of the avalanche shelter provides intermittent exposure of the metaconglomerate in cliffs up to 30 m high. Further exposures occur in rocky knolls on the hill-slopes of Aonach Baile na Creige.

In the road section, exposures commence 200 m south-west of Cuddies Point (NG 917 384), where a 15 m-high cliff on the south-eastern side of the road, covered by wire netting, exposes near-horizontally layered and foliated Lewisianoid hornblendic and biotitic felsic gneisses. The gneisses contain bodies of pink quartzofeldspathic gneiss, with biotite-rich schlieren flattened in the foliation, and a 10 m × 4 m lens of amphibolite.

Just to the north-east of the avalanche shelter, the gneisses are underlain by a massive dark-brown rock containing pale-pink elongated streaks. This is the basal Moine metaconglomerate, and the pink streaks are deformed quartzofeldspathic pebbles. The 30 m-high cliff to the south-west of the avalanche shelter is composed entirely of metaconglomerate (Figure 7.13). Locally, pebbles are up to 5 cm long and 2 cm wide and are closely packed. The pebbles include quartzofeldspathic gneiss, pegmatite and vein quartz. Elongated quartzofeldspathic streaks not readily recognized as pebbles also occur. Differences in pebble shape can be attributed to variations in the competence of the rock types. In exposures on the hillside above the road, pebbles are elongated on foliation surfaces to form rods, up to 8 cm in diameter and 1 m long, which plunge at approximately 20° to the north-east (May, 1959).

Thin sections show that the metaconglomerate matrix is composed largely of mafic minerals including biotite, muscovite, epidote and actinolitic hornblende, with quartz and feldspar. The prismatic hornblende porphyroblasts locally

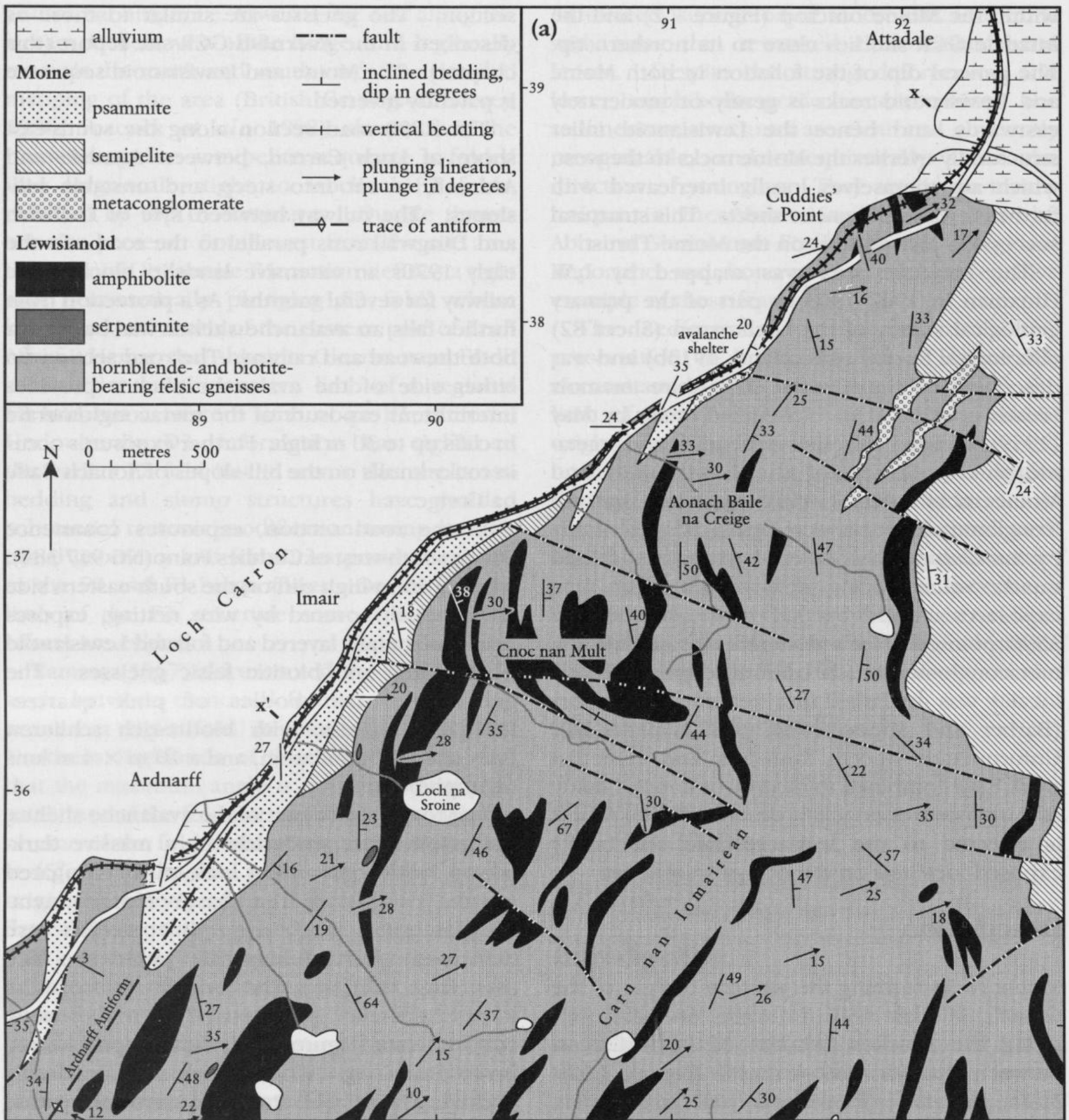


Figure 7.12 Geological map (a) and cross-section (x–x') (b) of the Attadale GCR site and surroundings Based on field mapping by F. May, and Barber and May (1976).

Figure 7.13 Flattened quartzofeldspathic clasts in schistose matrix, basal Moine conglomerate, above avalanche shelter, Attadale. The hammer is 37 cm long. (Photo: A.J. Barber.)

attain 2–5 cm in length, show a random orientation, and may penetrate the pebbles. Similar hornblende porphyroblasts are abundant in the Lewisianoid gneisses adjacent to the metaconglomerate outcrops (Barber and May, 1976). The hornblende porphyroblasts may be broken and bent and enclosed in augen within the matrix schistosity defined by aligned micas, but commonly they are elongate and define the lineation. In thin section they are partially or completely replaced by biotite (May, 1959).

Road cut exposures continue intermittently southward to Ardnarff. Three hundred metres to the south-west of the avalanche shelter, the metaconglomerate is underlain by dark-grey Moine pelite containing psammitic layers up to 1 m thick. The pelite is schistose and composed of biotite with subsidiary muscovite, quartz, plagioclase, epidote and clinozoisite; rare garnet crystals contain epidote inclusions and are enclosed by rims of biotite (May, 1959). Layering in the pelite is folded on a decimetre-scale into NE-plunging recumbent folds.

A kilometre farther to the south-west, near Ardnarff, similarly recumbently folded layered Lewisianoid gneisses are succeeded by Moine psammites. The psammites are composed predominantly of quartz and feldspar, with millimetre- to centimetre-thick micaceous layers and rare magnetite and epidote-rich layers up to 2 cm thick. Small garnet crystals occur rarely (May, 1959).

The rodding lineations in both the Lewisianoid and Moine rocks of the site area plunge to the north-east, parallel to the recumbent fold axes. In places, a fine ESE-plunging mineral lineation is superimposed on the rodding. Exposures along the road section show that Lewisianoid gneisses and interlayered Moine pelites and psammites are folded into reclined folds with NE-plunging axes. This accords with the fold sequence established elsewhere in the Glenelg–Attadale Inlier, for instance at the **Beinn a' Chapuill** GCR site.

Interpretation

At the Attadale GCR site, typical Lewisianoid gneisses of the Western Unit of the Glenelg–Attadale Inlier are structurally underlain by metaconglomerate containing clasts of quartzo-feldspathic gneiss and quartz-feldspar pegmatite. The felsic gneiss clasts and the dominantly mafic matrix to the metaconglomerate are probably derived mainly from the Lewisianoid basement. The contact between the Lewisianoid gneisses and the Moine succession evidently represents an inverted unconformity. The metaconglomerate is structurally underlain by a basal semipelite unit, followed by psammites, a sequence compatible with the basal Moine succession elsewhere in the North-west Highlands (Figure 7.3; Ramsay and Spring, 1962; see also **Allt Cracaig Coast** GCR site report, this chapter). Note that *c.* 800 m ESE of the avalanche shelter metaconglomerate is tightly infolded with Lewisianoid gneisses on the eastern side of the Glenelg–Attadale Inlier (Figure 7.12a). The units dip moderately south-east and the Basal Semipelite Formation is present along much of this margin, showing that the sequence here is regionally right-way-up and hence the Moine–Lewisianoid unconformity is repeated by large-scale tight recumbent folding.

In the road section between Attadale and Ardnarff, Moine metasedimentary rocks are interleaved with Lewisianoid gneisses and both units are folded into large-scale sideways-closing recumbent folds with NE-plunging axes. The Ardnarff Antiform is interpreted as a composite structure involving two earlier phases of folding. The first fold phase (D1) resulted in the inter-layering of the Lewisianoid and Moine units (e.g. **Rubha Camas na Cailinn** GCR site). Small-scale representatives of these long-limbed isoclines are present throughout the Moine outcrops in the area of the inlier. The second fold phase (D2) resulted in recumbent folding of the inter-layered Lewisianoid and Moine rocks and the formation of the associated lineations. This fold phase corresponds with the Beinn a' Chapuill phase of folding in Glenelg (e.g. **Beinn a' Chapuill** GCR site report, this chapter). The Ardnarff Antiform (Figure 7.12a) is primarily a later open fold, complementary to a synform to the west that passes through Am Meallan (Barber and May, 1976, fig. 2).

Folding was accompanied and followed by recrystallization of the rocks under amphibolite-facies metamorphic conditions, with the growth of hornblende porphyroblasts, which penetrate pebbles deformed during D2. Later deformation (?D3), represented by fold structures in the Moine, resulted in the formation of a new foliation which disrupted the hornblende porphyroblasts. Biotite, partially or completely replacing hornblende, recrystallized in the new foliation.

Conclusions

The Attadale road section provides the clearest and most complete cross-section across the western margin of the Glenelg–Attadale Inlier. It provides the most convincing outcrop of a local basal metaconglomerate to the Moine succession, structurally overlain by Lewisianoid gneisses resulting in an inverted unconformity. The site is of national importance in that it demonstrates unequivocally that the Lewisianoid gneisses represent the crystalline basement to the Moine and are not an intrinsic part of the Moine sequence, as once thought. Despite intense deformation that has brought the layering in the Lewisianoid basement into parallelism with the contact with its overlying Moine metasedimentary cover, original unconformable relationships can be inferred from the presence of derived Lewisianoid clasts in the metaconglomerate.

The section also demonstrates that Lewisianoid basement and Moine cover rocks were both affected by the same sequence of structural and metamorphic events during the Caledonian Orogeny and possibly during Knoydartian deformation and metamorphism. Early inter-layering of Moine and Lewisianoid rocks was followed by tight folding and recrystallization of both rock units in the amphibolite facies.

DORNIE–INVERINATE ROAD SECTION (A87) (NG 883 258–NG 906 231)

A.J. Barber

Introduction

The Dornie–Inverinate Road Section provides a highly accessible and well-exposed section through both the Western and Eastern units of the Lewisianoid Glenelg–Attadale Inlier and across the intervening shear-zone. Along strike it can be demonstrated that lenses of Moine metasediments were incorporated into this shear zone, indicating that at least the final juxtaposition of the two Lewisianoid units occurred after Moine deposition. The GCR site demonstrates the range of lithologies and structural features within the two rocks units. The site contains structures that are common to both Moine and Lewisianoid rocks and hence must post-date deposition of the Moine succession in the early Neoproterozoic. Examples of the Lower Devonian suite of lamprophyre dykes are found in the section. These relate to the Ratagain Pluton, which outcrops on the south-west side of Loch Duich. Dykes of the widespread Late Carboniferous camptonite-monchiquite suite are also seen (May *et al.*, 1993).

In the 1950s there was a major controversy among Highland geologists concerning the nature of inliers of Lewisianoid rocks within the Caledonian mountain belt, east of the Moine Thrust Belt. Some workers maintained that gneissose Lewisianoid rocks in the central part of the Northern Highlands, at Fannich, Scardroy and Monar, were an intrinsic part of the Moine stratigraphical succession (Sutton and Watson, 1953, 1954; Ramsay, 1954), rather than basement gneisses, as proposed by the earlier work of the Geological Survey (Peach *et al.*, 1913). This controversy was resolved by studies in the Glenelg–Attadale Inlier on the western margin of the mountain belt, where clear contrasts between the lithologies, structures and geological histories of the Lewisianoid gneisses and the surrounding metasedimentary Moine rocks were recognized (Peach *et al.*, 1910; Clifford, 1957; Ramsay, 1957b; Sutton and Watson, 1958; Sanders, 1972; Barber and May, 1976; Barber *et al.*, 1978; May *et al.*, 1993). The Dornie–Inverinate Road Section was described in detail by Barber and Soper (1973) and by Barber *et al.* (1978). It has been studied more recently by Storey (2002). Although the Archaean age of most of the Lewisianoid gneisses is now accepted, the relationship between the Western and Eastern units is not yet fully understood (e.g. see Storey, 2002; Storey *et al.*, 2004).

Description

A good section is provided by the exposures along the Dornie–Inverinate Road Section between Eilean Donan Castle at Dornie and the bridge across the An Leth Allt at Inverinate (Figure 7.14). The shear zone between the Western and Eastern units occurs about 800 m south-east of Eilean Donan Castle; the Western Unit is exposed for about 1 km north-west from here, whereas the Eastern Unit is exposed for some 3 km to the south-east. The Western Unit consists predominantly of pale-grey and pink, layered hornblende- and biotite-bearing felsic gneisses. The gneissose layering and foliation dip moderately to steeply to the east and a mineral lineation plunges to the north-east. Amphibolite occurs as thin layers, irregular clots, or thicker sheets within the gneisses, and pods of ultramafic rock are also present. An ultramafic pod, a few metres across, composed of a mass of randomly arranged dark-green actinolite crystals, occurs near the castle (NG 883 259). The felsic gneisses are interlayered with large lenticular bodies of pink homogeneous granodioritic gneiss, representing felsic intrusions, and black and white speckled amphibolite, representing mafic intrusions. Within a *c.* 50 m-thick amphibolite mafic sheet at NG 885 254, is a prominent white layer of coarse-grained meta-anorthosite, a few metres thick. It is composed largely of plagioclase with secondary epidote and garnet-pyroxene streaks, partly altered to amphibole (Barber *et al.*, 1978). The relict granulite-facies assemblages present in this large mafic sheet provide evidence of an early granulite-facies metamorphic event, which pre-dated the pervasive retrogressive amphibolite-facies metamorphism of the inlier.

About 1 km to the south-east of the castle at NG 887 252, there is a rapid transition from Lewisianoid gneisses, through badly weathered material, into mica-schist with a pervasive E-dipping schistosity. The schist contains *c.* 30 cm-long amphibolite lenses and small, scattered, white feldspar augen, and is interpreted as a 'tectonic schist', marking a major shear-zone developed under amphibolite-facies conditions. The shear zone that separates the Eastern and Western units, extends for over 4 km to the north-east where it joins the main outcrop of the Moine near Loch Long, and for over 12 km south-westwards through Glenelg to Loch Hourn (Figure 7.2). The nature of the rocks in the shear zone varies considerably along strike. They include lenses of Moine psammite, schistose pelite and semipelite with deformed pebbles, representing the basal meta-conglomerate and basal semipelite of the Moine succession, and lenses of migmatitic gneiss and amphibolite, derived from the underlying Western Unit. Large lenses of felsic and mafic Lewisianoid rocks occur within the shear zone at Creag nan Spor (NG 891 262), and

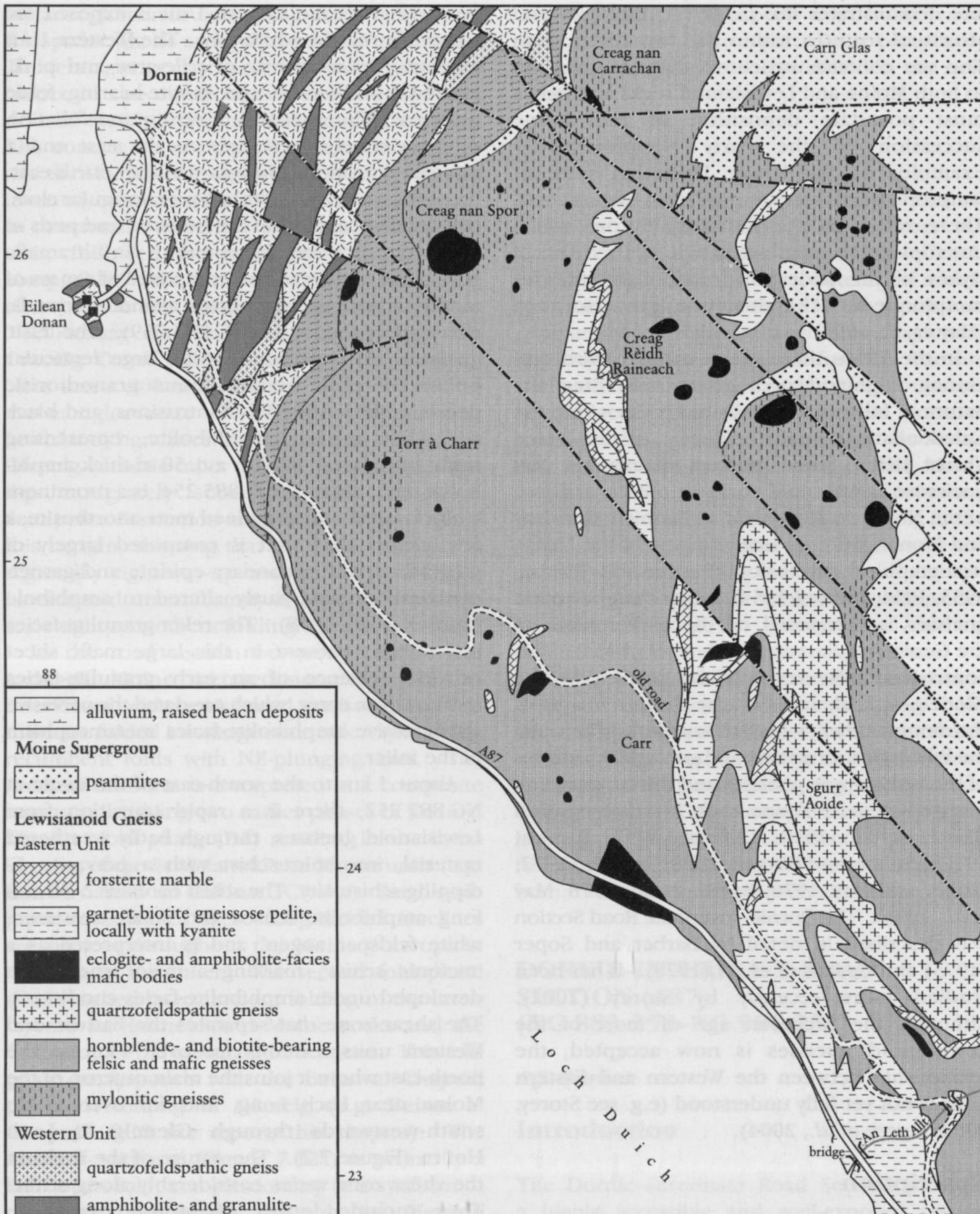


Figure 7.14 Map of the Dornie–Invernate Road Section GCR site. Based on field mapping by A.J. Barber.

lenses of Moine psammite and semipelite occur at Creag nan Carrachan (NG 898 266) (Figure 7.14).

South-east of the shear zone is the Eastern Unit of the Glenelg–Attadale Inlier. Like the Western Unit, the Eastern Unit consists predominantly of hornblende- and biotite-bearing felsic gneisses, but it also includes a great variety of other rock-types, mainly of sedimentary origin, such as metacarbonate rocks ('marbles'), kyanite-bearing gneissose pelites, graphite schistose pelites and iron-rich rocks. It also includes mafic and ultramafic meta-igneous rocks, now amphibolite and eclogite (see **Totaig** GCR site report, this chapter). In the road section, the tectonic schist passes rapidly south-east into blastomylonitic gneiss. The blastomylonite is layered on a millimetre- to centimetre-scale with alternating felsic and mafic layers, enclosing augen of garnet and feldspar porphyroclasts and rock fragments. At road level, the blastomylonitic layering is seen folded into long-limbed isoclinal folds. Adjacent to the contact with the schist, the layering is concordant with the schistosity, but within a few tens of metres it is folded on the scale of tens of metres, as seen in the road cutting at NG 888 249. The resultant folds have vertical axial planes and E-plunging axes, but are refolded on horizontal axial planes. In the lower part of the cliff, folded mylonites are cut by quartzofeldspathic veins, which themselves are folded in the upper part of the cliff.

