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

GCR Editor: **P.H. Banham**

JOINT NATURE CONSERVATION COMMITTEE

British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

Chapter 8

Moine (South)

INTRODUCTION

J.R. Mendum

The southern Moine area stretches from Loch Hourn and Glen Moriston in the north, south-westwards to Ardnamurchan and the Sound of Mull, where Palaeogene mafic lavas and intrusions overlie and intrude the Moine rocks. A small enclave of Moine rocks occurs in the south-west part of Mull adjacent to the Ross of Mull Granite Pluton. The Great Glen Fault bounds the area to the south-east, and to the west the Moine Thrust Belt lies offshore. The northern boundary of the area extends as far north as Cluanie and Glen Affric to include all the outcrops of the West Highland Granite Gneiss Suite (Figure 8.1). The area encompasses the mountainous watershed region of Inverness-shire and the north part of Argyllshire with numerous summits exceeding 900 m. Lower hilly areas and more-rolling, partly forested country occurs near to the Great Glen, on the Ardnamurchan peninsula, and in Morvern in the south.

The main features of the geology of the southern Moine area are the distinctive tripartite division of the Moine Supergroup into the Morar, Glenfinnan and Loch Eil groups, the presence of the West Highland Granite Gneiss Suite, and the overall structural pattern, dominated by the central 'Steep Belt' and the Sgurr Beag Thrust. The 'Steep Belt' is an area of complex, superimposed folding mainly affecting interbanded pelitic and psammitic rocks of the Glenfinnan Group that forms a central NE-trending spine to the region. It is an area of rugged, rocky and grassy mountains transected by roughly east–west breaches, which are infilled by Loch Quoich in the north, Loch Shiel in the centre, and Loch Sunart in the south. The Loch Eil–Loch Ailort transect provides a major through route from Fort William to Mallaig (Figures 8.1, 8.2; see **Fassfern to Lochailort Road Cuttings** GCR site report, this chapter). The Sgurr Beag Thrust separates the Sgurr Beag Nappe above, from the Moine and Knoydart nappes below (Figure 8.1). Glenfinnan Group and Loch Eil Group rocks lie within the Sgurr Beag Nappe. Lewisianoid inliers are restricted to the Morar area where they occur mainly in thrust sheets and lenses. The Moine rocks contain evidence of Neoproterozoic deformation and metamorphism, with the Grampian and possibly Scandian orogenic episodes superimposed on the earlier pattern. The igneous history of this area is varied and spans a long time-period. The oldest elements are the granite precursors of the West Highland Granite Gneiss Suite and early gabbro and dolerite bodies, emplaced at *c.* 870 Ma (Friend *et al.*, 1997; Millar, 1999; Rogers *et al.*, 2001). Pegmatitic granite and leuco-tonalite vein-complexes give isotopic ages between 784 Ma and 827 Ma (Rogers *et al.*, 1998), compatible with their formation during a Neoproterozoic Knoydartian tectonometa-morphic event. The foliated Glendessarry Syenite was intruded during the Grampian Event at *c.* 456 Ma (van Breemen *et al.*, 1979b). Deformed gabbro-diorite intrusions in Glen Scaddle, dated at *c.* 426 Ma (Strachan and Evans, 2008), and in Glen Loy, are in part sheared and amphibolitized, attesting to Scandian orogenic activity. The final phases of the Caledonian Orogeny in the late Silurian were marked by the emplacement of numerous acid to intermediate intrusions. The Strontian, Cluanie and Ross of Mull plutons and the Clunes Tonalite are the major bodies. Minor intrusions include abundant microdiorite sheets and dykes, granitic vein-complexes, porphyritic microgranodiorite dykes, appinitic intrusions, and rare lamprophyre dykes.

History of Research

The early workers of the Geological Survey moved down the Moine Thrust Belt to Lochalsh and Skye in the late 19th century (see Chapter 5), and it was only in the 1920s that the Survey commenced mapping in the southern Moine area. The complex nature of the geology, the wet weather, and the difficult nature of the ground made progress slow, particularly in the more-remote mountainous parts of the area. Work continued intermittingly from the 1950s to the 1980s, and the final 1:50 000 sheet, Sheet 73W (Invermoriston), was published in 1995 (British Geological Survey, 1995). However, much of the southern Moine area has no memoir coverage.

During the Second World War, the Knoydart Mica Mine was described by Kennedy *et al.* (1943) and shortly afterwards went in production. The mica was used for furnace windows and electrical components.

Academic work, commonly PhD studies involving detailed mapping, focused on the southern Moine area from the mid-1950s onwards. An early group, from Imperial

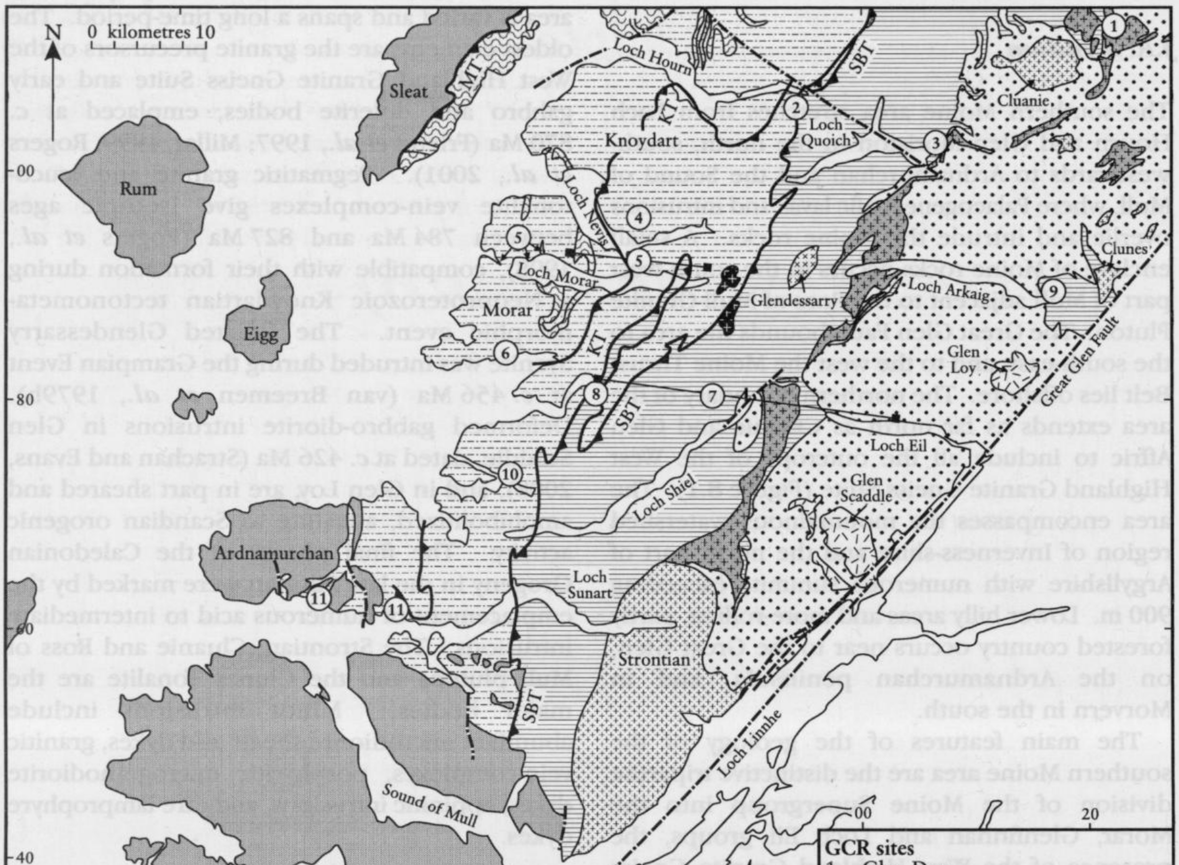


Figure 8.1 Simplified geological map of the Moine (South) area, showing the location of the GCR sites.

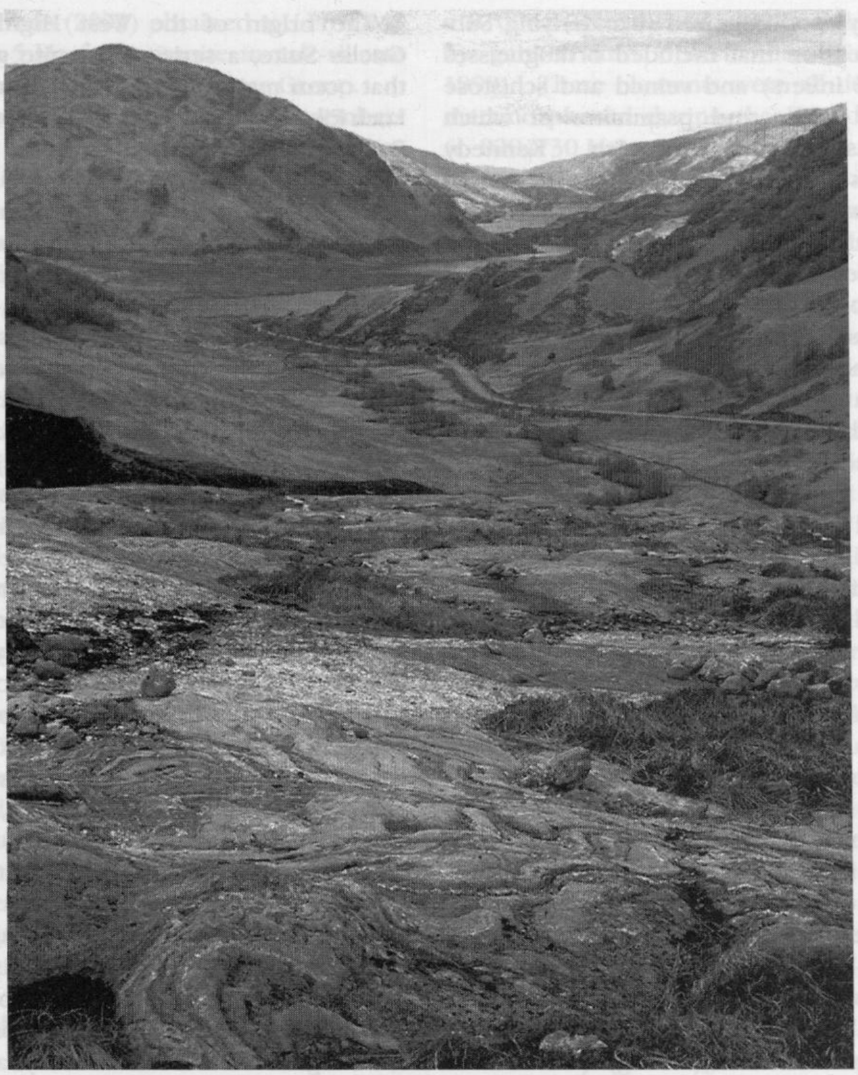


Figure 8.2 View westwards to Loch Eilt from The Muidhe (NM 857 815). In the foreground glaciated slabs show complex folded Glenfinnan Group pelitic and psammitic rocks cross-cut by thick pegmatitic veins that are themselves folded. The craggy and mainly grassy hills are typical of the 'Steep Belt'. (Photo: J.R. Mendum, British Geological Survey, reproduced with the permission of the director, British Geological Survey, © NERC.)