To the south-east, the blastomylonites pass gradually into fine-grained felsic gneisses with thin layers of amphibolite, still strongly folded on E-plunging fold axes, with mullions and folded rods exposed in the cliff face (NG 896 242). Similar outcrops are well exposed farther to the NNE on Creag nan Spor (Figure 7.15). The gneisses enclose mafic lenses and rounded bodies of coarser amphibolite and eclogite. Outcrops of forsterite-bearing metalimestone ('marble'), some with diopside nodules, and calc-silicate rocks occur in the grass slopes

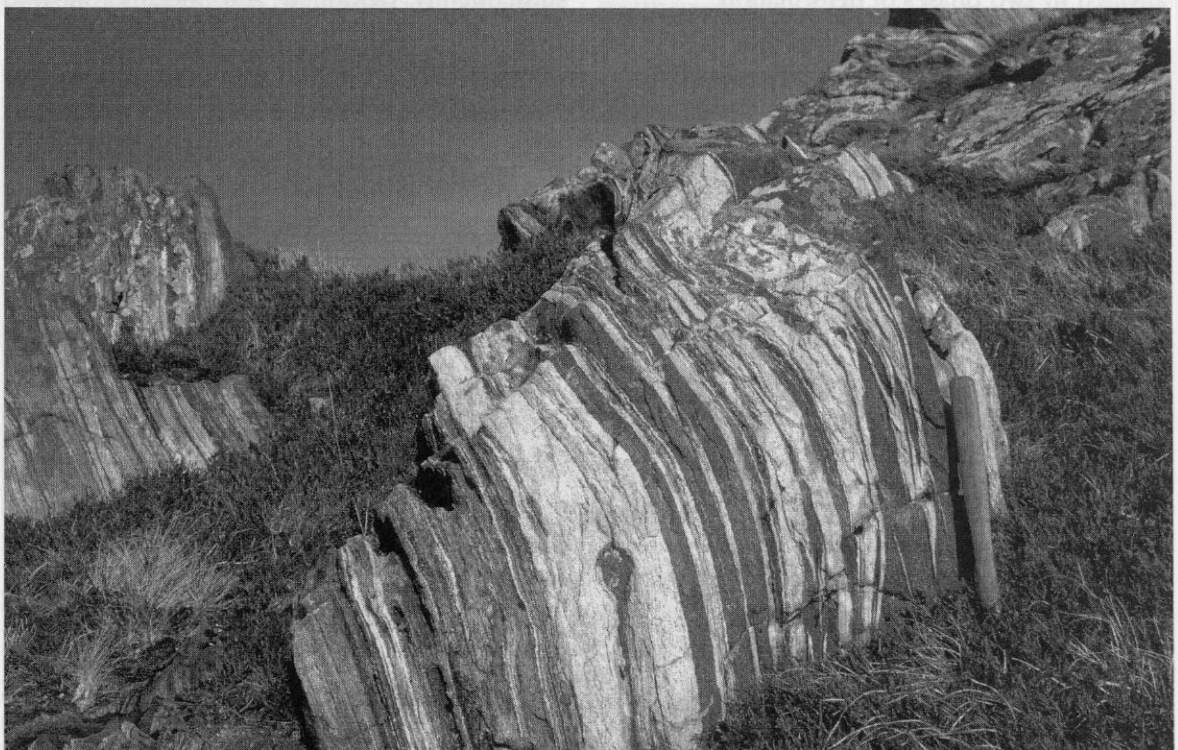


Figure 7.15 Layered gneiss produced by strong attenuation of quartzofeldspathic gneiss and amphibolite, Eastern Unit, Creag nan Spor. The hammer shaft is 33 cm long. (Photo: A.J. Barber.)

adjacent to the road below Carr (NG 894 244 and NG 902 237), and more extensively in the hill-slopes above the road (Figure 7.16). A 1 m-thick diopside-rich calc-silicate layer forms a vertical reaction zone between pink meta-limestone ('marble') and quartzofeldspathic gneiss in the cliff at NG 896 242. The south-eastern part of the section is composed predominantly of garnetiferous biotite-kyanite pelitic gneiss. The presence of kyanite suggests an origin as aluminous muddy sediments and attests to high-pressure metamorphism (see also **Druim Iosal** GCR site report, this chapter). At NG 905 233 garnetiferous kyanite-biotite gneissose semipelites are interfolded with hornblendic quartzofeldspathic gneisses. In places the gneissose semipelites contain veins of white quartz-feldspar pegmatite. Pegmatites concordant with the foliation are typically recrystallized, whereas cross-cutting pegmatites are folded or broken up into boudins; in one instance boudins pass around a fold in the layering, suggesting that the pegmatite was affected by two phases of deformation.

An ENE-trending brick-red lamprophyre dyke cuts the shear zone in the road section at NG 887 252. It belongs to the radial swarm related to the Silurian-age Ratagain Pluton, which outcrops on the south-western side of Loch Duich (Nicholls, 1951; May *et al.*, 1993). Two NE-trending, vertical basalt dykes with xenoliths, belonging to the late Carboniferous camptonite-mochiquite swarm cross-cut the Western Unit at NG 884 257.

Interpretation

The Dornie–Inverinate Road Section GCR site provides a continuous outcrop across the two units of the Lewisianoid Glenelg–Attadale Inlier and the intervening shear-zone. The Lewisianoid basement contains relics of its pre-Caledonian history, demonstrating that it represents continental fragments of different origins, ages, and with varied metamorphic and structural histories. It also demonstrates the extent to which the basement was subsequently deformed and metamorphosed,

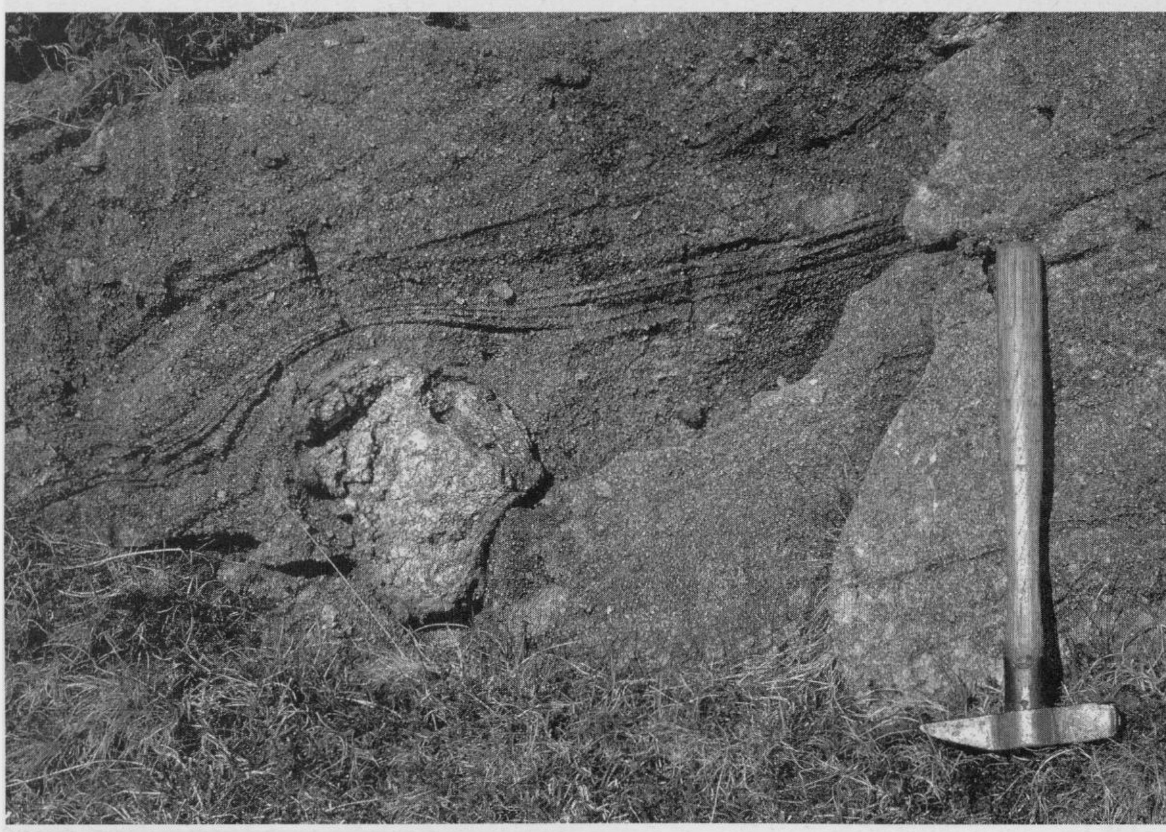


Figure 7.16 Diopside nodule enclosed in layered forsterite marble, Eastern Unit, Creag Reidh Raineach. The hammer is 37.5 cm long. (Photo: A.J. Barber.)

first during the Knoydartian event, and later during the Caledonian Orogeny.

Both the Eastern Unit and the Western Unit have been metamorphosed to very high grades: the Eastern Unit under eclogite-facies conditions at temperatures of 700°–800° C and pressures of 16–20 kbar (Sanders, 1988, 1989; Storey *et al.*, 2005); the Western Unit under granulite-facies conditions, at similar temperatures but at pressures of < 10 kbar (Storey, 2002). Isotopic ages show that metamorphism in the Eastern and Western units occurred at different times. The major metamorphic events within the Western Unit have been dated at between 2800 Ma and 2600 Ma and at *c.* 1750 Ma, with some evidence of disturbance at *c.* 1000 Ma (Moorbath and Taylor, 1974; Storey, 2002; Friend *et al.*, 2008). The ages obtained from the Western Unit are similar to those from Lewisian rocks of north-west Scotland and the Outer Hebrides, which form the Caledonian Foreland (e.g. Cohen *et al.*, 1991; Corfu *et al.*, 1994; Friend and Kinny, 1995). In contrast, the Eastern Unit underwent pervasive eclogite-facies metamorphism between 1100 Ma and 1000 Ma (Sanders *et al.*, 1984), and subsequent retrogression at *c.* 995 Ma (Brewer *et al.*, 2003; Storey *et al.*, 2005). Before this Grenvillian event, there is evidence of a *c.* 1450–1500 Ma metamorphic event and possibly of Archaean protoliths, but there is no evidence of any event at *c.* 1750 Ma (Storey, 2002). The evolution of the Eastern Unit has parallels with that of the Grenville Province, which forms the eastern margin of the Canadian continental shield (Rivers, 1997).

A possible interpretation of these relationships is that an easterly extension of the Lewisian basement was affected by an orogenic event at approximately 1050 Ma, corresponding to the Grenville Orogeny of eastern Canada. In this scenario the highly deformed zone between the Eastern and Western units in the Glenelg–Attadale Inlier would represent the Grenville Front, a zone of overthrusting marking the western limit of structural and metamorphic reworking of the older basement. It is also possible that the Eastern and Western units originated quite independently as separate segments of continental crust, tectonically juxtaposed during the Grenville Orogeny. In either case, the two units were certainly in proximity before deposition of the Moine Supergroup, which now unconformably overlies both units. The Grenvillian shear-zone boundary was reactivated during the Caledonian Orogeny.

The central part of the Western Unit shows only minor evidence of Caledonian reworking and granulite-facies assemblages and earlier intrusive and structural relationships in the gneisses are still present (see also **Avernish** GCR site report, this chapter). Towards the upper boundary of the Western Unit, the strike of the lithological units (e.g. the amphibolites) and the early foliation curve to become concordant with the overlying shear-zone. The Moine rocks within the shear zone have been strongly recrystallized and display a penetrative schistosity parallel to its margins. In the immediate hangingwall, the Eastern Unit is deformed and recrystallized into blastomylonite. Isoclinal folds of the layering that are seen in the road section relate to this mylonite formation event. Blastomylonite is also locally developed at the upper contact of the Eastern Unit with the main Moine outcrop (Figure 7.14). Farther south-west, near Glenelg, Storey *et al.* (2004) reported various shear-sense indicators, including delta-shaped porphyroclasts and shear bands cutting pegmatite stringers, which suggest a top-to-the-W shear sense across the main shear-zone.

In the central part of the Eastern Unit, in the hills above the road section, the original Lewisianoid rock-types and relationships have been preserved, but lithological units are folded into large-scale reclined folds with E-plunging axes (Figure 7.14). These folds also affect the Lewisianoid–Moine boundary on the eastern side of the inlier and the Moine rocks in the hangingwall; hence they must post-date Moine deposition. The folds mark a broad zone of deformation along the eastern margin of the Eastern Unit. Fold vergence is towards the north along this zone, but the dominant ESE-plunging extension lineation indicates that shearing was accompanied by transport towards the WNW, resulting in the rotation of fold hinges into the extension direction.

The Moine rocks exhibit granoblastic and schistose textures both in the marginal shear-zone and farther east, compatible with deformation and recrystallization under the lower- to middle-amphibolite-facies conditions. The Lewisianoid rocks must also have experienced the same metamorphic conditions, but new fabrics only developed where the Knoydartian/Caledonian deformation was pervasive. Elsewhere in the Western and Eastern units, relict pre-Caledonian textures and mineralogy are commonly preserved.

Conclusions

The Dornie–Inverinate Road Section site lies at the western margin of the Caledonian Orogen of northern Scotland just east of the Moine Thrust Belt. It provides a well-exposed cross-section through the Eastern and Western units that make up the Lewisianoid Glenelg–Attadale Inlier, the largest Lewisianoid basement inlier in the Caledonian Orogen. Moine rocks occur on either side of the basement inlier and in a narrow shear-zone that separates the Eastern and Western units. The varied nature of the Lewisianoid basement gneisses is very well displayed in the road section. Hornblende- and biotite-bearing felsic gneisses with subsidiary amphibolites and quartzofeldspathic gneisses dominate in the Western Unit. It was metamorphosed under granulite-facies conditions and shows an overall evolution similar to the Lewisian Gneiss Complex of the Foreland to the west. The Eastern Unit also contains hornblende- and biotite-bearing felsic gneisses, but it is unique in that it contains eclogite and forsterite-bearing metadolostone and metalimestone units ('marble'). It was metamorphosed under eclogite-facies conditions during the Grenvillian Orogeny and shows evidence of a very different evolution from the Western Unit. Although the two units were in close proximity prior to Moine deposition, they were subsequently juxtaposed along a shear zone that incorporates the Moine rocks. The shear zone may have formed during the Neoproterozoic Knoydartian event, and was certainly reactivated during the Caledonian Orogeny. Parts of the Lewisianoid gneisses were also deformed during these events, but along the road section there are low-strain zones that preserve the earlier-formed Archaean and Palaeoproterozoic relationships.

The Dornie–Inverinate Road Section provides crucial evidence of the complex history of different basement units that became incorporated into the Moine rocks during the Caledonian and earlier Knoydartian orogenic events. The Eastern Unit provides an important link with similar Grenvillian rocks in Canada and Scandinavia; thus the site is of international importance.

AVERNISH (NG 836 266–NG 835 257)

A.J. Barber

Introduction

The 2 km coastal section at Avernish on the northern shore of Loch Alsh exposes a section through part of the Western Unit of the Glenelg–Attadale Lewisianoid Inlier including its western contact with highly deformed Moine semipelite and metaconglomerate (Figure 7.2). In the central part of the Western Unit the felsic gneisses and amphibolitic mafic bodies are cut by mafic dykes, and show relict Archaean and Palaeoproterozoic features. However, deformation increases markedly towards its western contact. The adjacent Moine rocks are generally structurally concordant and intercalated with highly deformed Lewisianoid gneiss of the Western Unit (see also **Rubha Camas na Cailinn** and **Allt Cracaig Coast** GCR site reports, this chapter), illustrating that the Lewisianoid basement and its Moine cover were strongly deformed and metamorphosed together during the Caledonian and possibly earlier Knoydartian orogenic events. The Avernish GCR site lies immediately east of the trace of the Moine Thrust (Figure 7.17). Mylonitic and cataclastic structures at Avernish demonstrate the relationships between structural and metamorphic events in the internal parts of the mountain belt and those in the Moine Thrust Belt, which have been the subject of controversy in the tectonic interpretation of the Scottish Caledonides. The evidence at Avernish implies that high-grade rocks of the Caledonian mountain belt were juxtaposed tectonically against low-grade rocks of the Moine Thrust Belt at a relatively late stage of the orogeny.

B.N. Peach and J. Horne mapped the Avernish area during the primary geological survey of the Glenelg district (Geological Survey of Scotland, 1909). A brief account of the 'Western Lewisian' (now termed the 'Western Unit') and of the metaconglomerate, described as 'pseudo-conglomerate', is given in Peach *et al.* (1910). At this time the Moine outcrop was not recognized. Barber (1968) subsequently mapped this southern part of Lochalsh in detail, and Thomas (1973) carried out a reconnaissance geochemical study of the Western Lewisian, including the outcrop of Moine semipelite at Avernish. The

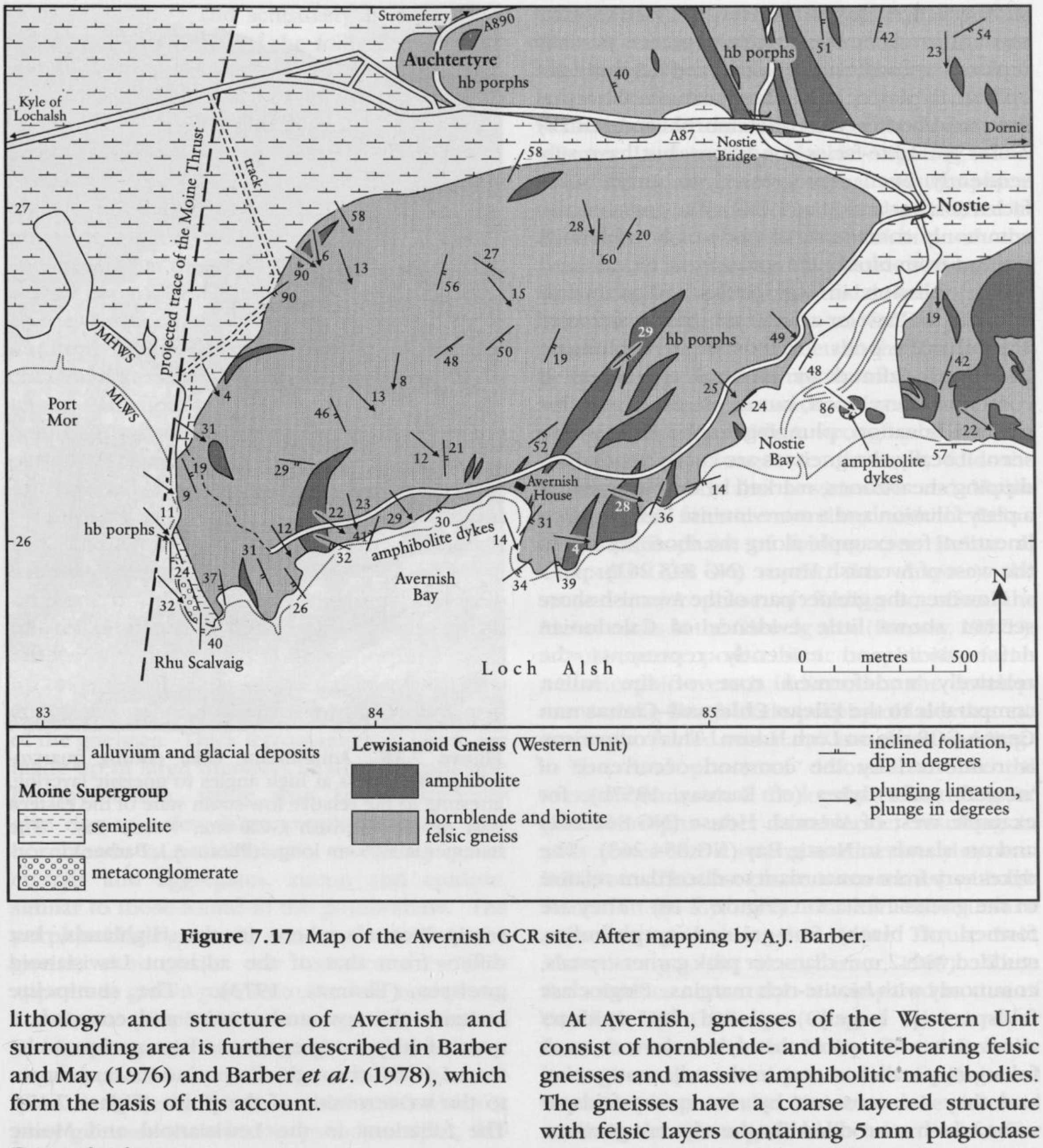


Figure 7.17 Map of the Avernish GCR site. After mapping by A.J. Barber.

lithology and structure of Avernish and surrounding area is further described in Barber and May (1976) and Barber *et al.* (1978), which form the basis of this account.

Description

Avernish is an area of low hills in the southern part of Lochalsh, situated south of Auchtertyre. The GCR site lies on the west side of the two-pronged peninsula on the north shore of Loch Alsh (Figure 7.17). Here, the coastal section between Port Mor and Nostie Bay provides almost continuous exposure of Moine and Lewisianoid rocks on glaciated shore platforms and in low raised cliffs. Inland, bracken-covered slopes with poor exposure rise to some 100 m above sea level.

At Avernish, gneisses of the Western Unit consist of hornblende- and biotite-bearing felsic gneisses and massive amphibolitic mafic bodies. The gneisses have a coarse layered structure with felsic layers containing 5 mm plagioclase porphyroblasts, alternating with thin hornblende- or biotite-rich layers. The layers are lenticular and are rarely traceable for more than a few metres along strike. Mafic pods or lenses, from metres to tens of metres across, are enclosed by the felsic gneisses, which also form screens between adjacent mafic bodies. Contacts between felsic gneisses and amphibolite are generally gradational. Typically, the amphibolite has a black and white speckled appearance, but is locally foliated. It is composed predominantly of hornblende, plagioclase and epidote. In thin section, both felsic gneisses and amphibolites show relict coarse-grained textures, with replacement of pyroxene by amphibole, garnets partially replaced by biotite and epidote, and exsolution of epidote in plagioclase. These textures show that the mafic bodies were metamorphosed initially under granulite-facies conditions, but have subsequently been retrogressed to amphibolite facies (Barber and May, 1976). The gneisses also commonly contain small pods of hornblendite derived from ultramafic rocks.

The foliation in the gneisses dips mainly towards the east or south-east, but is deflected around mafic pods. A prominent SE-plunging lineation, defined by mineral aggregates is commonly developed, but in places, a later fine mineral lineation, plunging to the ESE, is also seen. Locally, the gneisses are cut by gently ESE-dipping shear-zones, marked by development of a platy foliation and a more-intense ESE-plunging lineation, for example along the shore section to the west of Avernish House (NG 843 261).

However, the greater part of the Avernish shore section shows little evidence of Caledonian deformation and evidently represents the relatively undeformed core of the inlier, comparable to the **Eilean Chlamail–Camas nan Ceann** GCR site on Loch Hourn. This comparison is reinforced by the common occurrence of 'newer' mafic dykes (cf. Ramsay, 1957b), for example west of Avernish House (NG 842 261) and on islands in Nostie Bay (NG 854 263). The dykes vary from concordant to discordant relative to the gneissic foliation (Figure 7.18). They are formed of black, fine-grained amphibolite, studded with 2 mm-diameter pink garnet crystals, commonly with biotite-rich margins. Plagioclase feldspar is largely replaced by epidote/clinozoisite. In parts the dykes show a weak foliation, parallel to that in the adjacent gneiss, and they are cross-cut by rare quartz-feldspar veins, which are rodded like the adjacent gneisses. The gneisses adjacent to the dyke contacts contain small pink garnets, similar to those in the dyke, but garnets are rare elsewhere.

Important exposures occur on the shore platform and in the low cliffs surrounding Rhu Scalvaig (NG 834 257). Here, the foliation in Lewisianoid felsic gneisses dips at 30°–40° to the east. To the west, Lewisianoid gneisses are in sharp contact with a narrow outcrop of gneissose semipelite. The semipelite is composed of thin biotite-rich streaks and quartz lenses, intercalated on a centimetre-scale, and is garnetiferous. Its trace-element geochemistry is similar to Moine semipelites elsewhere in the Highlands, but differs from that of the adjacent Lewisianoid gneisses (Thomas, 1973). The semipelite contains thin psammite units and concordant quartz-feldspar segregations. Its outcrop can be traced NNW through discontinuous exposures to the western side of the point (Figure 7.17). The foliations in the Lewisianoid and Moine rocks are concordant. Metre-scale, Z-profile, reclined folds with E-plunging axes affect both groups of rocks and a rodding lineation parallel to the fold axes is present.

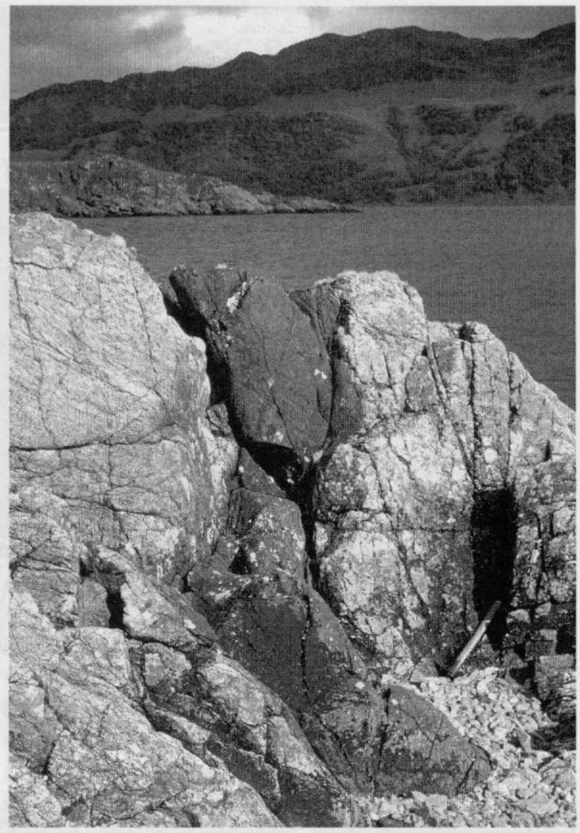


Figure 7.18 Amphibolite dyke cutting quartzo-feldspathic gneiss at high angles to gneissic layering, attesting to the relative low-strain state of the eastern part of the Avernish GCR site, Nostie Bay. The hammer is 37.5 cm long. (Photo: A.J. Barber.)

On the western side of Rhu Scalvaig, the gneissose Moine semipelite is underlain by schistose metaconglomerate that contains thin (*c.* 30 cm) psammite units. The matrix of the conglomerate is dominated by actinolite, biotite and chlorite, but the abundant clasts include: lenticular blocks of layered quartzofeldspathic gneiss, up to 1 m across; rounded blocks of hornblendic rock; and irregular twisted masses of vein quartz. The schistosity is commonly folded and the crests of the folds are filled by vein quartz and calcite. SE-dipping extensional shear bands are also developed. In thin section, actinolite, biotite and chlorite define the foliation, which encloses augen of relict hornblende, plagioclase and epidote. Clasts of amphibolite and hornblendic rocks are surrounded by radiating aggregates of actinolite needles, suggesting that the schistose matrix was formed, at least in part, from the breakdown of the clasts. Horne (in Peach *et al.*, 1910) interpreted these outcrops as 'crush conglomerate' or 'pseudo-conglomerate', formed tectonically by the shearing and disruption of hornblendic Lewisianoid gneiss. However, the rocks resemble the Moine metaconglomerate described at the **Attadale** and **Allt Cracaig Coast** GCR sites, and the close relationship with typical Moine psammites and semipelites indicates that they represent a basal metaconglomerate of the Moine.

North of Rhu Scalvaig (Figure 7.17) well-foliated pink quartzofeldspathic gneisses contain randomly orientated hornblende porphyroblasts up to 3 cm long. The size of the porphyroblasts apparently reflects the ferromagnesian content of the gneisses. Thick ferromagnesian layers are made up of large numbers of small hornblende porphyroblasts, while thin layers normally give rise to a few large porphyroblasts. The hornblende is poikiloblastic, enclosing quartz crystals and aggregates, zircon and epidote, similar to those found in the groundmass. The porphyroblasts generally transect the folds in the gneiss, although in one instance they have apparently grown parallel to the fold axial plane. Locally the porphyroblasts are pseudomorphed by biotite crystals that are randomly oriented, or aligned parallel to the foliation in the groundmass. At the base of the raised cliff at NG 834 263, platy gneisses show biotite pseudomorphs, flattened and extended on shear surfaces giving rise to an ESE-plunging mineral lineation. Similar semi-brittle features and an ESE-plunging lineation also occur in mylonitic rocks that form part of the Moine Thrust Belt to the west (see **Ard Hill** GCR site report, Chapter 5).

Interpretation

The metaconglomerate at the base of the Moine succession at Avernish indicates that the Moine rocks were deposited unconformably upon Lewisianoid gneiss basement. The effects of Caledonian (and possibly Knoydartian) deformation and metamorphic events on both rock groups can be clearly demonstrated in the narrow outcrop of Moine semipelite and psammite by Rhu Scalvaig. Here, the foliations in the Moine and adjacent Lewisianoid rocks are coplanar, effectively eliminating any original stratigraphical discordance. This deformation also resulted in the tight to isoclinal interfolding of the Lewisianoid basement and its Moine sedimentary cover seen in the Glenelg–Attadale Inlier (see for instance the **Rubha Camas na Caillin** GCR site report, this chapter). Garnets in the Moine semipelite indicate that deformation took place under amphibolite-facies metamorphic conditions.

Z-profile folds, with a strong axial rodding lineation that plunges to the east, fold the foliation in both the Lewisianoid and Moine rocks. These folds are correlated with the Beinn a' Chapuill phase of folding (see **Beinn a' Chapuill** GCR site report, this chapter), the second major phase of folding to affect the Moine rocks in the Glenelg area (Ramsay, 1957b). A subsequent post-tectonic amphibolite-facies metamorphic event is indicated by the development of the hornblende porphyroblasts that cut across the folded rocks and associated rodding.

The final phase of deformation on the Avernish peninsula is the local shearing of biotite pseudomorphs after hornblende, resulting in platy zones with a strong south-easterly mineral lineation. This last phase is correlated with the formation of mylonites, the earliest structural event recognized in the Moine Thrust Belt, immediately to the west (Barber, 1965). When the evidence at Avernish is compared to that of the **Ard Hill** GCR site (Chapter 5), it is clear here that events in the Moine Thrust Belt are later than the main penetrative folding and metamorphism of the Moine and Lewisianoid rocks in the Glenelg–Attadale Inlier and farther east in the orogen. High-grade amphibolite-facies rocks from the interior of the orogen have been tectonically juxtaposed against greenschist-facies rocks of the Moine Thrust Belt during a late stage in the Caledonian Orogeny.

Lewisianoid gneisses and amphibolites in the eastern part of Avernish peninsula show coarse-grained textures and cross-cutting dyke relationships, which indicate that these rocks, in the central part of the Western Unit of the Glenelg–Attadale Inlier, were relatively unaffected by deformation during the Caledonian Orogeny. Caledonian effects are only evident in rocks immediately adjacent to the Moine outcrop, or in localized shear-zones, where the gneisses develop a strong platy foliation, reclined folds and an ESE mineral lineation.

Conclusions

The occurrence of Moine semipelite and psammite at the Avernish GCR site, associated with a basal metaconglomerate containing clasts of the adjacent Western Unit of the Glenelg–Attadale Lewisianoid Inlier, confirms the original unconformable relationships between the Moine succession and the basement Lewisianoid gneisses. However, the parallel interlayering of the Moine and Lewisianoid rocks demonstrates that the two rock groups were both strongly deformed and tightly folded during the Caledonian Orogeny and possibly during the earlier Neoproterozoic Knoydartian event (cf. **Rubha Camas na Cailinn** GCR site report, this chapter). Localized mylonitic deformation in the Lewisianoid gneisses, the latest event in the tectonic history of the Glenelg–Attadale Inlier, is correlated with the earliest structural event in the Moine Thrust Belt. Hence, Caledonian deformation in the Moine Thrust Belt occurred significantly later than in the interior of the orogen. In contrast, outcrops of Lewisianoid gneisses and amphibolites to the east of Rhu Scalvaig demonstrate that the central parts of the Glenelg–Attadale Lewisianoid Inlier were little affected by Caledonian deformation. Here, the original Archaean and Palaeoproterozoic relationships are still largely preserved.

The Avernish GCR site is of national importance, as it demonstrates the critical relationships between Lewisianoid basement inliers and their Moine cover, and enables the sequence of structural and metamorphic events in the interior of the orogen to be compared with that in the Moine Thrust Belt.

TOTAIG (NG 872 255–NG 866 233)

A.J. Barber

Introduction

The Totaig GCR site, in the Eastern Unit of the Glenelg–Attadale Lewisianoid Inlier, includes the most extensive outcrops of eclogite in Britain, and it was from here that the rock type was first described in the British Isles (Teall, 1891). Eclogites form by metamorphism of original basalts, dolerites or gabbros under high-pressure conditions, equivalent to a crustal depth of 50 km or more. They have a high density and consist essentially of green omphacitic pyroxene and red-brown pyrope garnet. As in many other eclogite-bearing terranes (e.g. Heinrich, 1982), the eclogites in the Glenelg–Attadale Inlier are partially retrogressed to amphibolites (Alderman, 1936). In the Totaig area, eclogite and amphibolite layers are closely associated with outcrops of forsterite-bearing metadolostones ('marbles'), garnetiferous kyanite-biotite gneissose pelite, and hornblende- and biotite-bearing felsic gneiss. In addition, small outcrops of other unusual rock-types, such as iron-rich eulysite and schistose graphitic pelite are present. The distinctive assemblage is a complex admixture of Archaean or Palaeoproterozoic sedimentary and igneous rocks, which have been subject to high-pressure, eclogite-facies metamorphism.

High-grade metamorphic rocks within the Lewisianoid Glenelg–Attadale Inlier were used to draw a comparison with the Scourian gneisses of the Lewisian Gneiss Complex of the foreland, west of the Moine Thrust (Peach *et al.*, 1910). However, Sm-Nd and U-Pb dating of eclogite from the Totaig area showed that the eclogite-facies metamorphism occurred at *c.* 1080 Ma and its subsequent retrogression at *c.* 995 Ma (Sanders *et al.*, 1984; Storey, 2002; Brewer *et al.*, 2003; Storey *et al.*, 2005) and provided evidence of Grenvillian orogenesis. To date, the Glenelg–Attadale Inlier is the only significant area in Britain that shows any record of Grenvillian orogenesis.

Teall (1891) reported the occurrence of eclogite in the area around Totaig, but C.T. Clough first mapped the area for the Geological Survey in 1897 (Geological Survey of Scotland, 1909; Peach *et al.*, 1910). Sutton and Watson (1958) carried out further structural mapping. The mineralogy and petrology of some of the unusual rock-types in the Totaig area have attracted the attention of various authors; these include eclogite (Alderman, 1936), kyanite-eclogite (Tilley, 1937a; Sanders, 1988), websterite (Mercy and O'Hara, 1965; Rawson *et al.*, 2001), clinopyroxenite (Sanders, 1978), forsterite 'marble' (Read and Double, 1935) and eulysite (Tilley, 1936, 1937b).

Description

The Totaig GCR site covers an extensive area of heather moorland and vegetated and tree-clad hill-slopes inland from the rocky coastal section along Loch Alsh and Loch Duich, near Totaig in the central part of the Glenelg Inlier (Figure 7.2). Exposure is almost continuous along the shore, but poor on the hill-slopes above. More-extensive outcrops occur on the higher NE-trending ridges that lead up to Beinn Fhada (445 m), and in the steep cliffs facing Loch Alsh.

The geology of the Totaig area is shown in Figure 7.19. The rock units in the Eastern Unit strike north-east–south-west, with the foliation dipping gently to steeply to the south-east. A layer of hornblende- and biotite-bearing felsic gneiss interlayered with eclogite and amphibolite occurs in the northern part of the area, along the shore of Loch Alsh. To the south-east a major

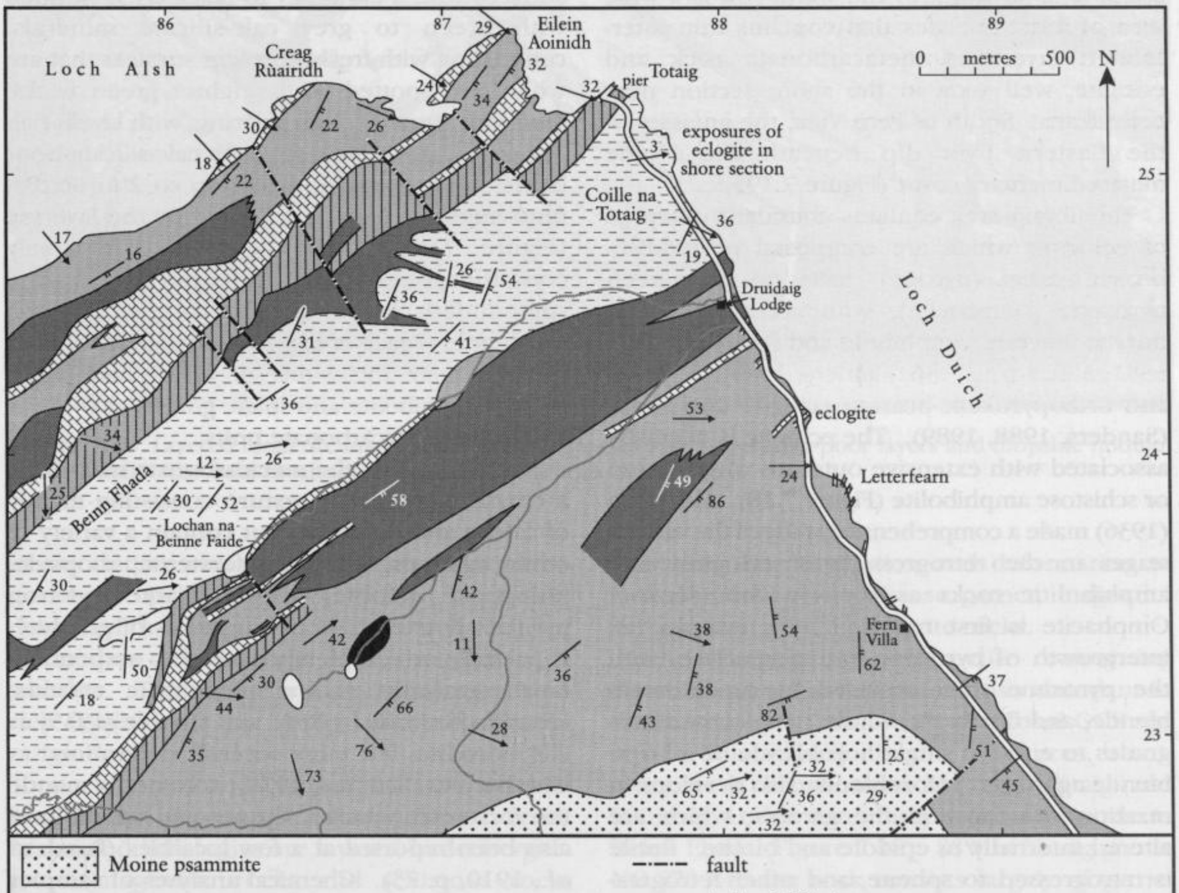


Figure 7.19 Map of Totaig GCR site. Based on Sutton and Watson (1958) and Geological Survey of Scotland (1909).

layer of forsterite-bearing metacarbonate rock and calc-silicate rock (together termed 'marble') extends down to the shore at Totaig pier. A thin mylonite zone separates the metacarbonate rocks from a 500 m-wide layer of gneissose garnetiferous kyanite-biotite pelite, which is exposed on Beinn Fhada, and in road cuttings and on the shore section between Totaig and Druidaig Lodge. A major zone of eclogitic rocks strikes south-west from Druidaig Lodge, although it passes into metalimestone to the south-west. Farther to the south-east is a wide area of felsic gneisses that contains thin intercalated layers of metacarbonate rock and eclogite, well seen in the shore section near Letterfearn. South of Fern Villa, the gneisses of the Eastern Unit dip beneath the Moine metasedimentary cover (Figure 7.19).

The Totaig area contains abundant outcrops of eclogite, which are composed of reddish-brown garnet (pyrope), pale- or grass-green pyroxene (omphacite), with accessory rutile, quartz, ilmenite, amphibole and feldspar (Teall, 1891; Alderman, 1936; Sanders, 1989). Kyanite- and orthopyroxene-bearing eclogite also occur (Sanders, 1988, 1989). The eclogite is normally associated with extensive outcrops of gneissose or schistose amphibolite (Figure 7.18). Alderman (1936) made a comprehensive study of the various stages in the retrogression of eclogites into amphibolitic rocks as seen in thin section. Omphacite is first replaced by a symplectitic intergrowth of pyroxene and plagioclase, with the pyroxene then replaced by green hornblende, and finally the whole symplectite retrogrades to either a single hornblende or a hornblende aggregate. Hornblende also develops in reaction rims around the garnets, which are altered internally to epidote and biotite. Rutile is retrogressed to sphene, and other retrogression products include scapolite and calcite. In many amphibolites, their high-pressure history can only be recognized by the presence of relict eclogitic textures.

In the field, dark-green hornblendite and pale quartz-feldspar veins cross-cut massive outcrops of eclogite. Eclogitic rocks show successive stages of deformation and retrogression into gneissose or schistose amphibolite, reflecting the intensity of deformation and veining. Pods of massive, relatively unaltered eclogite are typically enclosed in a carapace of amphibolite. It is evident that many former eclogite bodies are now represented only by foliated amphibolite.

The other major rock-type in the Totaig area is metacarbonate rock commonly termed forsterite 'marble'. Apart from the two main outcrops south-westwards from Totaig pier and Druidaig Lodge (Figure 7.19), many smaller layers occur within the felsic gneisses, and are particularly well exposed along the shore of Loch Duich. Similar lithologies are described in the **Dornie–Inverinate Road Section** and **Druim Iosal** GCR site reports (this chapter). The 'marble' outcrops have rough weathered surfaces with a dark-grey to black crust studded with green to grey calc-silicate minerals, contrasting with freshly broken surfaces that are white and spotted with brighter green flecks. Outcrops show a rough layering, with layers rich in calc-silicates alternating with calc-silicate-poor layers. Pale-green nodules, up to 2 m across, form augen structures wrapped by the layering (Figure 7.20). They consist of coarsely crystalline, randomly orientated diopside surrounded by rims of rusty-weathering amphibole (Peach *et al.*, 1910, plates II and III). More-angular inclusions of other rock-types, mainly amphibolite and mafic gneiss, also occur within the metacarbonate units.

In thin section, the metacarbonate units have a coarse granoblastic texture consisting mainly of calcite and dolomite, but contain a variety of other minerals, including forsterite, diopside, phlogopite, chlorite, sphene, apatite and iron pyrites. Forsterite, enclosing trails of graphite, is partially or completely altered to serpentine. Small granular yellow pleochroic crystals, identified initially by Read and Double (1935) as chrondrodite, but more recently determined as clinohumite (Sanders, 1972), commonly mantle the forsterite crystals. Garnet and spinel have also been reported at a few localities (Peach *et al.*, 1910, p. 23). Chemical analyses of samples of forsterite 'marble' from Totaig pier and elsewhere in the Eastern Unit show that their magnesium content lies close to that of pure dolostones (Moorhouse and Moorhouse, 1983; May *et al.*, 1993). The diopside nodules may have formed by the reaction of dolomite with chert nodules. Angular inclusions of other rock-types perhaps represent remnants of originally continuous layers or dykes within the metacarbonate rocks, disrupted by deformation.