College, London, included P.S. Simony, J.S. Spring and P.W.G. Tanner, who worked in Kintail and Knoydart and linked with Ramsay's work in the Glenelg area (see 'Introduction', Chapter 7). Another group at the University of Edinburgh, supervised by M.R.W. Johnson, included I.W.D. Dalziel, G.C. Clark, R.L. Brown and J.B. Howkins, who worked in the Glenfinnan–Loch Ailort area. D. Powell, R. St J. Lambert and A.B. Poole were other significant contributors to these field-based studies, notably in the Morar–Lochailort area. D. Barr, B.H. O'Brien, A.M. Roberts and P.A. Rathbone from Liverpool University were supervised by A.L. Harris and carried out work on the southern Moine area. Other notable PhD work was carried out by R.A. Strachan in the Glenfinnan–Loch Eil area and by N.R.W. Glendinning in the western Moine; both studies contributed significantly to our understanding of the sedimentary environments during deposition of the Moine Supergroup (Strachan, 1985, 1986; Glendinning, 1988).

Based on their Geological Survey mapping, Richey and Kennedy (1939) suggested a tripartite division of the structurally and stratigraphically lowest Moine rocks, now termed the 'Morar Group', into Lower and Upper Psammite 'groups' separated by a 'Striped and Pelitic

Group'. They also recognized an underlying 'Sub-Moine' succession that included orthogneisses (Lewisianoid inliers) and veined and schistose semipelites, pelites and psammites in which bedding was difficult to discern. Kennedy (1955) subsequently revised the structural interpretation significantly, and postulated that the coherently bedded Moine rocks formed the Morar Nappe, which was folded by the later Morar Antiform to give a 'window' into the lower succession. He recognized that the Lower Psammite and parts of the Moine succession were duplicated in the structurally lower rocks and argued that Lewisianoid gneiss was present. When Kennedy presented his model, there was considerable discussion as to the nature of the 'Lewisianoid' gneiss inliers, the possible correlations with the Glenelg area, and the wider tectonic interpretations of the postulated tectonic (?Grampian and Scandian) events. Kennedy's interpretations, both in Morar and on the wider scale, were not well received, but there was little discussion of the structural detail and nature and position of the slide or thrust boundaries of the different elements. Lambert (1958) later argued that the Moine–Sub-Moine boundary was in fact a gradational metamorphic boundary, but it was the detailed work of Ramsay and Spring (1962) in Knoydart, Poole (1966) in North Morar, and Powell (1966) in Morar and Lochailort, that determined the nature of the structural boundaries and detailed stratigraphy. This work, combined with the publication of Sheet 61 (Arisaig) (Institute of Geological Sciences, 1971), enabled more-coherent interpretations of the Morar Group rocks to be made by Poole and Spring (1974) and Powell (1974). It was recognized that the Lewisianoid rocks lay either in thrust contact with the adjacent Moine succession, or in the cores of tight to isoclinal folds.

The recognition of the Sgurr Beag Thrust, a shear zone that separates the Morar and Glenfinnan groups (Tanner *et al.*, 1970; Tanner, 1971; Rathbone and Harris, 1979; Powell *et al.*, 1981) proved to be a key in the understanding of the regional overall structure of the Moine succession. The Quoich (or Loch Quoich) Line that marks the eastern margin of the central 'Steep Belt' and broadly coincides with the south-eastern boundary of the Glenfinnan Group, was first recognized by Clifford (1957), but its overall significance was recognized by Roberts and Harris (1983) and Strachan (1985).

The origin of the West Highland Granite Gneiss Suite, a series of granite gneiss bodies that occur mainly along the Glenfinnan Group–Loch Eil Group boundary, has been controversial. Bailey and Maufe (1916) interpreted the southernmost body, the Ardgour Granite Gneiss, as a deformed, pre-metamorphic intrusion. Harry (1954) and Dalziel (1966) suggested that the Ardgour body formed *in situ* by K-metasomatism of Moine sediments during high-grade metamorphism. Mercy (1963) suggested that the Ardgour Granite Gneiss could have a magmatic origin. On the basis of geochemical data, Gould (1966) concluded that it has a uniform granitic composition, distinct from the adjacent Moine metasediments, and was intruded as an Al-undersaturated magma which incorporated metasedimentary material from the Moine rocks at depth. Barr *et al.* (1985) re-investigated the granite gneiss occurrences in the North-west Highlands and concluded that they represent a series of deformed and metamorphosed intrusive granite sheets. The relationship of the granite gneiss with associated metagabbro bodies at Glen Doe was first studied by Peacock (1977), but it was Millar's work (1990, 1999) that showed the intimate relationship between the two suites of rocks and suggested that the granite gneiss and the metagabbro were part of a bimodal, rift-related suite of magmatic rocks (see **Glen Doe** GCR site report, this chapter).