An unusual type of peridotite consisting of olivine, clinopyroxene, garnet and magnetite, forms a rocky knoll 200 m south-west of Druidaig Lodge (NG 878 245), where it occurs

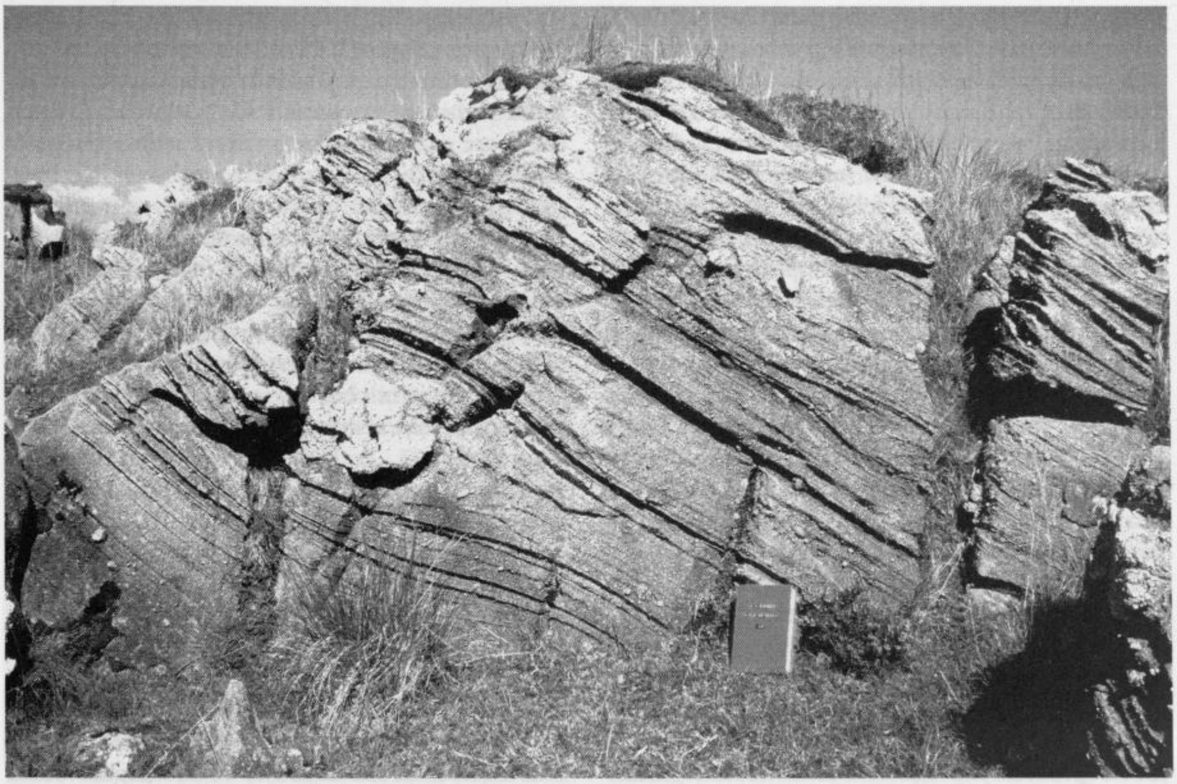


Figure 7.20 Layered forsterite marble with calc-silicate-rich and calc-silicate-poor layers and diopside nodule, Beinn Fhada. The field notebook is 16 cm high. (Photo: A.J. Barber.)

in association with other iron-rich rocks within gneissose pelite. Tilley (1936) originally described the rock and termed it a 'eulysite', but in modern terminology it is classified as a wehrlite. The olivine is a manganiferous iron-rich fayalite and the clinopyroxene lies in the range diopside-hedenbergite. Outcrops in the Totaig area are conspicuous because of their blue-black, iron-manganese weathered crust. Associated lithologies are layered hedenbergite-garnet-magnetite rocks and schistose rocks containing the iron amphiboles grunerite and cummingtonite. Tilley (1937b) also reported the occurrence of the pink manganese minerals pyroxmangite and rhodonite, the latter in veins up to 2 cm thick, in grunerite schist. Wehrlite has a very high density, reflecting its iron and manganese content, and in addition to olivine (fayalite), also contains iron-hypersthene, hedenbergite (or pyroxmangite), spessartine-almandine garnet, calcite, magnetite and apatite (e.g. Tilley, 1936). In thin section, olivine and pyroxene are seen partially altered to grunerite, which also occurs as fibrous vein fillings. Field relationships suggest that the wehrlite has been altered by later hydration and deformation to form the adjacent schistose garnet, magnetite and cummingtonite-grunerite rocks.

Gneissose biotite-rich pelite containing abundant garnet and kyanite is also abundant in the Eastern Unit (see also **Druim Iosal** GCR site report, this chapter). In the Totaig area, it outcrops as a broad zone between Totaig and Druidaig Lodge extending south-westwards to Beinn Fhada (Figure 7.18). SSW of Totaig pier at NG 870 243 the rock consists largely of garnet and quartz, with some kyanite and shimmer aggregate, whereas just south-west of Druidaig Lodge at NG 878 245 kyanite or shimmer aggregate are dominant (Clough in Peach *et al.*, 1910, p. 27). In the latter exposures kyanite crystals up to 10 cm long enclose garnet; staurolite has also been reported here. Clough also noted that the pelitic gneiss contains graphitic layers up to 20 cm thick, for example 120 m SSE of Lochan Beinne Faide at NG 862 235.

Hornblende- and biotite-bearing felsic gneisses constitute a large part of the Lewisianoid outcrop in the Totaig area (Figure 7.19). The gneisses are characterized by an alternation of felsic and mafic layers ranging from 1 cm up to several metres in thickness. Locally, it can be seen that the gneisses have formed from agmatites. Amphibolite has been intruded by quartz-feldspar veins and subsequently deformed, so that mixed felsic and mafic materials are sheared or flattened to form thin layers. At some localities the felsic component contains garnet, omphacite, oligoclase, and locally kyanite, K-feldspar, rutile and biotite, representing an eclogite-facies assemblage (Sanders, 1979, 1989). The mafic component is represented by eclogite, and the two components are interlayered on millimetre- to metre-scale (e.g. Figure 7.21). Clearly the two components are closely related, having been tightly folded and metamorphosed together under eclogite facies.

Fine-grained, blastomylonitic felsic gneisses were mapped by Sutton and Watson (1958) as a thin unit along the shores of Loch Alsh near Creag Ruairidh and Eilein Aoinidh. Here, the gneisses appear to immediately overlie the highly deformed Moine rocks within the shear zone that separates the Eastern and Western units. Blastomylonitic gneisses also occur on either side of the wide outcrop of the garnetiferous gneissose pelite and are well exposed near Totaig pier (Figure 7.19). They are finely layered on a centimetre- to millimetre-scale with intrafolial tight to isoclinal folds common. Such rocks are extremely fine grained with a compact texture, and are studded with ovoid less-deformed augen up to several centimetres across that contain porphyroclasts of garnet, hornblende, plagioclase and rarely omphacite. The blastomylonites were derived from coarser-grained rocks, including eclogites, by intense deformation and recrystallization. The fine-grained matrix has a granoblastic texture indicating that recrystallization continued after deformation.

Interpretation

The Eastern Unit of the Glenelg–Attadale Inlier in the Totaig area represents a high-grade complex of Archaean and/or Palaeoproterozoic metasedimentary and meta-igneous rocks, metamorphosed under eclogite-facies conditions, but now largely retrograded to amphibolite facies. The interest of the area lies in the preservation of numerous high-pressure metamorphic relics including eclogite, forsterite 'marble', pelitic

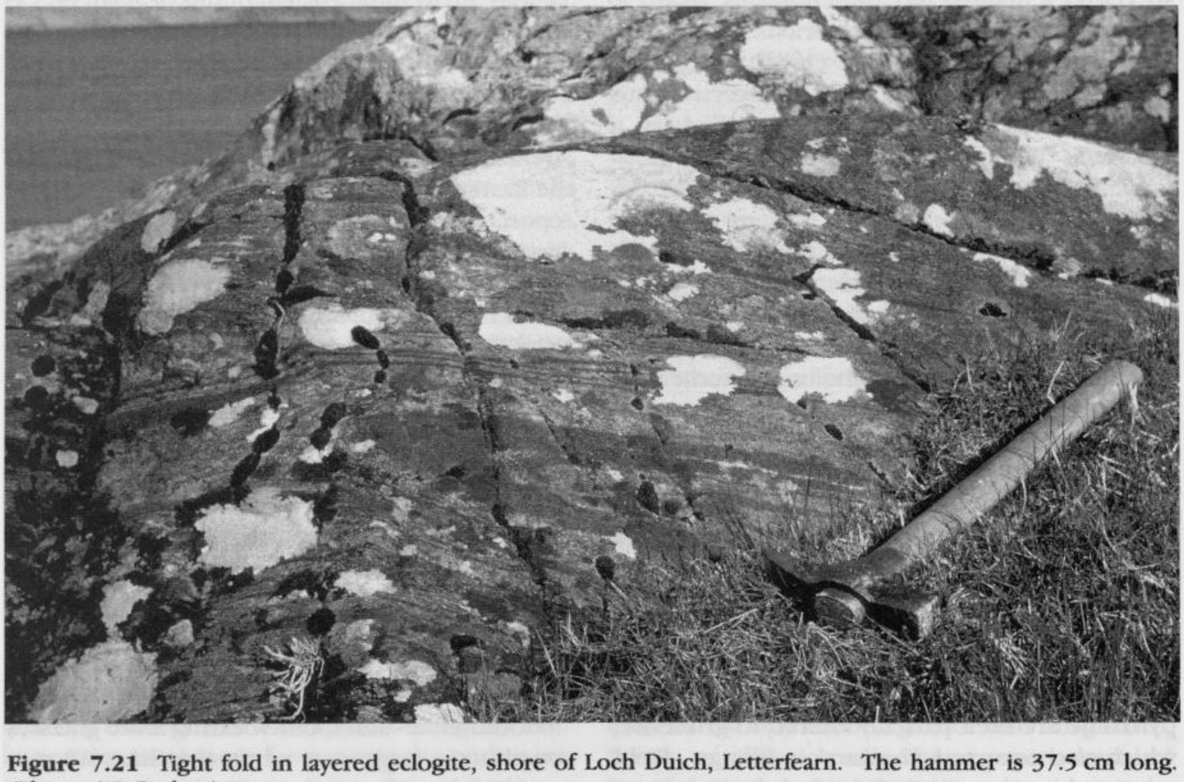


Figure 7.21 Tight fold in layered eclogite, shore of Loch Duich, Letterfearn. The hammer is 37.5 cm long. (Photo: A.J. Barber.)

gneiss, garnet quartzofeldspathic gneiss with omphacite and other unusual rock-types such as wehrlite, cummingtonite-grunerite schist, garnet-magnetite schist, schistose graphitic pelite, clinopyroxenite and websterite.

The oldest part of the complex is probably the felsic gneisses, which are dominantly granodioritic or tonalitic, and are intimately mixed with mafic rocks. This part of the complex may represent the basal part of a volcanic arc complex, composed of acid and basic intrusions. The mafic rocks may have originally included large layered laccolithic bodies in which cumulates developed, represented by websterite (Mercy and O'Hara, 1965; Rawson *et al.*, 2001) and the Al-Ti-augite cumulate described by Sanders (1978), as well as small cross-cutting basalt dykes. Most of the mafic rocks in the complex were subsequently converted to eclogite during the Grenville Orogeny (see below).

The Sm-Nd ratio of an eclogite analysed by Sanders *et al.* (1984) gave a model Nd age of approximately 1700 Ma, suggesting that the basic magma from which it formed separated from the mantle at that time. Geochemical analyses show that the eclogites have tholeiitic and nepheline-normative basaltic compositions (Sanders, 1989; Mercy and O'Hara, 1968). The latter are unlike the mafic intrusions of the Lewisian Gneiss Complex in the foreland to the Moine Thrust Belt and thus attest to a different pre-Grenvillian evolution of the Eastern Unit.

The forsterite 'marbles' and the garnet kyanite pelites were both clearly derived from sedimentary rocks. They are closely associated with the wehrlites and the other iron-rich rock-types, suggesting that some of these rocks are also of sedimentary origin. Their enrichment in Fe and Mn, and silica and calcium contents, have prompted a comparison with the banded ironstones of the Lake Superior region in the United States and Canada (Tilley, 1936). Where the latter lie within the aureole of the Duluth Gabbro, they have developed similar mineral assemblages to those seen in the Totaig wehrlite and associated iron-rich rocks (Tilley, 1936). The gneissose pelites, forsterite 'marbles' and the iron-rich rocks possibly represent shales and limestones with chert nodules that were deposited as an evaporitic sequence in a sabkha-like environment (see also **Druim Iosal** GCR site report, this chapter). The occurrence of graphitic layers within the pelites indicates that locally these sediments included high proportions of organic matter. It is likely that the sediments were deposited unconformably on a basement now represented by the meta-igneous rocks, although there is no direct evidence for an unconformity.

The Sm-Nd ages on eclogite of 1082 Ma and 1010 Ma (Sanders *et al.*, 1984) and the U-Pb zircon age of *c.* 995 Ma in retrogressive amphibolite (Brewer *et al.*, 2003) show that the Eastern Unit underwent eclogite-facies metamorphism followed by rapid exhumation during the Grenville Orogeny. Eclogite with similar ages have been dated in the Grenville Province in Canada (Indares and Dunning, 1997) and in the Sveconorwegian Orogen in south-west Sweden (Möller, 1998).

A range of thermobarometric measurements on mineral assemblages from the eclogite, gneissose pelite and websterite of the Totaig area and elsewhere in the Eastern Unit give peak metamorphic temperatures around 730° C at pressures of 16–20 kbar, indicating that the Eastern Unit was buried to a depth of 50–60 km during the Grenville Orogeny (Sanders, 1988, 1989; Rawson *et al.*, 2001; Storey *et al.*, 2005). Rapid exhumation is indicated by the common occurrence of exsolution phenomena in pyroxenes from the eclogitic rocks, implying isothermal decompression. In the inlier large basic bodies have been completely disrupted with the resultant fragments occurring as isolated boudins, whereas mafic dykes have been rotated into concordance with the layering in the surrounding gneisses; all testify to the intensity of the deformation, a significant component of which may be of Grenvillian age. Temperley and Windley (1997) suggested that exhumation of the high-pressure Glenelg–Attadale Inlier was caused by top-to-the-E shearing along a low-angle detachment that also involved the Moine metasediments. However, the presence of an apparently unconformable basal meta-conglomerate in the overlying Moine succession (for instance at the **Attadale** and **Allt Cracaig Coast** GCR sites) suggests that the uplifted eclogitic-facies complex was exposed at the surface before the deposition of Moine sediments that occurred between *c.* 950 Ma and 870 Ma (e.g. Friend *et al.*, 2003; see also 'Introduction', this chapter). The amphibolite-facies retrogression, dated by U-Pb in zircon at *c.* 995 Ma (Brewer *et al.*, 2003), pre-dates the youngest population of detrital zircons (*c.* 950 Ma) recovered from the Moine. It may be that the blastomylonites developed in the Lewisianoid gneisses of the Eastern Unit represent shear zones related to the exhumation of the complex. An unconformable relationship between the blastomylonites and the overlying Moine succession is indicated by the distribution of these units on the north-eastern side of Loch Duich (see Figure 7.14); the shearing responsible for the formation of the blastomylonites appears to have occurred mainly before deposition of the Moine sequence.

Subsequent to deposition of the Neoproterozoic Moine succession, the metasedimentary cover and the Glenelg–Attadale basement were deformed in the Caledonian Orogeny and possibly during the earlier Knoydartian Orogeny. The first phase of deformation appears to have resulted in tight to isoclinal folding of the cover and basement into anticlines and synclines, producing the alternating Moine and Lewisianoid strips that now characterize the Glenelg–Attadale Inlier. In the Totaig area these strips were refolded by the Letterfearn Fold, as seen clearly in outcrops of Moine rocks above Fern Villa (NG 875 234) (Sutton and Watson, 1958). The Letterfearn Fold is a reclined F2 fold with an E-plunging axis and E-dipping axial plane. It is one of a series of kilometre-scale F2 structures that fold the eastern boundary of the Glenelg–Attadale Inlier (see **Beinn a' Chapuill** GCR site report, this chapter).

Conclusions

The Totaig GCR site lies within the Eastern Unit of the Glenelg–Attadale Inlier and contains the first recorded, best-exposed and most studied eclogites in Britain. Petrological and geochemical studies, isotopic dating, thermobarometric measurements and experimental studies have all been carried out on the eclogites and associated rock-types over the past 100 years. The GCR site is also unique in Britain for its variety of other unusual rock-types. These include garnetiferous quartzofeldspathic gneiss containing omphacite, clearly related to the eclogite *sensu stricto*, garnetiferous kyanite-biotite gneissose pelite, forsterite 'marble' containing a great variety of calc-silicate minerals, and iron-rich rock-types, such as garnet-magnetite rock and grunerite-cummingtonite schist, and rare ultramafic rocks, including wehrlite, websterite and clinopyroxenite. These rock types have been intensively studied and the work constitutes a major contribution to the mineralogical and geochemical literature.

The Grenvillian Sm-Nd age of *c.* 1080 Ma obtained from the eclogites at Totaig (Sanders *et al.*, 1984) was unexpected, but has been confirmed by more-recent U-Pb zircon geochronological studies (Brewer *et al.*, 2003). The ages have led to a major re-assessment of the correlation of the Glenelg–Attadale Inlier with both the Lewisian gneisses of the foreland, west of the Moine Thrust Belt, and with the other Lewisianoid inliers in the Moine succession. They also provoked a radical revision of the Proterozoic tectonic history of the Scottish Caledonides. The significance of these results is still the subject of active controversy among Highland geologists. The area remains suitable for further studies that hopefully may resolve some of the outstanding problems. The area is of national and international importance, as it provides a potential link between eclogite-facies terranes of similar age in Canada and Scandinavia.

ALLT CRACAIG COAST (NG 799 176–NG 788 169)

A.J. Barber

Introduction

The Allt Cracaig Coast GCR site and its hinterland provide a clear example of an inverted Moine cover–Lewisianoid basement unconformity. Inverted Moine rocks lie structurally beneath Lewisianoid gneisses at the western margin of the Glenelg–Attadale Inlier, and sedimentary structures show that the E-dipping Moine psammites 'young' westwards and downwards, away from the overlying Lewisianoid gneisses. A deformed meta-conglomerate has locally been identified in the basal Moine units. Gneissic layering in the Lewisianoid rocks, which is normally parallel to transposed bedding in the adjacent Moine, here shows a recognizable angular discordance. It is clear that the Moine sediments were originally deposited unconformably on a crystalline Lewisianoid basement that had already undergone intensive deformation and metamorphism. The section is historically important, as it was here that the Lewisianoid and Moine rocks of the

Northern Highlands were shown to be distinct structural and stratigraphical units, which had been deformed and metamorphosed together during the Caledonian Orogeny and possibly earlier during a Knoydartian orogenic event.

The area around Glenelg was originally mapped by C.T. Clough as part of the primary survey of the Glenelg (Sheet 71) (Geological Survey of Scotland, 1909), and the geology is described in the accompanying memoir (Peach *et al.*, 1910). Bailey and Tilley (1952) briefly visited the Allt Cracaig section and confirmed the occurrence of conglomeratic rocks along the Moine–Lewisianoid boundary. Following detailed structural mapping, Ramsay (1957b) produced a revised geological map and published a full account of the geology, with details of the structure and of the relationships between the Moine and Lewisianoid rocks. The work of Clough and Ramsay has been drawn upon extensively in the present account. The Allt Cracaig coastal section is complementary to the **Attadale** and the **Eilean Chlamail–Camas nan Ceann** GCR sites.

Description

The Allt Cracaig coastal section extends for 2.5 km along the Sound of Sleat between Port a' Ghàraidh and Rubha a' Chamais Bhàin (Figure 7.22). It consists of a discontinuous shore platform, backed in places by low cliffs. The hill-slope above the shore, as far as the Glenelg–Arnisdale road, is forested and outcrops on this slope are currently inaccessible. To the south-east of the road, heather and bracken-covered hills around Mam nan Uranan (208 m) contain scattered ice-smoothed rock outcrops.

Moine rocks outcrop along the shore, south from Leac nan Tàillearan (NG 793 174) and extend inland up the hill-slope to the south-east, with a maximum outcrop width of 500 m. The bedding and foliation in the Moine psammites dips some 30° towards the south-east. To the south-east, Moine psammites are structurally overlain by a thin unit of Moine pelite, followed by metaconglomerate, and finally by Lewisianoid gneisses.