Some of the earliest geochronological work was by Giletti *et al.* (1961), who pioneered Rb-Sr dating on micas from the Knoydart Mica Mine and Sgurr Breac, obtaining ages between 690 Ma and 750 Ma (see **Knoydart Mica Mine** GCR site report, this chapter). This work gave the first hint of Neoproterozoic tectonothermal events within the Moine outcrop, and the character and significance of the 'Knoydartian' and 'Morarian' events has proved controversial ever since. Similar Neoproterozoic ages were soon obtained from muscovites in pegmatites elsewhere in the Moine area (Long and Lambert, 1963; van Breemen *et al.*, 1974; Piasecki and van Breemen, 1983; Powell *et al.*, 1983). More-accurate U-Pb monazite and zircon dating (van Breemen *et al.*, 1974, 1978; Rogers *et al.*, 1998) from many of these pegmatite bodies has confirmed their Neoproterozoic ages, with the pegmatites thought to be pre- or syn-D2. Dating on other rocks has also yielded Neoproterozoic ages: Vance *et al.* (1998) obtained Sm-Nd ages of 823 Ma and 788 Ma from garnets in the Morar Pelite, and

Tanner and Evans (2003) obtained a U-Pb TIMS age of 737 ± 5 Ma from titanite in calc-silicate rocks in the upper part of the Morar Group.

The early geochronological work on members of the West Highland Granite Gneiss Suite gave contradictory results (Brook *et al.*, 1976; Aftalion and van Breemen, 1980). More recently, U-Pb dating of zircons has concluded that the original granite intrusion occurred at *c.* 873 Ma (Friend *et al.*, 1997; Rogers *et al.*, 2001). Millar (1999) also obtained an 873 ± 6 Ma emplacement age from a metagabbro at Glen Doe, where the mafic rocks clearly cut the granite gneiss. Most authors now accept that this *c.* 870 Ma event was extensional. Several authors (Dalziel and Soper, 2001; Ryan and Soper, 2001) argued that all the Neoproterozoic tectonothermal events could be explained by extensional events. However, recent studies that combined isotopic dating with metamorphic petrology (e.g. Vance *et al.*, 1998; Zeh and Millar, 2001; Tanner and Evans, 2003) appear to show that the 'Knoydartian' and 'Morarian' events were contractional orogenic events. One puzzling aspect of these Neoproterozoic events is that elsewhere in the region there is no evidence of orogenic events of comparable age, and Scotland was, at the time, probably situated in the middle of the Rodinia supercontinent. The nature and extent of these pre-Caledonian orogenic events remains somewhat unclear (e.g. see Oliver, 2002).

Geological history

The geological history of the southern Moine area has many similarities with the central and northern Moine areas. The dominantly arenaceous Moine succession was deposited in early Neoproterozoic times in a wide shallow fluviatile and marine basin whose basement was composed of Lewisianoid rocks. In the southern Moine outcrop, the basement–cover relationship is only exposed in the Morar area. Pelitic and semipelitic units representing mud and silt deposition are found within the lower Morar Group rocks, but are more abundant in the overlying Glenfinnan Group. The upper Loch Eil Group is dominated by psammites derived from mature marine sands. Studies of detrital zircons suggest that the Moine sands were derived from the Grenville Belt and Canadian Shield areas (Friend *et al.*, 2003).

Granite sheets were intruded into the Moine succession during the early Neoproterozoic at *c.* 870 Ma (Friend *et al.*, 1997), followed closely by gabbro and dolerite intrusions (Millar, 1999). These elements were all deformed and metamorphosed during the Knoydartian event (*c.* 820–730 Ma). Recent isotopic dating and metamorphic studies suggest that this was an orogenic event that resulted in compressional stacking of the succession (Vance *et al.*, 1998; Zeh and Millar, 2001; Tanner and Evans, 2003; see **North Morar** GCR site report, this chapter). It is unclear whether this Knoydartian event also resulted in the formation of the distinct Moine, Knoydart and Sgurr Beag nappes. A considerable time-gap followed before the rocks were reworked during the early Ordovician Grampian Event of the Caledonian Orogeny. This event refolded the earlier structures and also resulted in metamorphism to middle-amphibolite facies, though probably at lower pressures than those prevailing during the earlier Knoydartian event. The reworking occurred mainly within the 'Steep Belt' in Glenfinnan Group rocks, with deformation and metamorphism occurring coeval with the intrusion of the Glendessarry Syenite at 456 Ma. Isotopic work has so far provided little evidence of the Scandian Event in the southern Moine area, but Strachan *et al.* (2002a) assigned the main Caledonian reworking to this event. These authors interpret the thrust geometry in the southern Moine succession as part of a coherent foreland-propagating sequence linked to the Moine Thrust Belt and draw analogies with the structural sequence in Sutherland. Following Scandian deformation, a period of strong uplift occurred in late Silurian time, accompanied by intrusion of the gabbro, tonalite and granodiorite plutons and related minor intrusions. Devonian sandstones and conglomerates were probably deposited on parts of the southern Moine area following the major period of uplift, particularly along the Great Glen, but only small remnants are now preserved (Stoker, 1983).