The Lewisianoid gneisses are part of the Western Unit of the Glenelg–Attadale Inlier. They comprise layered hornblende- and biotite-

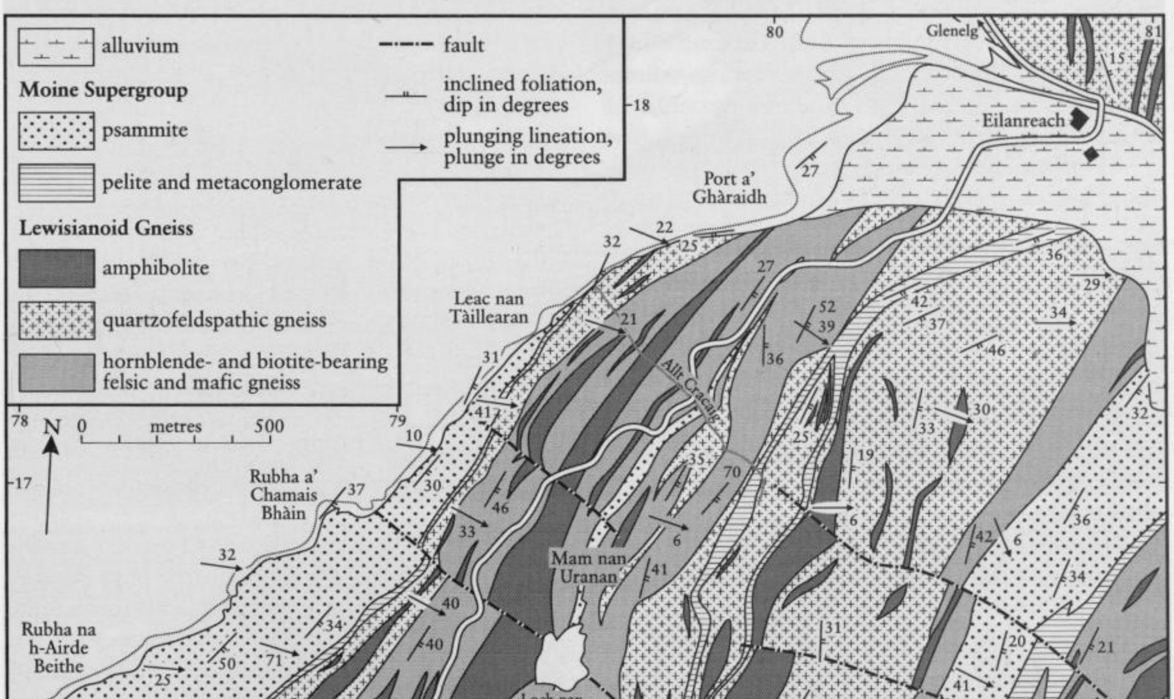


Figure 7.22 Map of the Allt Cracaig Coast GCR site. After Ramsay (1957b).

bearing felsic gneisses interbanded with lenticular amphibolite bodies and subsidiary ultramafic pods. A particularly large basic body can be traced south-westwards from Port a' Ghàraidh, to the west of Loch nan Uranan (Figure 7.22) as far as the shores of Loch Hourn (Ramsay, 1957b). Adjacent to the contact with the Moine rocks pink quartzofeldspathic gneiss also occurs. This lithology contains randomly orientated hornblende porphyroblasts, up to 2 cm long, which cut across the felsic layering.

A layer of schistose metaconglomerate, less than 10 m thick, underlies the Lewisianoid gneisses and, together with an associated pelite, can be traced south-west from Leac nan Tàillearan (NG 793 174) in discontinuous outcrops along the margin of the Moine outcrop (Figure 7.23). Clough (in Peach *et al.*, 1910) listed the best outcrops of the metaconglomerate at NG 793 173, NG 783 161 and NG 780 156, but currently these outcrops lie within the forested area. Clough noted that the metaconglomerate contains pebbles of quartz, red feldspar and yellow-green epidote, in a dark-grey foliated micaceous matrix. The pebbles are flattened in the foliation and are commonly elongated, parallel to the lineation in the Lewisianoid gneisses. The grain size ranges from millimetre-sized grains, to boulders up to 1 m or so. Pebbles larger than 1–2 cm show an internal foliation, commonly discordant to the foliation in the matrix. These pebbles have clearly been

Figure 7.23 Schistose conglomerate at inverted base of Moine rocks, with clasts of vein quartz, 800 m WSW of Mam nan Uranan (NG 790 167). The hammer head (top left) is *c*. 3 cm across.. (Photo: British Geological Survey, No. P214739, reproduced with the permission of the Director, British Geological Survey, © NERC.)

derived from the nearby Lewisianoid gneisses, but the clasts show less-intense deformation and recrystallization than the adjacent gneisses. The pebbles in the metaconglomerate are generally matrix-supported, but at NG 787 165 clast-supported boulders of hornblende schist, up to 1 m long, occur.

The matrix of the metaconglomerate contains large flakes of biotite typically orientated sub-parallel to the overall foliation, but in places discordant and crenulated. Epidote grains are common, and at NG 787 165 abundant small red garnets and black hornblende crystals are prominent, the latter as needles or stout prisms, which locally cross-cut the foliation. The hornblende crystals resemble those in the adjacent Lewisianoid gneisses and also occur in the pelite beneath the metaconglomerate, but are absent from outcrops north of NG 787 165. The pebbles in the metaconglomerate become smaller and less abundant structurally downwards into the underlying pelite (Clough in Peach *et al.*, 1910).

The Moine pelite is schistose with biotite and muscovite defining the schistosity, but thin interbeds of quartzose psammite are common. Pink pea-size garnets occur in both pelitic and psammitic layers, and needles and flakes of actinolitic amphibole are abundant in some layers. Microcline occurs locally in the micaceous layers (Peach *et al.*, 1910, p. 51). Cross-cutting hornblende and microcline appear to be restricted to this westernmost Moine outcrop; neither mineral has been reported from Moine pelite outcrops within the inlier farther to the east.

Moine psammite underlies the pelite, and is well exposed along the coastal section. The psammite is a grey, uniform, fine-grained, quartzofeldspathic-rich rock, in which original clasts of red feldspar and grey opalescent quartz may still be recognized (Clough in Peach *et al.*, 1910, p. 53). The psammite is banded with centimetre-thick, pale-grey, quartz-feldspar layers, alternating with millimetre-thick, dark-grey, biotitic micaceous layers reflecting original compositional variations. Some darker layers contain abundant magnetite and ilmenite, and other heavy-mineral grains, suggesting that the psammites form part of the Arnisdale Psammite, the lowest psammite unit in the Morar Group of this area (Ramsay and Spring, 1962; Holdsworth *et al.*, 1994). Cross-bedding is common, and shows that the beds are inverted and young to the west. Irregularly folded laminae, confined between uniformly planar layers, are interpreted as slump folds or convolute bedding (cf. Peach *et al.*, 1910, fig. 6).

The western outcrops of the Moine psammites contain few pegmatitic veins or lenses or migmatitic segregations, unlike Moine pelites and psammites farther to the east. The beds and some thin concordant quartz veins are locally deformed into long-limbed tight folds.

Clough (in Peach *et al.*, 1910, p. 21) described discordances between lithologies and layering in the Lewisianoid gneisses and the underlying Moine succession in the Allt Cracaig area. At the south-west end of the section, hornblende schist lies adjacent to Moine contact, but to the north-east pink quartzofeldspathic gneiss intervenes and thickens to 10–15 m; farther north-east a second body of hornblende schist lies adjacent to the contact. Locally, an angular difference of up to 12° between the strike of the layering in Moine and Lewisianoid rocks is mapped (e.g. at NG 783 161). Ramsay (1957b) confirmed these observations, but this locality is now forested.

Interpretation

The interlayered Moine and Lewisianoid rocks in the Glenelg–Attadale Inlier normally show similar structural and metamorphic features, and in most areas the foliation and compositional banding of both groups of rocks appear to be conformable. However, in the Allt Cracaig coastal section on the western side of the inlier, the Moine rocks show evidence of only moderate deformation and a lower grade of metamorphism (lower-amphibolite facies). The unconformable relationships between Lewisianoid and Moine rocks can also be clearly established. A distinction can be made between those features that are restricted to the Lewisianoid rocks, and therefore record their pre-Moine history, and those features common to both rock units, that are caused by Caledonian (and possibly Knoydartian) deformation. The Lewisianoid gneisses show evidence of a complex tectonic and metamorphic history. Fold patterns are not replicated, and pegmatites and basic bodies are absent from the adjacent Moine rocks. It is clear that prior to deposition of the Moine succession the Lewisianoid rocks have been folded, metamorphosed under middle amphibolite-facies conditions, and intruded by mafic bodies and by pegmatites.

Based largely from his observations in the Allt Cracaig area, Clough (in Peach *et al.*, 1910) marshalled the arguments for an original unconformable relationship between the Lewisianoid and Moine rocks. A convincing element was the occurrence of a basal metaconglomerate containing recognizable Lewisianoid clasts immediately adjacent to the Moine–Lewisianoid contact, which itself could be mapped out as discordant (see above). In addition, there are marked contrasts between the structural and metamorphic features of the two rock units. Clough (in Peach *et al.*, 1910) also reported that in continuously exposed vertical sections (e.g. at NG 786 164) no thrust plane or other structural discontinuity could be detected between the Lewisianoid gneisses and the underlying Moine succession. He concluded that the contact is a plane of unconformity, modified by later deformation.

After deposition of the Moine sediments, both rock groups have been intensely affected by the Caledonian Orogeny and possibly by the earlier Knoydartian events. The Lewisianoid basement and its Moine cover were folded and interleaved to produce the present alternating outcrop pattern seen in the inlier (see also **Rubha Camas na Cailinn** GCR site report, this chapter), in places resulting in an inverted structural succession. In the Moine rocks, metaconglomerate clasts were flattened and elongated, tight to isoclinal folds developed locally, and an ESE-plunging lineation was formed. During the folding, both groups of rocks were intensely deformed, drawing the contacts between rock units into near-parallelism. Original angular Lewisianoid–Moine unconformable relationships were largely destroyed. However, at the Allt Cracaig Coast GCR site the relatively lower strain has resulted in the preservation of a modified unconformity, cross-cutting relationships between mafic dykes and felsic gneisses in the Lewisianoid gneisses, and of sedimentary structures in the Moine psammites (compare with the **Rubha Camas na Cailinn** GCR site). Metamorphism during the Knoydartian and subsequent Caledonian orogenic events has resulted in pervasive recrystallization of the Moine psammites and pelites and formation of a penetrative schistosity. A later metamorphic event is represented by the prismatic amphibole crystals and large biotite flakes that cross-cut foliation planes; these occur in both the recrystallized Lewisianoid gneisses and the Moine basal metaconglomerate and pelite.

Conclusions

The Allt Cracaig Coast GCR site exhibits critical relationships between the Moine metasedimentary succession and the Lewisianoid basement gneisses of the Glenelg–Attadale Inlier. The Lewisianoid–Moine contact is marked by basal metaconglomerate containing Lewisianoid clasts derived from the adjacent gneisses. Different lithological units within the gneisses are found adjacent to the Moine succession along the contact, and locally an angular discordance between the layering in the Lewisianoid gneisses and the Moine rocks can be recognized, albeit modified by the later deformation. The Lewisianoid gneisses show ample evidence of an extensive earlier history of intrusion, deformation and metamorphism, which pre-dates deposition of the Moine sediments. Hence, the Moine rocks originally constituted a sedimentary sequence of conglomerate, shale and sandstone, resting unconformably on the Lewisianoid basement. During the Caledonian and possibly the earlier Knoydartian orogenies, Moine and Lewisianoid rocks were folded, overturned, and internally deformed and metamorphosed, strongly modifying the unconformity and the adjacent rock units.

Elsewhere in the Northern Highlands, Moine and Lewisianoid rocks are normally so highly deformed and strongly metamorphosed that it is not possible to establish their original relationships. Even in the eastern part of the Glenelg–Attadale Inlier the two units appear conformable. Hence, the Allt Cracaig Coast GCR site is of national importance as it is one of the few places that a convincing Moine–Lewisianoid unconformity can be demonstrated.

DRUIM IOSAL (NG 851 160–NG 861 162)

A.J. Barber

Introduction

The Druim Iosal GCR site area, south-east of Glenelg, exposes a number of rare and unusual metasedimentary rock-types that form part of the Lewisianoid gneisses of the Eastern Unit of the Glenelg–Attadale Inlier. Within the felsic and mafic gneisses, which elsewhere constitute the bulk of the Eastern Unit, are layers of forsterite-bearing metadolostone and metalimestone ('marble'), calc-silicate rock, schistose graphitic pelite and gneissose garnetiferous kyanite-biotite pelite (Figure 7.24). The area includes one of the largest outcrops of kyanite-bearing rocks in the British Isles.

These Lewisianoid rocks were metamorphosed under high-pressure eclogite-facies conditions during the Grenvillian (*c.* 1080 Ma) orogenesis (Sanders *et al.*, 1984; Storey, 2002; Brewer *et al.*, 2003; Storey *et al.*, 2005), approximately coeval with the formation of eclogites (see **Totaig** GCR site report, this chapter). The encircling Moine metasedimentary rocks that surround the Eastern Unit were deposited after the Grenvillian Orogeny (see Friend *et al.*, 2003). The Lewisianoid rocks, together with Moine psammites, were later extensively deformed into large-scale fold interference patterns during the Caledonian and possibly Knoydartian orogenies. This folding is discussed in detail in the **Beinn a' Chapuill** GCR site report (this chapter).

Although eclogites (by definition of mafic composition) are relatively rare, their petrology has been very well studied (e.g. Carswell, 1989). Eclogite-facies rocks of felsic or pelitic composition, as found at Druim Iosal, are more varied and liable to retrogression and have generally been poorly studied (e.g. Koons and Thompson, 1985).

The area around Druim Iosal was mapped by C.T. Clough as part of the primary geological

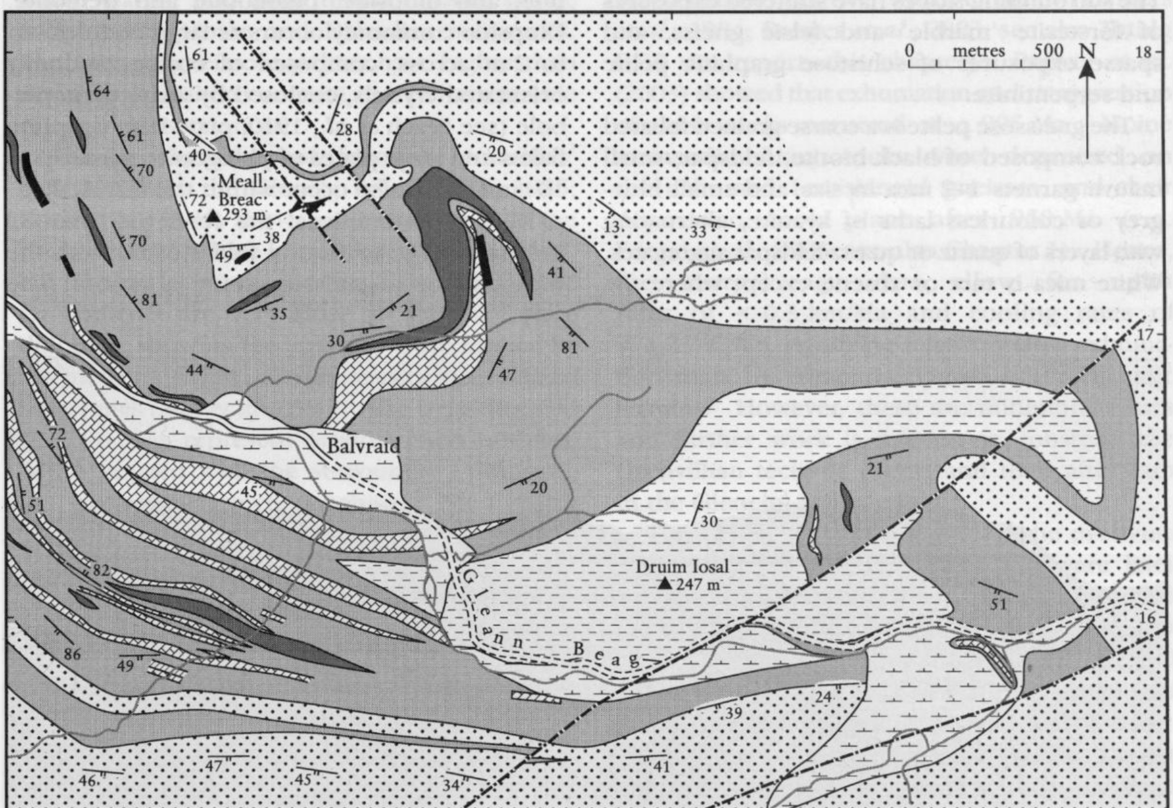


Figure 7.24 Map of the Druim Iosal GCR site. After Ramsay (1957b).

mapping of the Glenelg area (Geological Survey of Scotland, 1909; Peach *et al.*, 1910). Ramsay (1957b) subsequently remapped the area in detail. Little petrological work has been done at the Druim Iosal site, but Sanders' (1988, 1989) work at other localities in the Glenelg area is applicable to the rocks described here.

Description

Druim Iosal consists of two large rocky crags at the eastern end of Gleann Beag, with the steep NW-facing cliffs rising north-eastwards to a peat and heather-covered plateau, some 300 m high (Figure 7.25). The crags are composed of gneissose garnetiferous kyanite-biotite pelite, which outcrops over an area of about 1 km^2. The surrounding slopes have scattered exposures of forsterite 'marble' and felsic gneiss, and sparse exposures of schistose graphitic pelite and serpentinite.

The gneissose pelite is a coarse-grained foliated rock composed of black biotite, feldspar, small mauve garnets 1–2 mm in size and small blue-grey or colourless laths of kyanite, alternating with layers of quartz or quartz-feldspar aggregates. White mica is rare or absent, except where the kyanite has been retrograded to shimmer aggregate. Coarser feldspar and quartz layers form boudins up to 20 cm thick. Layers rich in randomly orientated pale greenish-blue kyanite crystals, individually up to 2 cm long, are seen. Zones with abundant anhedral ruby-red garnets up to 1.5 cm across are also common.

Forsterite 'marble' occurs in Gleann Beag immediately west of Druim Iosal (Figure 7.24). The 'marble' weathers with a rough black surface with small projecting calc-silicate minerals, but when freshly broken the rock is white to pale green, with bright green spots. The meta-dolostone is layered, defined by the varying proportions of calc-silicate minerals. These include forsterite crystals 2–3 mm in size, which may be partly or completely altered to serpentine, and diopside, phlogopite and tremolite. Diopside commonly occurs as large nodules, up to 2 m across, composed of coarse randomly orientated crystals, enclosed by a rim of amphibole (see Peach *et al.*, 1910, plate III). Graphite flakes and large plates of phlogopite mica, up to 10 cm across, also occur within the marble.

West of Druim Iosal the forsterite 'marble' units converge to form a fold closure with the wide outcrop of gneissose pelite in its core. The

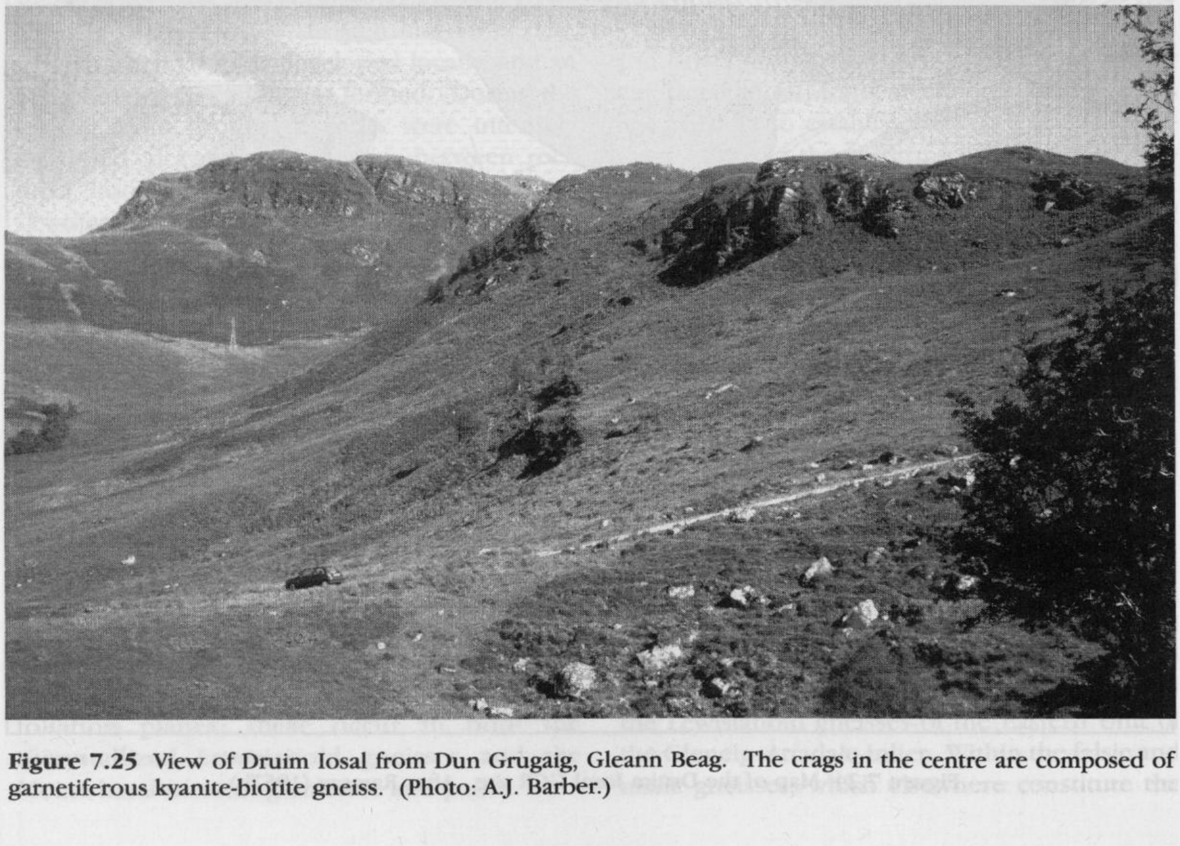


Figure 7.25 View of Druim Iosal from Dun Grugaig, Gleann Beag. The crags in the centre are composed of garnetiferous kyanite-biotite gneiss. (Photo: A.J. Barber.)

geometry of the eastern part of the Druim Iosal outcrop and its relationship to the surrounding Moine rocks suggests that the gneissose pelite occupies the core of a kilometre-scale fold interference structure (Figure 7.24), more details of which are described in the **Beinn a' Chapuill** GCR site report (this chapter).

Interpretation

The significance of the gneissose pelites lies in their composition, origin and metamorphic evolution. Chemical analyses of the pelites (Clough in Peach *et al.*, 1910, p. 28; Rock *et al.*, 1986) suggest that their protolith was an aluminous mudstone. Their geochemistry is similar to kyanite-bearing gneissose pelites of South Harris, but quite different from pelitic rocks in the Moine and Dalradian sequences. The Glenelg gneissose pelites have higher than normal magnesium contents, more characteristic of evaporite sequences.

The geochemistry of forsterite 'marbles' collected from the Glenelg Inlier (Rock, 1985; Rock *et al.*, 1986) shows major variations in the proportion of silicate impurities in the 'marbles', but all samples are magnesium-rich. The Mg and Ca contents are very close to those of pure dolomite, showing the 'marbles' were formed by the metamorphism of dolostones or dolomitized limestones (May *et al.*, 1993). The large diopside nodules may represent original chert nodules, which reacted with the surrounding dolomitic limestone during metamorphism. The Glenelg 'marbles' are again geochemically similar to those of South Harris. The assemblage of dolostones with chert nodules, and Mg-rich aluminous pelites, is characteristic of evaporitic sabkha environments (Chowns and Elkins, 1974).

The occurrence of forsterite 'marbles', gneissose pelites and schistose graphitic pelites clearly demonstrates a sedimentary origin of some of the rocks of the Eastern Unit. However, other rocks such as the mafic rocks (amphibolite and eclogite) and most of the felsic gneisses are of undoubted igneous origin. Thus, the Eastern Unit is a mix of orthogneisses and paragneisses. It is unclear whether the orthogneisses intruded into an older sedimentary sequence, or whether the sediments were deposited unconformably on an already existing orthogneiss basement and hence may be younger.

In gneissose pelite samples from other outcrops of the Eastern Unit in the Glenelg area, the association of kyanite and orthoclase feldspar, plus the occurrence of omphacite, indicate that the rocks have been metamorphosed under eclogite-facies conditions (Sanders, 1989). Using various geothermometers and geobarometers on a range of rock types of the Eastern Unit, Sanders (1989) estimated peak metamorphic temperatures in the range of 700°–740° C and pressures of 15–16.5 kbar. More recently Storey *et al.* (2005) calculated that peak conditions attained 750°–780° C and *c.* 20 kbar. These values show that the Eastern Unit was metamorphosed under eclogite-facies conditions, characteristic of crustal depths of the order of 50–60 km. Sm-Nd and U-Pb dating of eclogites from the Totaig area showed that eclogite-facies metamorphism occurred around 1080 Ma and was related to the Grenvillian Orogeny (Sanders *et al.*, 1984; Brewer *et al.*, 2003; see also **Totaig** GCR site report, this chapter). Brewer *et al.* (2003) showed that exhumation and retrogression of these rocks occurred at *c.* 995 Ma. Moine metasedimentary rocks were deposited on the exhumed Lewisianoid gneisses, and their deposition took place after 950 Ma (e.g. Friend *et al.*, 2003; see also Chapter 1). Hence, the current age data allow for uplift rates of < 0.3 km/Ma and cooling rates of < 1.25° C/Ma, signifying relatively slow exhumation rates by comparison with other eclogitic terrains. However, these are minimum values and further work is needed to constrain the Grenvillian tectonic events and their aftermath in the Glenelg–Attadale Inlier.

The Lewisianoid basement and the overlying sedimentary cover of Moine rocks were later involved in the possibly Knoydartian and certainly Caledonian orogenic events. Basement and cover were folded (D1) into tight isoclinal folds to form the alternating 'slices' of Lewisianoid and Moine rocks seen in the inlier. These 'slices' were in turn folded by two further phases of folding, as described in detail in the **Beinn a' Chapuill** GCR site report (this chapter). Refolding of F1 folds by the Beinn a' Chapuill Fold was responsible for the interference pattern represented by the outcrop of the gneissose pelites around Druim Iosal. Metamorphism and partial recrystallization under amphibolite-facies conditions accompanied the deformation and folding. This metamorphism resulted in retrograde mineralogies in the high-grade metamorphic mineral assemblages in the Eastern Unit, but in prograde mineralogies linked to generation of the main foliation and linear structures in the surrounding Moine sequence.

Conclusions

The gneissose garnetiferous kyanite-bearing pelites at Druim Iosal, east of Glenelg, represent one of the largest and best-exposed outcrops of kyanite-bearing rock in the British Isles. Their chemical composition and association with forsterite 'marble', suggests they were originally deposited in a sabkha-like environment as a sequence of magnesian aluminium-rich mudstones and dolomite and dolomitic limestone units. They form part of the Eastern Unit of the Glenelg–Attadale Lewisianoid Inlier, which is composed of rocks of both sedimentary and igneous origin.

Mineral assemblages in the gneissose pelites, the forsterite 'marbles' and the associated eclogitic rocks, provide evidence that the rocks were metamorphosed and deformed under eclogite-facies conditions, which occur when rocks are subducted to at least 50 km depth in the Earth's crust. Sm-Nd and U-Pb isotopic dating has shown that this high-pressure metamorphism was related to the Grenvillian Orogeny and occurred at *c*. 1080 Ma.

The Glenelg–Attadale Lewisianoid Inlier is made up of two separate segments of continental basement; a Western Unit, mainly composed of orthogneisses of probable Archaean age, similar to the Lewisian Gneiss Complex of the foreland; and an Eastern Unit, comprising orthogneisses and paragneisses which may have had an earlier Archaean or possibly Proterozoic history but which were strongly reworked during the Grenvillian Orogeny. There is little or no evidence for structures relating to the Grenvillian orogenesis in the Western Unit of the Glenelg–Attadale Inlier (see **Eilean Chlamail–Camas nan Ceann** GCR site report, this chapter), and only tentative indications of its presence in other parts of Scotland. Hence, the Grenville 'orogenic front' appears to be marked only by the highly sheared Moine outcrop, which separates the two Lewisianoid segments.

The Druim Iosal GCR site is of national importance in that it displays a variety of metasedimentary rock-types of the Eastern Unit of the Glenelg–Attadale Inlier that have an unusual geochemistry and origin. The rocks have also undergone eclogite-facies metamorphism, dated as Grenvillian in age. The site is complementary to the **Totaig** and **Dornie–Inverinate Road Section** GCR sites which also describe parts of the Eastern Unit.

BEINN A' CHAPUILL (NG 815 147–NG 847 154)

A.J. Barber

Introduction

At the Beinn a' Chapuill GCR site a *c*. 2 km-wide, sickle-shaped outcrop of Moine psammites, enclosed by Lewisianoid rocks of the Eastern Unit of the Glenelg–Attadale Inlier defines a kilometre-scale fold interference pattern (Figure 7.26). The Moine outcrop lies north-west of the Strathconon Fault and extends west and north almost to Gleann Beag. It can be demonstrated that the Moine and Lewisianoid rocks were first interlayered on a fine scale, and then refolded by two subsequent phases of folding. This site provides one of the clearest and best-documented examples of a large-scale refolded fold in the British Isles. Together with structures at Loch Monar (see **Loch Monar** GCR site report, this chapter), it formed a model for the recognition and interpretation of similar structures in fold mountain belts throughout the world (e.g. Ramsay and Huber, 1987).

C.T. Clough first mapped the Beinn a' Chapuill area as part of the primary geological survey of the Glenelg (Sheet 71) (Geological Survey of Scotland, 1909), and an account of the geology was included in the accompanying memoir (Peach *et al*., 1910). J.G. Ramsay subsequently remapped the area in detail with particular attention to the minor structures and the structural relationships between Moine and Lewisianoid rocks. Ramsay (1957b) proposed a complex sequence of structural events to account for the structural features and the outcrop pattern in the area.

Description

Beinn a' Chapuill (742 m) is a castellate mountain surrounded by steep cliffs that rise to a rocky plateau at a height of 600–700 m. It lies to the south of Gleann Beag and 4.4 km SSE from Glenelg. The GCR site covers an area of about 4 km^2. Moine rocks are very well exposed in the steep cliffs, and on the plateau where they form

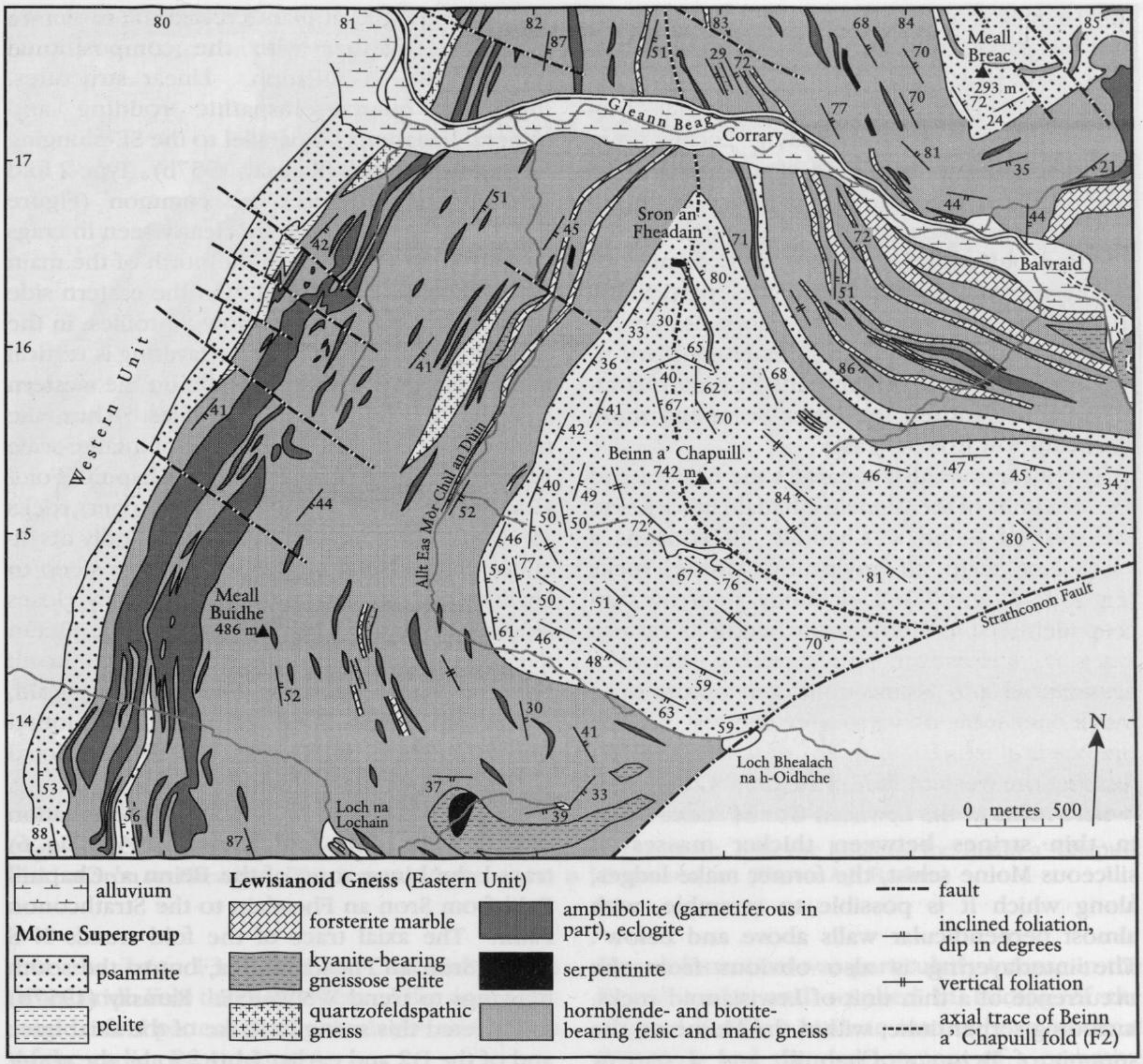


Figure 7.26 Map of the Beinn a' Chapuill GCR site, after Ramsay (1957b). The outcrop pattern of the Moine is the result of large-scale fold interference between the two main fold phases.

ice-smoothed rock outcrops. Lewisianoid rocks occupy the lower ground where they are relatively poorly exposed; the best exposures occur in burn sections but lithological units may be traced along strike between small outcrops on the grass and heather-covered slopes.

The Lewisianoid rocks in the Beinn a' Chapuill area belong to the Eastern Unit of the Glenelg–Attadale Inlier. The dominant lithologies are hornblendic and biotitic felsic gneisses that underlie the lower slopes of the mountain and the hilly ground to the west, rising to Meall Buidhe (Figure 7.26). A range of other lithologies form narrow strips interlayered with the gneisses, orientated roughly parallel to the Lewisianoid–Moine boundary. They include forsterite 'marble', quartzofeldspathic gneiss, gneissose pelite and serpentinite. Mafic rocks, including amphibolite, garnet-amphibolite and eclogite, form two major bodies on the western side of the Lewisianoid outcrop and abundant small lenses in the felsic gneisses (Figure 7.26). The Lewisianoid gneisses in the western part of the outcrop, adjacent to the narrow strip of Moine that separates the Eastern and Western units, have been intensely deformed and recrystallized into blastomylonites.

The Moine rocks constitute the bulk of Beinn a' Chapuill itself and are predominantly grey, uniform psammites, with their original bedding now modified to pale centimetre-scale siliceous and feldspathic layers alternating with millimetre-scale dark-grey micaceous layers. Micas are commonly aligned in the foliation, generally sub-parallel to the transposed bedding. Locally, there are pebbly layers, with vein quartz and quartz-feldspar clasts, typically 1–2 cm in size, but up to 4–5 cm across. The pebbles are flattened in the foliation but are also elongated to form rods projecting from weathered surfaces, particularly in the hinges of minor folds. Both psammites and pelites contain quartz veins concordant to the layering and irregular veins of pink quartz-feldspar pegmatites, the latter becoming more abundant towards the east.

The shear zone that separates the Eastern and Western units of the Glenelg–Attadale Inlier lies to the west of Beinn a' Chapuill. It contains a significant strip of mylonitic Moine rocks (Figures 7.2 and 7.26), including a narrow outcrop identified as Moine pelite, along its eastern margin. However, interlayering between Lewisianoid and Moine units also occurs on a much finer scale, down to a few metres. Clough (in Peach *et al.*, 1910, p. 18) describes the cliff forming the western face of Beinn a' Chapuill as 'where rocks of the Lewisian Gneiss series occur in thin stripes between thicker masses of siliceous Moine schist, the former make ledges, along which it is possible to scramble, with almost perpendicular walls above and below'. The interlayering is also obvious from the occurrence of a thin unit of Lewisianoid rocks, including serpentinite, within the Moine on the summit of Beinn a' Chapuill, and a narrow outcrop of Moine rocks which tracks parallel to the main Moine–Lewisianoid contact to the north-east of Beinn a' Chapuill and in Gleann Beag. Moine psammites also occur in narrow strips or infolds within Lewisianoid gneisses west and south-west of Meall Buidhe (Figure 7.26).

The Beinn a' Chapuill area shows a clear sequence of structural features. The fine layering in Moine rocks is folded into intrafolial, tight to isoclinal folds. An axial-planar cleavage that forms the dominant foliation/schistosity is developed in the hinges of these early 'F1' folds. The interlayering of Moine and Lewisianoid rocks described above may be also related to this early folding (see 'Interpretation').

Later folding phases resulted in both small- and large-scale structures. Open to tight F2 folds with E-dipping axial planes refold the earlier F1 isoclines, together with the compositional layering and S1 foliation. Linear structures, including quartzofeldspathic rodding and mineral lineations lie parallel to the SE-plunging F2 minor fold axes (Ramsay, 1957b). Type-2 fold interference structures are common (Figure 7.27). These structures are clearly seen in crags near Sron an Fheadain to the north of the main mass of Beinn a' Chapuill. On the eastern side of the crags, the F2 folds show S-profiles; in the central part of the outcrop the layering is vertical and folded into M-shapes, while on the western side the 'F2' folds show Z-profiles. Thus, the minor folds define a hinge zone of a large-scale F2 fold, termed the 'Beinn a' Chapuill Fold' (Ramsay, 1957b), which has younger rocks (Moine) in its core. Although technically a syncline, the fold-axis plunge varies from steep to shallow and in parts the fold effectively closes sideways. Ramsay (1957b) termed it the 'Beinn a' Chapuill antiform' (see below). To the north lies the complementary Gleann Beag Fold, which has Lewisianoid garnetiferous biotite-kyanite gneisses in its core (see **Druim Iosal** GCR site report, this chapter).

From variations in orientation of the foliation of both limbs of the fold, Ramsay (1957b, fig. 6) traced the hinge zone of the Beinn a' Chapuill Fold from Sron an Fheadain to the Strathconon Fault. The axial trace of the fold trends N–S in the Sron an Fheadain area, but to the south it swings to trend WNW–ESE. Ramsay (1957b) interpreted this swing in strike of the axial trace and of the D2 and earlier fabrics to be the result of refolding by a later major fold structure, the Beinn a' Chaonich–Beinn Mhialairidh Fold. The axial plane of this F3 fold trends north-east and dips about 35° to the south-east (Ramsay 1957b, p. 505). Minor folds, normally manifest as crenulations of micaceous layers, are related to this phase of folding, and locally there is the development of a crude axial-planar crenulation cleavage. Quartz-feldspar rodding and weak mineral lineations are locally developed parallel to the F3 fold axes, and plunge moderately steeply to the south-east. In addition, quartz-feldspar pegmatites are present along the axial planes of some F3 minor folds.

Hence, in the Beinn a' Chapuill area, three major folds control the outcrop pattern. The F2 Beinn a' Chapuill and Gleann Beag folds control the distribution of the main lithological units,

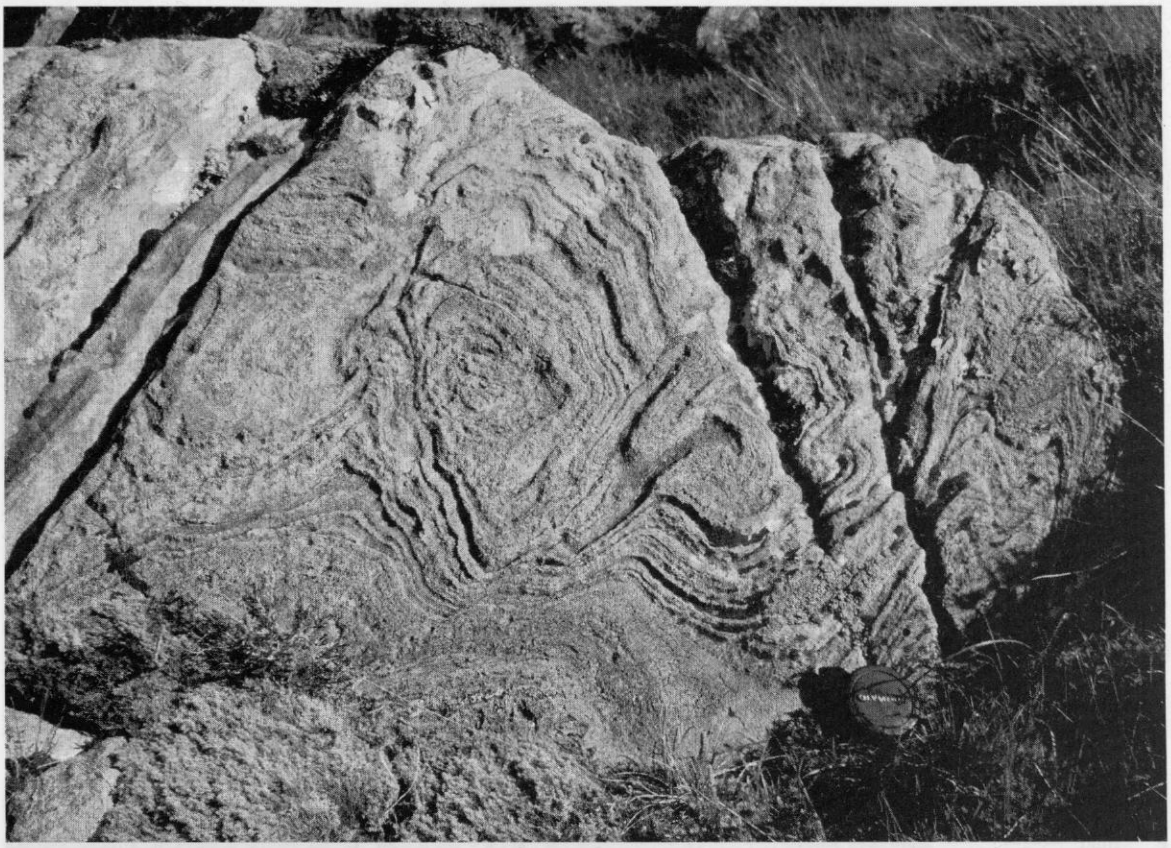


Figure 7.27 Fold interference structure in layered Moine psammite, near the hinge of the Beinn a' Chapuill Fold at Sron an Fheadain. The lens cap (lower right) is 5.2 cm across. (Photo: A.J. Barber.)

but the later F3 Beinn a' Chaonich–Beinn Mhialairidh Fold that has generated the near right-angle refold pattern that controls the orientation of the earlier D2 structures.