Main lithologies

Lewisianoid inliers

Lewisianoid rocks are found locally as thrust-bounded lenticular sheets in the immediate hangingwall of the Sgurr Beag Thrust (see **Kinloch Hourn** GCR site report, this chapter). However, their main occurrence in the Moine (South) area is in the central part of the Morar

Antiform associated with the lower part of the Morar Group succession. Here, Lewisianoid gneisses are found in the cores of tight to isoclinal anticlinal infolds (Powell, 1974) and possibly also occur as thrust sheets (Kennedy, 1955). The gneisses are typically layered felsic and mafic orthogneisses. The interlayered hornblendic material, epidotic and pyritic nature of the gneisses, and the occurrence of mafic and ultramafic pods, are characteristic features of Lewisianoid inliers (see **North Morar** GCR site report, this chapter). Their complex history is represented by several phases of mafic intrusion and by different generations of quartz-feldspar pegmatite veins. The thickness of the gneissic layering ranges from several metres, down to a few millimetres where the rocks have been highly sheared during the Knoydartian or Caledonian orogenic events.

Moine–Lewisianoid relationships are not as clear in the southern Moine area as farther north. Basal Moine conglomerates are absent and the Moine–Lewisianoid contacts are commonly the sites of ductile thrusting (see **Kinloch Hourn** and **North Morar** GCR site reports, this chapter). Where the basal contact of the Moine succession is seen in its relatively unmodified state in Morar, the thinly interbedded psammites, semipelites and pelites of the Basal Pelite Formation appear to lie with marked unconformity on the Lewisianoid gneisses.

Moine Supergroup

The overall stratigraphy of the Moine rocks broadly youngs from basal units in the west to the highest units in the east. Three tectonostratigraphical divisions of the Moine succession were first recognized in the southern Moine area (Johnstone *et al.*, 1969), and these divisions are now formally termed the 'Morar Group', the 'Glenfinnan Group' and the 'Loch Eil Group' (Holdsworth *et al.*, 1994). However, relationships between the three groups are partly tectonic and their regional lateral extent, and internal facies variations still remain surprisingly poorly known. The A830 road sections between Corpach and Arisaig constitute the type area for the Moine stratigraphy (see **Fassfern to Lochailort Road Cuttings** GCR site report, this chapter). The Morar Group consists predominantly of psammite, with subordinate pelite + semipelite formations. Glenfinnan Group rocks consist mainly of interlayered psammite, semipelite and pelite, but in parts major gneissose semipelite + pelite formations, locally thick psammite units, and small amphibolite bodies occur. The Loch Eil Group rocks are dominantly psammites. The stratigraphical successions and constituent formations are summarized in Figure 8.3.

The Morar Group–Glenfinnan Group boundary is normally marked by the Sgurr Beag Thrust with the Glenfinnan Group and Loch Eil Group rocks forming the overlying Sgurr Beag Nappe. However, on the Ross of Mull a stratigraphical transition, albeit considerably deformed, is recorded (Holdsworth *et al.*, 1987). Glendinning (1988) noted that the Upper Morar Psammite Formation contained more-semipelitic units and became thinner towards its eastwards limit around Loch Eilt, suggesting a possible facies change south-eastwards into Glenfinnan Group lithologies. Facies changes are well documented at the Glenfinnan Group–Loch Eil Group boundary, with transitional sequences noted by Roberts and Harris (1983), Strachan (1985), and Peacock *et al.* (1992). In the southern Moine area this boundary corresponds with the Quoich Line, a major monoform that separates the 'Steep Belt' to the north-west from the 'Flat Belt' to the south-east.

The Moine rocks represent a sequence of fluviatile and marine sands, silts and muds laid down in a wide shallow basin. Glendinning (1988) documented the sedimentology of the Upper Morar Psammite and concluded that the formation represented a mainly tidal shelf deposit with proximal and minor fluvial sands prograding northwards over more-distal sands, silts and muds. Cross-bedding foresets indicate that tidal currents were predominantly towards the NNE. Recent work by Bonsor and Prave (2008) has re-interpreted the sedimentological features as indicating an alluvial braidplain environment of deposition. Farther east, Strachan (1986) also suggested that the Loch Eil Group psammites were of shallow-marine origin. Soper *et al.* (1998) erected a model for Moine deposition in two E-facing half-graben basins. They suggested that the Morar Group formed as a predominantly rift succession in a more westerly basin, passing upwards and laterally eastwards into the Glenfinnan Group rocks that represented a thermal subsidence phase. The Loch Eil Group rocks represented a further phase of rifting with Lewianoid rocks effectively forming a basement high underlying the 'Steep Belt' to the west of the basin-bounding fault.