Interpretation

Clough (in Peach *et al.*, 1910) presented the arguments for an original unconformable relationship between the Lewisianoid and Moine rocks in the Glenelg area (see **Attadale** and **Allt Cracaig Coast** GCR site reports, this chapter). From the structures mapped in the Moine and Lewisianoid rocks at the Beinn a' Chapuill GCR site, the sequence of tectonic events that affected both the Moine sediments and the gneissose Lewisianoid basement can be established.

The earliest phase of deformation that affected the Moine and Lewisianoid rocks resulted in the interlayering of the two rock groups and may well have been Knoydartian (see Storey, 2002). This deformation was particularly intense in the Moine rocks, and resulted in folding of the original bedding laminae into tight to isoclinal 'F1' folds and the development of a pervasive foliation, generally parallel to the attenuated bedding. The deformation was accompanied by pervasive recrystallization and probably amphibolite-facies metamorphism. The 'F1' folds were certainly responsible for some of the interlayering of the Moine and Lewisianoid rocks, representing original synclines and anticlines (see also the **Rubha Camas na Cailinn** GCR site report, this chapter). Ramsay (1957b, p. 504) reported that later ('F2') tight folds are coaxial and have similarly orientated axial planes to the 'F1' structures yet locally refold the 'F1' isoclines. He regarded both sets of folds as having formed in essentially similar strain regimes related to the same phase of movement, in contrast to folds of later phases, which he attributed to differently orientated strain regimes. The refolded isoclines are responsible for many of the interference structures seen in the Moine outcrops.

The second phase of deformation is represented on a large scale by the 'F2' Beinn a' Chapuill Fold which folds the interlayered Moine and Lewisianoid layers, together with the earlier foliation and the associated isoclinal folds. The folding of interlayered Moine and Lewisianoid in Beinn a' Chapuill is shown on Clough's cross-section (in Peach *et al.*, 1910, fig. 1) as a synform. Ramsay (1957b), on the other hand, analysed the foliation orientation and deduced that the fold limbs converge upwards in the central part of the Moine outcrop (Ramsay, 1957b, fig. 7). Thus he interpreted the Beinn a' Chapuill Fold as a synclinal antiform. The Lewisianoid rocks of Gleann Beag to the north occupy a complementary synform, followed by a further antiform cored by Moine rocks on Meall Breac farther to the north-east.

Amphibolite-facies metamorphism occurred during or following this 'F2' phase of deformation, resulting in the development of granoblastic textures in the psammite, the formation of a mica foliation in pelitic layers and the development of quartz and quartz-feldspar rodding and the mineral lineation. The penetrative ESE- to SE-plunging rodding and mineral lineation suggest that the whole complex was transported north-westwards towards the foreland. This movement rotated many of the fold axes in both Lewisianoid and Moine rocks such that they also now plunge to the ESE.

The third phase of deformation is represented by the 'F3' Beinn a' Chaoinich–Beinn Mhialairidh Fold. This fold deforms the earlier 'F2' Beinn a' Chapuill Fold and all its associated structures. Ramsay (1957b) provided a comprehensive analysis of the effects of the third phase of folding on the earlier structures. The folding was accompanied by only minor recrystallization and crenulation of mica in fold hinges suggesting that the metamorphic grade was lower during this deformation phase. Clough (in Peach *et al.*, 1910) suggested that this phase of folding was linked to sinistral movements along the Strathconon Fault, which strikes near-parallel to the fold axial plane and truncates the Moine outcrop to the south-east. However, Ramsay (1957b) pointed out that features associated with the present fault trace are all brittle structures, but this does not preclude the possibility of more-ductile deformation at an earlier stage of fault movement when the rocks lay at deeper crustal levels.

Conclusions

Beinn a' Chapuill exposes one of the clearest and best-documented examples of a kilometre-scale refolded fold in the British Isles. The excellent exposure on the mountain has facilitated analysis of the complex structural sequence of deformation phases that led to the interlayering, folding and refolding of Lewisianoid basement gneisses and their cover of Moine metasedimentary rocks. Three deformation phases include an early phase of isoclinal folding probably resulting in the fine-scale interlayering of Lewisianoid gneisses and Moine rocks. This was followed by a set of reclined tight folds (F2) that include the Beinn a' Chapuill Fold itself and was associated with amphibolite-facies metamorphism. These F2 folds were subsequently refolded on a large scale by a NE–SW-trending fold, whose axial plane strikes north-east, near-parallel to the Strathconon Fault.

Ramsay's seminal work on the effects of folding on the geometrical relationships between early structures and later superimposed folds, based on his studies at Beinn a' Chapuill and at Loch Monar, led to the establishment of a school of structural studies which has had a profound influence on the development of structural geology throughout the world over the past 40 years (see Ramsay, 1967; Ramsay and Huber, 1983, 1987). Hence, the site is of international importance.

EILEAN CHLAMAIL–CAMAS NAN CEANN (NG 774 129–NG 793 117)

A.J. Barber

Introduction

The Eilean Chlamail–Camas nan Ceann GCR site covers a 2.6 km-long coastal section on the northern shore of Loch Hourn that provides a cross-section through the basement Lewisianoid gneisses of the Western Unit of the Glenelg–Attadale Inlier and intercalated Moine psammites. As the strain is lower than in other areas of the inlier, the section shows many of the felsic and mafic igneous protoliths that make up the Lewisianoid gneisses, in parts still displaying cross-cutting relationships. It demonstrates the history of the Lewisianoid rocks prior to Moine deposition and the extent to which both the Lewisianoid gneisses and the Moine rocks were modified during the Caledonian and possibly Knoydartian orogenies.

South of the village of Glenelg, the outcrop of the Western Unit broadens to *c.* 4 km wide across the strike (Figure 7.2). It is bounded to the west by inverted Moine rocks that represent the original sedimentary cover to the basement (see **Attadale** and **Allt Cracaig Coast** GCR site reports, this chapter), and to the east by the major shear-zone that separates the Western and Eastern units. The rocks of the inlier have generally been strongly deformed such that the major internal lithological units lie near-parallel with the Lewisianoid–Moine boundary (Figure 7.28). Nevertheless, at Eilean Chlamail–Camas nan Ceann zones of lower strain are present and two generations of mafic intrusive rocks can generally be distinguished.

The Glenelg area was mapped by C.T. Clough as part of Glenelg Sheet 71 (Geological Survey of Scotland, 1909) and described in the accompanying memoir (Peach *et al.*, 1910). Much of the following description is drawn from Clough's account. During detailed mapping in the mid-1950s, J.G. Ramsay distinguished the different lithological units within the Western Unit and also made a detailed study of the minor structures and of the Lewisian–Moine relationships (Ramsay, 1957b). Ramsay's detailed field maps at the scale of 1:10 560 form the basis for Figure 7.28.

Description

The Eilean Chlamail–Camas nan Ceann site provides a clean coastal section along an extensive wave-washed platform between high- and low-tide marks. Exposures also extend into cliffs up to 20 m high behind the shore section. The rock platform is interrupted by small bays and coves with shingle beaches and locally is obscured by large boulders, seaweed and barnacles.

The predominant lithologies of this Western Unit are pale-grey and pink, thinly layered felsic

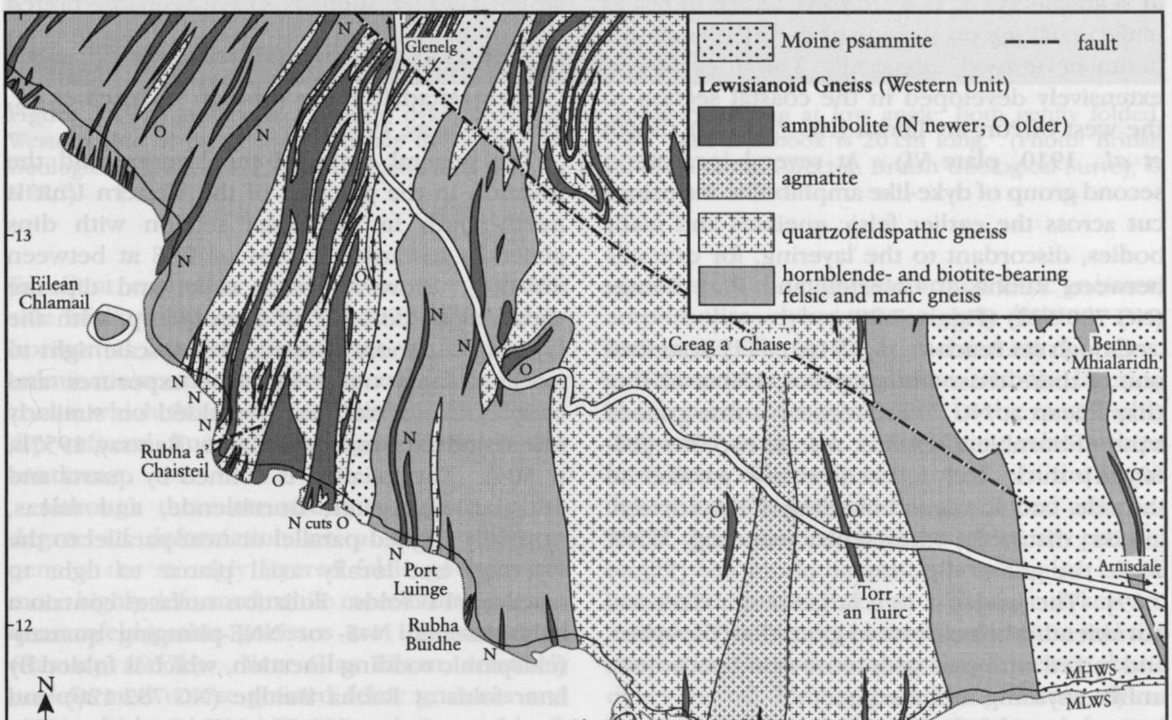


Figure 7.28 Map of the Eilean Chlamail–Camas nan Ceann GCR site. Modified from field maps of J.G. Ramsay.

gneisses composed mainly of quartz, plagioclase feldspar, hornblende and biotite. Quartzofeldspathic layers alternate with those rich in hornblende and/or biotite on a millimetre- to decimetre-scale, with occasional pods of amphibolite and ultramafic actinolitic rock (e.g. Peach *et al.*, 1910, plate VIII). The gneisses also contain thin, pale yellow-green, epidote-rich layers and lenses. Homogeneous pink quartzofeldspathic gneisses are also an important rock-type here, forming two main outcrops, one approximately 500 m wide centred on Rubha a' Chaisteil, the other outcropping for approximately 1 km between Glas Eilean and Camas nan Ceann (Figure 7.28).

The gneisses contain sheets, lenses and screens of dark-grey-weathering, black to greenish-black amphibolite. The margins of these amphibolite bodies are commonly parallel to the layering in the surrounding gneiss, but in places cross-cut the layering at a low angle. Plate IV of the Glenelg memoir (Peach *et al.*, 1910) illustrates one of these amphibolites from Rubha a' Chaisteil (NG 776 123). The amphibolites typically contain quartzofeldspathic veins, either as segregations or as intrusions, which in places make up a high proportion of the rock, such that it can be termed 'agmatite'. This rock type is extensively developed in the coastal section to the west of Port an Tairbh (NG 790 117) (Peach *et al.*, 1910, plate VI). At several localities a second group of dyke-like amphibolite intrusions cut across the earlier felsic gneisses and mafic bodies, discordant to the layering, for example between Rubha a' Chaisteil and Port Luinge (NG 780 122) (Figure 7.28).

Clough (in Peach *et al.*, 1910, p. 41) described one of these cross-cutting dykes, 150 m ENE of Glas Eilean at NG 7880 1168, as 'a fine-grained band of hornblende schist, one or two feet [30–60 cm] thick and foliated nearly parallel to the side, cuts the broad banding of the adjacent gneiss distinctly, the schist running WNW while the gneiss dips east at about 65° [Figure 7.29]. The gneiss is to a large extent dark and hornblendic, but coarser in grain than the schist, and mixed with pale-grey more-acid bands quite unlike anything in the schist.'

Ramsay (1957b) distinguished 'older' and 'newer' groups of intrusive amphibolitic rocks. The 'older' group contains a much higher proportion of quartz-feldspar veins, and are commonly recrystallized, whereas the 'newer' group contains very few veins and are not pervasively recrystallized. Although the 'newer' mafic intrusions do not cut the Moine psammites, the development of veining is comparable to that in adjacent Moine psammites (Ramsay, 1957b, p. 495). 'Older' and 'newer' intrusions are readily distinguished where cross-cutting relationships are preserved, but this distinction is not possible where the rocks have been highly deformed. The distribution of 'newer' and 'older' mafic intrusions is shown on Figure 7.28.

A narrow outcrop of Moine rocks occurs in the coastal section between Rubha a' Chaisteil and Port Luinge (NG 779 122). The Moine rocks are pervasively deformed fine-grained psammites, with alternating quartz-feldspar and mica-rich layers, on a millimetre- to centimetre-scale. They have a strong foliation with a prominent SE-plunging mineral lineation on the foliation surfaces. On their western side, the psammites are in contact with Lewisianoid quartzofeldspathic gneisses, whereas on their eastern side they are in contact with felsic hornblende-biotite gneisses (Figure 7.28). Various Lewisianoid lithologies lie in contact with the Moine along strike. These relationships have been interpreted as demonstrating an unconformable relationship between the Lewisianoid and Moine rocks in the Glenelg–Attadale Inlier (Clough in Peach *et al.*, 1910; Ramsay, 1957b).

The general strike of the layering and the foliation in the gneisses of the Western Unit is north–south in the coast section with dips generally towards the east or ESE at between 40°–60°. However both strike and dip are variable on the scale of the outcrop, with the layering commonly folded. Small-scale tight to isoclinal folds occur in most exposures and early isoclines are locally refolded on similarly orientated axes and axial planes (Ramsay, 1957b, p. 504). The foliation is defined by quartz and feldspar aggregates, hornblende, and micas, normally aligned parallel or near-parallel to the layering, but locally axial planar to tight to isoclinal 'F1' folds. Foliation surfaces contain a subhorizontal N–S- or NNE-plunging quartzofeldspathic rodding lineation, which is folded by later folds at Rubha Buidhe (NG 782 120) and Camas nan Ceann (NG 794 117) (Ramsay, 1957b, p. 509). In highly deformed rocks, a SE-plunging mineral lineation is present, defined by elongated quartz and feldspar crystals and micas (Ramsay, 1962, fig. 8). In places the mineral lineation may be seen superimposed on the rodding lineation.

Figure 7.29 Amphibolitic 'Scourie dyke' cross-cutting gneissic layering at low angle; both gently folded, Western Unit of the Glenelg–Attadale Inlier (NG 7880 1168). The notebook is 20 cm long. (Photo: British Geological Survey, No. P571654, reproduced with the permission of the Director, British Geological Survey, © NERC).

Excellent examples are seen on the western side of Port Luinge (NG 781 122), where sub-horizontal rodding lineations deformed in culminations and depressions are cut by shear zones, which themselves contain a strong down-dip mineral lineation, plunging towards the south-east.

Although there are strong variations in the degree of deformation on a small scale, in general the strongly layered felsic gneisses are more highly deformed, while more-homogeneous quartzofeldspathic gneisses are less deformed (Ramsay, 1957b). Near Glas Eilean, relatively undeformed coarse-grained felsic gneisses and quartzofeldspathic gneisses may be traced both along- and across-strike into their pervasively deformed equivalents (Ramsay, 1957b). Massive hornblendic and amphibolitic mafic lithologies are least deformed and are commonly preserved as pods in reconstituted quartzofeldspathic gneisses. In the highly deformed felsic gneisses, amphibolite dykes are tightly folded (see Ramsay, 1957b, fig. 2), segmented into boudins, and drawn out into parallelism with the layering in the surrounding gneisses. In the most highly deformed examples, cross-cutting relationships have been effectively obliterated. In the larger dykes, hornblende schist is developed adjacent to the dyke margins, with the schistosity parallel to the margin; equigranular amphibolite is still preserved in the interior. Thinner dykes are completely altered to hornblende schist and the distinction between 'older' and 'newer' basic dykes is no longer possible. Where dykes have been intruded into the less-deformed homogeneous quartzofeldspathic gneisses, for example between Rubha a' Chaisteil and Port Luinge (NG 778 123) (Figure 7.28), original angular relationships, although modified, are still observed.

Interpretation

The Eilean Chlamail–Camas nan Ceann section throws some light on significant parts of the Archaean and Palaeoproterozoic geological history of the basement Lewisianoid gneisses and their unconformable cover of Moine metasedimentary rocks.

The oldest components of the Western Unit are the hornblende- and biotite-bearing felsic gneisses and included mafic and ultramafic pods, sheets and lenses, all of probable Archaean age. Little is known of the nature and conditions of their origin or emplacement into the crust. Granodioritic bodies, now represented by the more-homogeneous pink quartzofeldspathic gneiss, intruded this early igneous complex, and were in turn intruded by the 'older' mafic dykes and sheets (Ramsay, 1957b). The complex was then metamorphosed to amphibolite facies or possibly higher grade, with mobilization of the more-felsic components resulting in formation of quartz-feldspar pegmatite veins that intruded the basic dykes. In the northern part of the Glenelg–Attadale Inlier it has been demonstrated that the Western Unit was metamorphosed to granulite facies at this stage (Barber and May, 1976; Storey, 2002). The 'newer' basic dykes were intruded into the complex somewhat later.

The rock types and the sequence of events in the Western Unit of Glenelg have similiarities to those of the Lewisian Gneiss Complex of the foreland, to the west of the Moine Thrust Belt (Clough in Peach *et al.*, 1910; Ramsay, 1957b; Storey, 2002). The felsic gneisses, mafic and ultramafic pods, and the granodioritic bodies can be correlated with similar units in the Scourian gneisses of the Foreland. The 'newer' basic dykes are equated with the Scourie dykes which intrude the Scourian/Badcallian rocks of the Foreland. Ramsay (1957b, p. 495) considered the possibility that the metamorphism that converted these mafic dykes to amphibolite and generated the quartz-feldspar pegmatite veins was equivalent to the Laxfordian metamorphic event of the Foreland at *c.* 1750 Ma; recent U-Pb TIMS zircon dating by Storey (2002) has confirmed this hypothesis. Ramsay (1957b) also suggested the metamorphism that affected the 'older' mafic dykes may relate to the Laxfordian event, but the U-Pb zircon data of Storey (2002) suggest that this high-grade metamorphism and agmatite generation occurred some 2600–2800 Ma, equivalent to the Scourian event in the Foreland.

Many of the tight to isoclinal folds seen in the gneisses of the Western Unit probably relate to their pre-Moine history. Structures can only be confidently assigned to post-Moine Knoydartian or Caledonian events at the margins of the Lewisianoid inlier, where the adjacent Moine rocks show a platy foliation, local small-scale tight to isoclinal folding, and a SE-plunging mineral lineation. Similar structural features are only developed locally within the Western Unit Lewisianoid gneisses with shearing apparently focused on the basement–cover boundary. This early deformational event that affected the rocks of the Glenelg–Attadale Inlier was also responsible for the folding and the interlayering of the Lewisianoid and Moine (see **Beinn a' Chapuill** and **Rubha Camas na Cailinn** GCR site reports, this chapter).

Conclusions

The well-exposed rocky coastal section between Eilean Chlamail and Camas nan Ceann provides a natural cross-section across the Western Unit of the Glenelg–Attadale Inlier that enables the relationships between the various constituent rock units to be studied. The distribution and characteristics of the dominant lithological units, the Archaean-age hornblende- and biotite-bearing felsic gneisses, included mafic and ultramafic bodies, and the pink granodioritic quartzofeldspathic gneisses are well displayed. A feature of this section is the relative low state of deformation of the Lewisianoid rocks, which has allowed the preservation of the cross-cutting relationships between the gneisses and a later swarm of Palaeoproterozoic mafic dykes (Scourie dykes), now represented by amphibolites. Two sets of mafic intrusions can be distinguished; 'older' amphibolite bodies that show penetrative deformation and are intruded by abundant quartz-feldspar veins, and a 'newer' set of mafic dykes that show only local deformation fabrics. In parts cross-cutting relationships between 'newer' and 'older' dykes are preserved.

The section clearly demonstrates the important role that lithology plays in controlling the degree of deformation. Deformation preferentially affected the quartz-feldspar-rich units, especially where they are interlayered on a small scale with hornblende- and biotite-rich layers, whereas the homogeneous quartzofeldspathic rocks show less evidence of deformation, and hornblendic mafic and ultramafic rocks remain relatively undeformed.

The Eilean Chlamail to Camas nan Ceann section provides evidence of the sequence of metamorphic and structural events that affected the Western Unit Complex prior to the deposition of the Moine. This sequence of events can be compared with the Lewisian Gneiss Complex of the Foreland, where the gneisses are unaffected by the Caledonian Orogeny. As the site includes both Lewisianoid and Moine rocks, it also allows the discrimination between structural and metamorphic features in the Western Unit rocks of pre-Moine age and those imposed during the Caledonian or Knoydartian orogenic events. The site is of national importance.

RUBHA CAMAS NA CAILINN (NG 850 089–NG 852 079)

A.J. Barber and M. Krabbendam

Introduction

At the peninsula Rubha Camas na Cailinn on the northern shore of Loch Hourn, complex and tightly interfolded Moine and Lewisianoid rocks are exposed on a wave-washed rock platform. The rocks occur south-east of the Strathconon Fault at the southernmost extremity of the Glenelg–Attadale Inlier (Figure 7.2). In this area Lewisianoid gneisses form strips less than 1 km in width, much narrower than farther north, and Rubha Camas na Cailinn is situated at the southern tip of one such strip. Early 'F1' folds refolded by F2 folds were instrumental in the interfolding of Moine and Lewisianoid rocks. The Moine rocks surrounding the gneisses comprise psammite, pelite and semipelite, the basal units of the Morar Group (Ramsay and Spring, 1962; Holdsworth *et al.*, 1994). The gneisses at the GCR site are assigned to the Western Unit of the Glenelg–Attadale Inlier, but narrow strips of the Eastern Unit occur about 1 km to the north-east (Figure 7.2).

The Arnisdale area was mapped by C.T. Clough as part of the primary geological survey of the Glenelg (Sheet 71) (Geological Survey of Scotland, 1909). J.G. Ramsay remapped the area in the late 1950s, paying particular attention to the structure, the relationships between the Lewisianoid and Moine rocks, and the Moine stratigraphy (see Ramsay and Spring, 1962). Most of the following description and Figure 7.30 are derived from Ramsay's detailed work.

Description

At the seaward fringe of Rubha Camas na Cailinn on Loch Hourn, 2.5 km SSE of Arnisdale, is an ice-smoothed and wave-washed rock platform that provides a total section some 180 m long and 10–15 m wide. On the headland, Moine psammites are interlayered with three distinct strips of Lewisianoid gneisses (Figure 7.30), whereas farther east only psammites are present. The psammites constitute the lower part of the Arnisdale Psammite Formation (Morar Group) and are pale- to dark-grey with prominent internal layering defined by feldspathic psammite alternating with thin mica-rich semipelite, representing original silty layers in the sandstone succession. The psammite is partly garnetiferous and a prominent schistosity is developed in the more-micaceous layers. The psammites also contain pale yellow-green layers rich in epidote, and thin dark-grey heavy-mineral bands rich in magnetite and ilmenite (Ramsay and Spring, 1962).

The Lewisianoid gneisses are composed mainly of pink and white quartzofeldspathic layers, with intervening thin black hornblende- and biotite-rich layers on a 2–3 cm scale. These are interlayered with thicker mafic layers of black amphibolite, up to 20 cm in width, and pods of black to dark-green ultramafic hornblendite. A mica and hornblende foliation is developed parallel to the gneissic layering, particularly in the thinner layers. Both Lewisianoid gneisses and semipelitic layers in the Moine contain concordant quartz veins and pegmatitic quartzofeldspathic segregations. Within the gneisses, some quartzofeldspathic lenses are clearly isolated tight to isoclinal fold cores, the relics of folding and boudinage of pegmatite veins.

The overall layering and foliation in both Moine and Lewisianoid units are parallel, and strike roughly north–south with a moderate to steep easterly dip (Figure 7.30). Numerous tight to isoclinal folds occur at the site. Most of these are tight F2 folds, with steeply E-dipping axial planes, E-plunging fold axes and a strong Z-asymmetry. A strong mineral and rodding L2 lineation in both Moine and Lewisianoid rocks plunges 40°–60° eastwards, generally parallel to

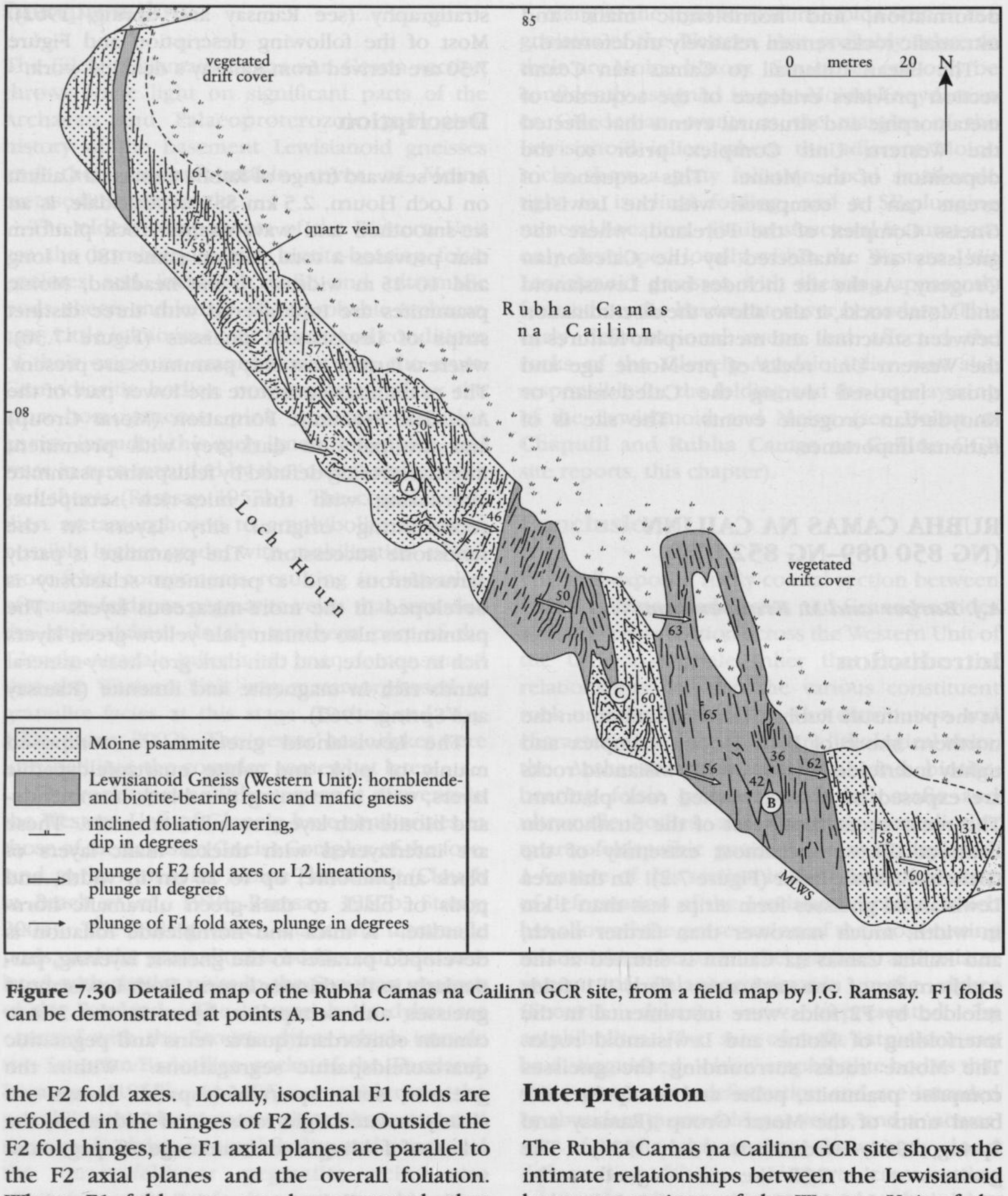


Figure 7.30 Detailed map of the Rubha Camas na Cailinn GCR site, from a field map by J.G. Ramsay. F1 folds can be demonstrated at points A, B and C.

the F2 fold axes. Locally, isoclinal F1 folds are refolded in the hinges of F2 folds. Outside the F2 fold hinges, the F1 axial planes are parallel to the F2 axial planes and the overall foliation. Where F1 fold axes can be measured, they plunge 30°–40° to the south-east, rather than to the east. Thus, F1 and F2 folds are coplanar, but not coaxial. Locally, the Moine–Lewisianoid contact is folded by F1 tight to isoclinal folds (Figure 7.31). There is no evidence of shearing or basal conglomerate development along the Moine–Lewisianoid contact. The rocks have also been affected by minor post-recrystallization small-scale open folding.

Interpretation

The Rubha Camas na Cailinn GCR site shows the intimate relationships between the Lewisianoid basement gneisses of the Western Unit of the Glenelg–Attadale Inlier and the Moine psammites that formed its original sedimentary cover. Both Lewisianoid and Moine rocks have been strongly deformed and metamorphosed under amphibolite-facies conditions during Knoydartian and Caledonian orogenic events resulting in a complex interference fold geometry that also highlights the competency differences between basement and cover. Although the compositional

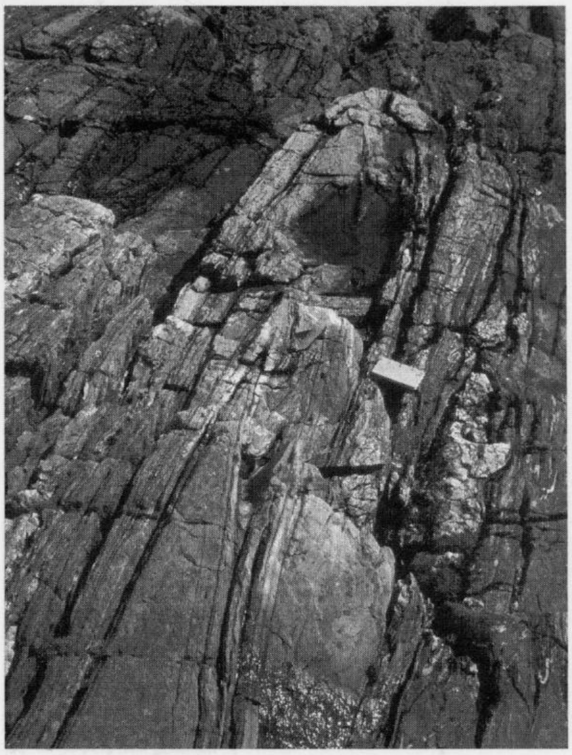


Figure 7.31 Plan view of tight fold closure of Lewisianoid gneiss, cored by Moine psammites. Parasitic folds of probable F1 age are visible left of the notebook. The notebook is 20 cm long. Rubha Camas na Cailinn (NG 8502 0798). (Photo: M. Krabbendam, BGS No. P571662, reproduced with the permission of the Director, British Geological Survey, © NERC.)

layering in both Lewisianoid and Moine rocks is parallel, the two rock groups are lithologically readily distinguished. The original unconformable relationship between the two units has been described in the **Allt Cracaig Coast** GCR site report, this chapter.

The absence of a basal pelitic unit and local metaconglomerate may be an original feature of the Moine depositional basin, with the Moine succession deposited on an irregular surface of Lewisianoid gneisses, or it may reflect early extensional shearing during the Knoydartian event.

In his discussion of Moine–Lewisianoid relationships, Ramsay (1957b) argued that both shearing ('sliding') and folding were instrumental in the tight interleaving of Moine and Lewisianoid rocks in the Glenelg area. Later detailed work from just north of Rubha Camas na Cailinn in the Arnisdale area on the structural relationship between lineations and folding suggested that folding was more important than shearing (Ramsay, 1960). Ramsay and Spring (1962) also showed that in the Arnisdale area a near-continuous outcrop of Moine Basal Pelite Formation follows the Moine–Lewisian contacts on both the east and west sides of the Lewisian 'strips'. Such a symmetrical outcrop pattern is characteristic of folding, rather than shearing. At Rubha Camas na Cailinn it is clear that the disposition of the Moine and Lewisianoid layers results from tight to isoclinal folding, involving both F1 and F2 folds. The site is one of the best places in the Glenelg area to observe F1 folds affecting the Moine–Lewisianoid contact.

The earliest phase of deformation resulted in the formation of anticlines of Lewisianoid basement gneiss and intervening synclines of Moine psammite, resulting in alternating outcrops of the two rock groups. Both units contain long-limbed tight to isoclinal intrafolial minor folds related to this phase of deformation. F1 folds were strongly modified and the layers attenuated by F2 folding, which was accompanied by pervasive recrystallization under amphibolite-facies conditions. The dominant S2 schistosity and the L2 lineation, which is co-linear with the F2 fold axes, were formed at the same time. The structures in Moine and Lewisianoid rocks were brought into conformity, a parallelism reinforced by the cumulative effect of the multiple deformation phases.

Parallelism of mineral lineations and fold axes is commonly explained by wholesale rotation of fold axes towards the finite stretching direction (e.g. Sanderson, 1973; Alsop and Holdsworth, 2002). However at Rubha Camas na Cailinn this mechanism cannot be invoked, as the earlier F1 fold axes do not lie parallel to the mineral lineation, unlike the later F2 fold axes. Some alternative mechanism must have been responsible for the parallelism of F2 fold axes and L2 mineral lineation. The D2 structures are probably Caledonian in age, although the earlier D1 structures are likely to be Knoydartian (Neoproterozoic).

The field relationships at the GCR site, dominated by folding, are incompatible with the suggestion of Temperley and Windley (1997) that many of the structures in Glenelg are the result of Grenvillian (*c.* 1000 Ma) extension. At Rubha Camas na Cailinn, the Moine and Lewisianoid rocks share the same structures and responded to post-Moine deformation in a similar fashion, indicating that rheological behavoir of the basement gneisses and their metasedimentary cover was little different at the time of deformation.

Conclusions

A well-exposed rock platform around the small peninsula of Rubha Camas na Cailinn provides an excellent natural section across interfolded Lewisianoid basement gneisses and their Moine metasedimentary cover. Early F1 folds are refolded by later F2 folds that formed coeval with the peak of metamorphism; this sequence of structures was responsible for the formation of thin 'strips' of Archaean Lewisianoid gneisses within the wider outcrops of early Neoproterozoic Moine psammites. The sequence of structural events can be correlated with that found in many other areas in the Northern Highlands of Scotland. The structural and metamorphic features in the Moine are the product of Caledonian and earlier Knoydartian tectonic events. The intimate relationships of the Lewisianoid and Moine rocks and their similar structural geometry show that the Lewisianoid gneisses and enclosing Moine psammites shared in these events to the same degree. This implies that the mechanical behaviour of the crystalline basement and the metasedimentary rocks was similar under amphibolite-facies metamorphic conditions.

The site provides a good example of infolding of crystalline basement and sedimentary cover on a very fine scale under high-grade metamorphic conditions. This model is applicable to many other orogenic belts throughout the world and as a result the site is of national and international importance.

ARD GHUNEL (NG 702 120–NG 709 117)

R.F. Cheeney

Introduction

In the Lewisianoid gneisses of the Moine Nappe in the Sleat peninsula of Skye, are several ultramafic lenses that show rare and striking examples of concentric mineral zonation of talc, actinolite and biotite-bearing assemblages. The lenses are small and variable in character but type examples lie in the well-exposed coastal sections and inland crags of Ard Ghunel. Geochemical evidence indicates that the lenses originated as lenticular ultramafic intrusions, within the dominantly quartzofeldspathic orthogneisses. Metamorphic and metasomatic reactions during regional metamorphism that accompanied intense Caledonian reworking probably produced the internal zonation. Ultramafic lenses do occur commonly within the foreland Lewisian gneisses and in the Lewisianoid inliers, but rarely show well-developed zoning. Unfortunately much of the originally exposed material at Ard Ghunel has disappeared or been damaged due to the over collection of specimens.

The two principal rock units around Ard Ghunel are Moine psammites and Lewisianoid gneisses, the latter forming a probable extension of the Western Unit of the Glenelg–Attadale Inlier. All of these rocks lie within the Moine Nappe, with the Moine Thrust cropping out some 2 km to the north-west.

Clough (in Peach *et al.*, 1907) provided the first description of the rocks, and Bailey (1955), in discussing metamorphism in this part of Skye, described their petrography. The account that follows, based mainly on Matthews' (1967) study of the metamorphism, chemistry and paragenesis of the pods, describes their appearance around their time of discovery.

Description

The GCR site encompasses Druim Bàn, a hill on the peninsula of Ard Ghunel that juts out from the eastern side of the Sleat peninsula. The best exposures are seen at the eastern extremity of the peninsula. The Lewisianoid gneisses range from quartzofeldspathic orthogneisses, through epidotic, hornblende-, biotite-, and garnet-bearing varieties, to garnet amphibolites and rare occurrences of almost monomineralic actinolite, diopside and orthite rocks. Discordant amphibolite sheets and quartzofeldspathic migmatitic veining also occur. The subsidiary Moine rocks that form much of the southern part of Ard Ghunel peninsula are almost exclusively gneissose arkosic psammites, which share all of their minor fold structures with the Lewisianoid rocks.

The zoned ultramafic bodies comprise about a dozen separate, mineralogically zoned pods, in groups of two or three, scattered through a relatively confined structural horizon within the Lewisianoid gneisses. In cross-section, the pods present a well-defined lenticular to circular outline, up to 3 m long, but more commonly less than 1 m, with the long axis aligned with the gneissosity outside the pods. Internally they are essentially undeformed. The best-developed examples (now destroyed) were built up of concentric, onion-like monomineralic zones (Matthews, 1967). When formed, there was some variation between the pods, dependent on their host country rock. Where the host rock is amphibolite, the lenses typically contain: a core of talc and dolomite with minor magnetite; a surrounding zone of coarser, radiating, prismatic actinolite, with crystals up to 10 cm long; an outer zone of finer actinolite rock; and finally an envelope of large, tangentially orientated biotite flakes (Figure 7.32). The crystals in each zone are clearly visible to the naked eye, and apart from the biotite and the coarser actinolite, they are randomly orientated. Each zone is typically of the order of 10 cm thick. Individual lenses show some mineralogical variation with chlorite, diopside, or fuchsite (chrome mica) moderately abundant in parts.

In the lenses that are enclosed in the quartzo-feldspathic gneisses the talc-dolomite core is typically absent, but concentrations of albite-rich, untwinned plagioclase feldspar, commonly associated with an enrichment of biotite, occur in the immediately adjacent gneisses. Otherwise, the contacts of the ultramafic lens are sharp against the host gneisses in which Baravaig generation structures are abundant (Cheeney and Matthews, 1965).

Interpretation

The Lewisianoid gneisses and Moine rocks in Sleat were strongly deformed during the Caledonian deformation. Caledonian metamorphism reached a peak of lower-amphibolite facies, with growth of almandine garnet, early in the deformational history of the area (Cheeney and Matthews, 1965). This metamorphism probably involved retrogression and wholesale recrystallization of the pre-existing Lewisianoid assemblages, with earlier igneous textures only preserved in local low-strain zones. In this context the ultramafic lenses within the Lewisianoid gneisses pose particular problems. Although the bulk composition of the cores to the lenses resembles that of a siliceous dolomite, the trace-element geochemistry inside the contact zone between the biotite and outer actinolite zones shows a strong ultrabasic igneous affinity, with Ni and Cr being particularly abundant. This suggests that the mineral assemblages in the lenses resulted from metamorphic and metasomatic reactions between the ultramafic rock and host felsic and mafic gneisses during Caledonian regional metamorphism (Matthews, 1967). The relative mobility of Mg in particular, as indicated by its linear concentration gradient from core to envelope, appears to have been a principal factor controlling the disequilibrium zonation. K_2O, CO_2 and H_2O must have entered the chemical system from outside the immediate vicinity of the lenses, but Si and Ca would appear to have moved relatively freely within the bodies independent of the proximal host rock, although not to equilibrium concentrations. In contrast, Al appears to have remained effectively immobile. The metamorphic condition of the pods prior to their Caledonian modification and retrogression is unclear.

The age and emplacement mechanism of the ultramafic pods is not known, although they may well represent boudinaged remnants of larger Archaean or Palaeoproterozoic intrusive masses, genetically related to an extensive, NE–SW-trending sheet of serpentinite that crops out between 1 km and 3 km to the south-west (Matthews, 1967).

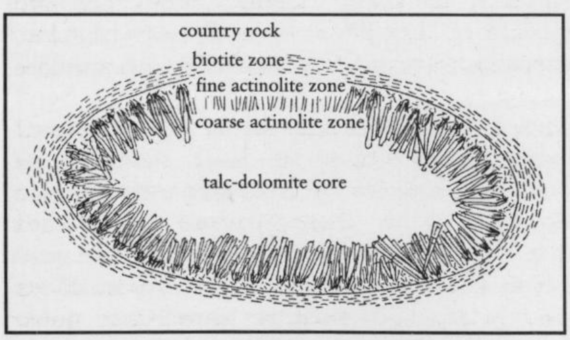


Figure 7.32 Diagrammatic representation of the mineralogical zones developed in the Ard Ghunel ultramafic body. After Matthews (1967).

Conclusions

At the Ard Ghunel GCR site small lenses of mineralogically zoned ultramafic rocks occur within Lewisianoid gneisses of the Moine Nappe. The Moine psammites and Lewisianoid gneisses near Ard Ghunel were strongly deformed and metamorphosed to almandine amphibolite facies during the Caledonian Orogeny. Where enclosed within amphibolite, the metre-sized ultramafic pods have talc-dolomite cores, surrounded by successive zones of coarse actinolite, fine actinolite and biotite. Where enclosed in quartzofeldspathic gneisses, zones of albite and biotite enrichment occur in the adjacent gneisses. The mineral zonation is probably the result of incomplete metamorphic and metasomatic reactions between original Archaean or Palaeoproterozoic ultramafic intrusive masses and the more-quartzofeldspathic country rocks. Zoned ultrabasic pods are very rare in the UK, and the only other occurrence is in Shetland. Hence the site is of national importance, but unfortunately, the pods have been severely damaged by over collection, and little remains of the original exposures.