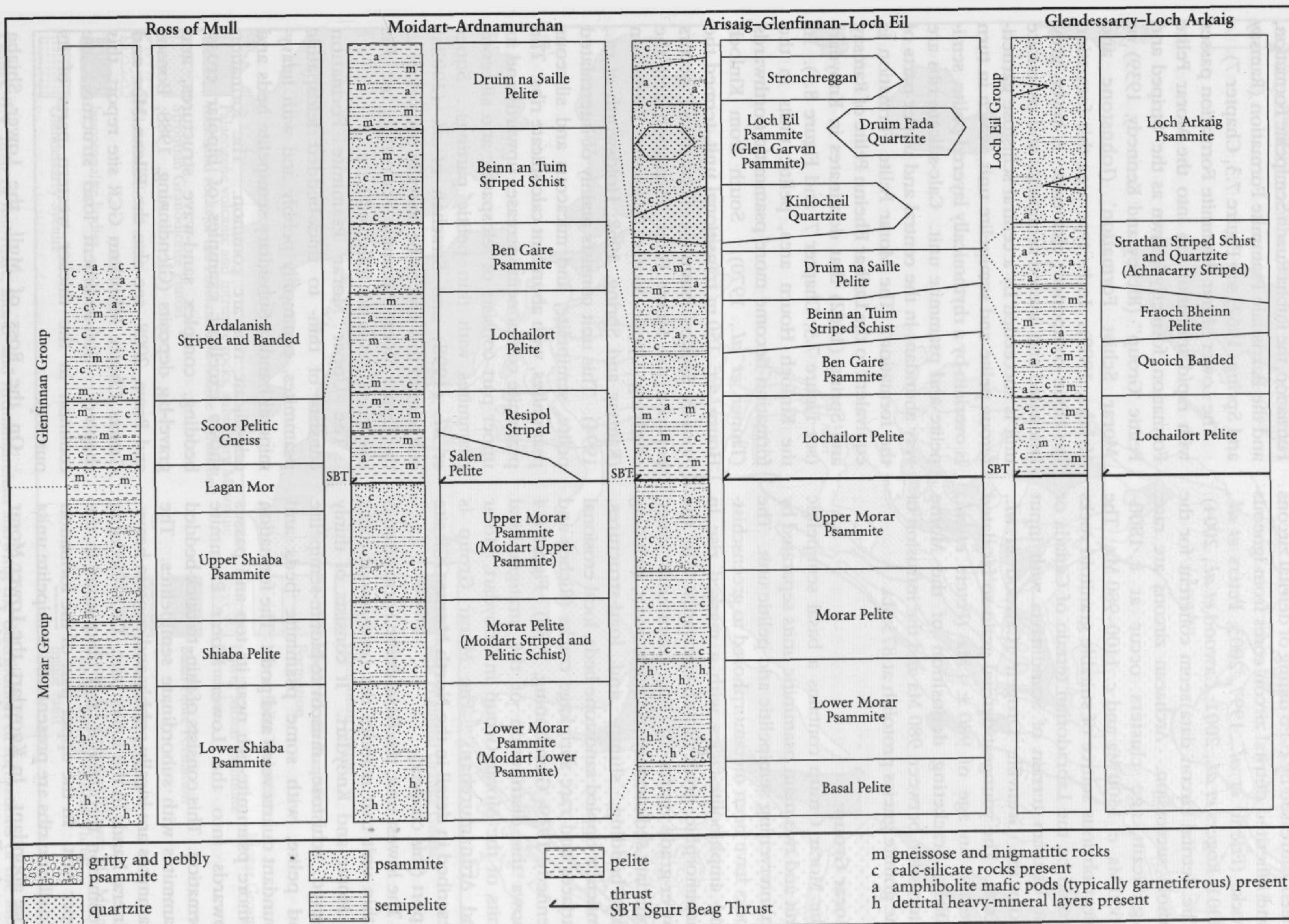


Figure 8.3 Tectonostratigraphy of the Moine succession within the Moine (South) area, showing the main formations.

The provenance of the Moine succession has been addressed by U-Pb dating of detrital zircons and inherited detrital zircon cores from igneous rocks (Friend *et al.*, 1997, 2003; Peters *et al.*, 2001; Rogers *et al.*, 2001; Cawood *et al.*, 2004). The detrital zircon data seem coherent for the whole succession. Archaean zircons are rare; significant age clusters occur at *c.* 1800–1600 Ma, *c.* 1500 Ma and *c.* 1100–980 Ma. The most obvious source of suitable granitoid rocks would be the Labradorian terrain of Canada or the Gothian terrain of Scandinavia with input from the Grenville Orogen (Cawood *et al.*, 2004). The youngest detrital grain so far dated yielded an age of 980 ± 4 Ma (Peters *et al.*, 2001), bracketing deposition of the Moine succession between 980 Ma and the intrusion of the granite gneiss protolith at 873 Ma.

Morar Group

The Morar Group contains a basal semipelitic unit and two main psammitic units separated by an intervening semipelitic and pelitic unit. The rocks have been metamorphosed to greenschist- and amphibolite-facies with a marked rise in metamorphic grade south-eastwards. In the lower-grade parts of the psammitic units, abundant sedimentary structures occur, including cross-bedding, slump- and load-structures, lenticular rippled sandstone beds, local erosional surfaces and rare shrinkage cracks (Richey and Kennedy, 1939; Glendinning, 1988). Figure 8.4 shows the distribution of the stratigraphical units of the Morar Group in Knoydart, Morar and Ardnamurchan. The Morar Group is described in detail in the **North Morar** GCR site report (this chapter).

The lowest unit, the Basal Pelite Formation, is a thin unit that mantles the Lewisianoid rocks in Morar and Knoydart. It consists of thinly layered, schistose, muscovite-biotite-semipelite and pelite, with some psammite beds and abundant quartz veins and pods. The formation is more psammite-rich near its top and passes upwards into the Lower Morar Psammite Formation. This consists of thin- to thick-bedded psammites with subordinate semipelites. The psammites are locally pebbly and contain heavy-mineral bands in the lower part. Cross-bedding is common throughout, and ubiquitous in the upper part. In the upper part of the formation calc-silicate ribs are present and semipelite units more abundant. In Knoydart, the Lower Morar Psammite Formation can be divided into three separate formations, the Arnisdale Psammite Formation, the Rubha Ruadh Semipelite Formation, and the Barrisdale Psammite Formation (Ramsay and Spring, 1962; see Figure 7.3, Chapter 7).

The Lower Morar Psammite Formation passes with rapid transition up into the Morar Pelite Formation, formerly known as the 'Striped and Pelitic 'Group'' (Richey and Kennedy, 1939) or 'Morar Schist Formation' (Johnstone and Mykura, 1989). In its type area this formation has three component elements. A lower, grey, laminated and layered semipelite and psammite unit is succeeded by a central schistose garnetiferous pelite and semipelite unit, which in turn is overlain by a rhythmically layered pelite, semipelite and psammite unit. Calc-silicate ribs are very abundant in the central and upper parts of the formation. The Morar Pelite Formation is equivalent to the Ladhar Bheinn Pelite of Ramsay and Spring (1962) that dominates in Knoydart (see Figure 7.3, Chapter 7, and Figure 8.3). In the Kinloch Hourn area, pelitic units in the formation become more psammitic northwards (Tanner *et al.*, 1970). South from Kinloch Hourn, a *c.* 150 m transitional unit, termed the 'Aonach Sgoilte Psammite Formation', occurs between the Morar Pelite Formation and the overlying Upper Morar Psammite Formation (Ramsay and Spring, 1962; Holdsworth *et al.*, 1994). This unit consists mainly of intercalated pelite, semipelite, and micacous and siliceous psammites, with abundant calc-silicate ribs. The psammite component increases upwards and its upper part consists of feldspathic and siliceous psammites with thin pelitic partings. Soper *et al.* (1998) and Strachan *et al.* (2002a) considered this unit to be laterally equivalent to the Upper Morar Psammite Formation, but this interpretation is not followed here.

The Upper Morar Psammite Formation consists of thin- to thick-bedded feldspathic psammites, commonly pebbly and with heavy-mineral bands. Subsidiary semipelite beds and calc-silicate ribs are common. The formation shows excellent examples of bipolar cross-bedding, complex sand-wave structures, and gravel-lag deposits (Glendinning, 1988; Bonsor and Prave, 2008; see also the **Eilean Mòr and Camas Choire Mhuilinn** GCR site report, this chapter). Soft-sediment load structures are common in the thicker western parts of its outcrop.

On the Ross of Mull, the Lower Shiaba Psammite, the Shiaba Pelite and the Upper

Figure 8.4 Map of Knoydart, Morar and Ardnamurchan showing the distribution of formations of the Morar Group.

Shiaba Psammite are correlated with the Lower Morar Psammite, the Morar Pelite and the Upper Morar Psammite formations respectively (Holdsworth *et al.*, 1987, 1994; Figure 8.3).

Glenfinnan Group

The stratigraphy of the Glenfinnan Group rocks is less well defined and documented than that of the Morar Group, but is generally characterized by laterally more-variable semipelitic and pelitic units that are susceptible to migmatization. Structural dislocations and large- and small-scale complex folding are generally present. Together with original facies changes these give rise to a complex package in which the original stratigraphical template is very difficult to restore. An attempt has been made to collate the various local stratigraphies and suggest correlations (Figure 8.3), but this inevitably differs from Holdsworth *et al.* (1994) and earlier attempts (e.g. Roberts *et al.*, 1987).

Near **Kinloch Hourn**, the Reidh Psammite Formation, a gneissose and locally migmatitic psammite unit containing small lenses of Lewisianoid gneiss, occurs immediately above the Sgurr Beag Thrust (Tanner, 1971; Roberts *et al.*, 1987). However, its outcrop extends only some 5–6 km to the south, the unit being cut out just north of Loch Quoich. The psammite passes eastwards with rapid transition into the Lochailort Pelite Formation (Sgurr Beag Pelite Formation farther north), a thick, gneissose, locally garnetiferous, layered semipelite and pelite unit, with subsidiary psammite layers (Brown *et al.*, 1970). Small amphibolite lenses and calc-silicate ribs are present. The Lochailort Pelite stretches from Kinloch Hourn southwards in the immediate hangingwall of the Sgurr Beag Thrust as far as Moidart, where it contains several distinct psammite units (Brown *et al.*, 1970). Between Loch Moidart and Loch Sunart two units appear to lie stratigraphically beneath the Lochailort Pelite Formation but still within the Sgurr Beag Nappe. These are the Salen Pelite Formation and the Resipol Striped Formation (formerly 'Assemblage') (Figure 8.3). The Salen Pelite Formation is mainly a gneissose pelite and semipelite, with an apparent stratigraphical transition up into the overlying striped gneissose psammites, semipelites and pelites of the Resipol Striped Formation (Roberts *et al.*, 1987). Individual pelite units, one *c.* 200 m thick, can be traced north from Resipol to central Moidart, where they appear to merge with the Lochailort Pelite outcrop. In Mull a psammite, gneissose pelite and quartzite unit, the Lagan Mor Formation, is interpreted to represent a sedimentary transition from Morar Group to Glenfinnan Group rocks. The overlying Scoor Pelitic Gneiss Formation, a gneissose garnetiferous pelite and semipelite with abundant calc-silicate lenses, is probably laterally equivalent to either the Salen Pelite Formation or the Lochailort Pelite Formation (Figure 8.3).

In Moidart the Lochailort Pelite is overlain by the Beinn Gaire Psammite Formation, a *c.* 650 m-thick psammite unit with garnetiferous semipelite and pelite interbeds and minor calc-silicate ribs and heavy-mineral bands (Brown *et al.*, 1970). The psammite unit thins northwards, and in eastern Morar and the Glenfinnan area the Lochailort Pelite Formation is directly overlain by the Beinn an Tuim Striped Schist Formation (Dalziel, 1966), which passes north-east along strike into the Quoich Banded Formation (Roberts and Harris, 1983). These units consist of thinly interlayered psammite, semipelite and pelite with some thicker gneissose pelite and siliceous psammite units also present. Locally, massive lenticular quartzite units are present. This is the archetypal Glenfinnan Group lithology and normally shows a wide range of fold structures. The equivalent unit on Mull, the Ardalanish Striped and Banded Formation, a sequence of interbedded semipelite, pelite and micaceous psammite with abundant calc-silicate lenses, and amphibolite pods in its upper part, forms the bulk of the Glenfinnan Group succession and is the youngest unit exposed. However, on the mainland the Druim na Saille Pelite Formation, a thick gneissose, partly migmatitic, garnetiferous pelite and semipelite unit with patches of oligoclase-rich gneisses overlies the Beinn an Tuim Striped Schist in Ardgour (Dalziel, 1966). Amphibolite lenses and calc-silicate ribs are common in both these units.

Farther north in the eastern part of the 'Steep Belt' around Glen Dessarry and Loch Quoich, are extensive outcrops of the Quoich Banded Formation (Roberts and Harris, 1983), which along strike in Glendessarry were termed the 'Strathan Striped Schists and Quartzite' (Roberts *et al.*, 1984). The overlying Quoich Pelite Formation, a thick gneissose garnetiferous pelite and semipelite unit with amphibolite pods, but lacking calc-silicate lenses, can also be traced south into Glen Dessarry, where it is termed the

'Fraoch Bheinn Pelite Formation' (Roberts *et al.*, 1984). Roberts *et al.* (1983) initially correlated these upper Glenfinnan Group formations with the Beinn an Tuim Striped Schist and Druim na Saille Pelite formations respectively. Subsequently, Roberts *et al.* (1987) correlated the Quoich Banded Formation with the Reidh Psammite and Resipol Striped formations, and the Quoich Pelite and Fraoch Bheinn Pelite formations with the Lochailort Pelite Formation (see also Holdsworth *et al.*, 1994). The early correlations (as shown on Figure 8.3) give a more-coherent regional pattern and are preferred here.

Between Loch Arkaig and Loch Lochy, adjacent to the Great Glen Fault, within an area dominated by Loch Eil Group rocks, an antiformal inlier exposes migmatitic interlayered psammites and semipelites with abundant calc-silicate layers and lenses. These are termed the 'Achnacarry Striped Formation' and are interpreted as Glenfinnan Group rocks (see **Eas Chia-Aig Waterfalls** GCR site report, this chapter). Lithologically and structurally they are equivalent to the Achnaconeran Striped Formation of the Moine Central area that occurs extensively farther north-east in Glen Moriston and Glen Urquhart.

Loch Eil Group

The Loch Eil Group is the youngest group of the Moine succession and is dominated by psammites. In many areas it is not divided into component formations, but where detailed work has been carried out, individual psammite and quartzite units have been delineated. The total thickness is estimated to be 4–5 km (Strachan, 1985; Soper *et al.*, 1998). It consists mainly of feldspathic and siliceous psammites, with subsidiary micaceous psammite and semipelite interbeds and abundant calc-silicate rock lenses. Sedimentary structures are common, notably cross-bedding, but small-scale grading, convolute bedding, and ripple-lamination are also present (Strachan, 1985). Although the Loch Eil Group rocks are typically rather monotonous (e.g. Dalziel, 1966), in parts lenticular quartzite and feldspathic quartzite units up to 1500 m thick can be recognized (Stoker, 1983; Strachan, 1985). In addition around Loch a' Chràthaich, north of Glen Moriston, May and Highton (1997) mapped out three discrete semipelite units up to 100 m thick in the psammite sequence. In Glen Moriston it is suggested that the Loch Eil Group psammites may pass laterally and transitionally into the underlying Achnaconeran Striped Formation at their eastern margin (May and Highton, 1997).

At the western end of Loch Eil, the Glenfinnan Group–Loch Eil Group boundary is transitional from pelite to psammite over only 2–3 m (Strachan, 1985). The state of strain is generally low here and cross-bedding has been recorded within 5 m of the contact. In many places members of the West Highland Granite Gneiss Suite occur along the Glenfinnan Group–Loch Eil Group boundary and hence obscure contact relationships (see for instance the **Quoich Spillway** GCR site report, this chapter). Nevertheless, transitional units have been recognized in several places. In the Quoich Dam area, transitional units are the Lower Garry Psammite Formation and the Garry Banded Formation (Roberts and Harris, 1983). The Lower Garry Psammite Formation contains excellent cross-beds, slump-folding and pebbly layers, admirably exposed in Coir' an t-Seasgaich (NH 077 035). The overlying Garry Banded Formation consists of some 200 m of psammite, quartzite, gneissose pelite and semipelite interlayered on the scale of 10 cm to 1 m. The Quoich Granite Gneiss separates the two formations and all the units contain concordant to locally discordant amphibolite sheets or dykes. The Loch Eil Group Upper Garry Psammite Formation, which consists of feldspathic and siliceous psammite with subordinate semipelite and pelite and calc-silicate lenticles, overlies the Garry Banded Formation. Sedimentary structures are present locally. When traced eastwards the Upper Garry Psammite and Lower Garry Psammite appear to converge to become a single unit.

Between Glen Dessarry, Loch Affric and Loch Loyne, the distinction between the Glenfinnan and Loch Eil groups is unclear. Around Loch Cluanie, Peacock *et al.* (1992) placed the Glenfinnan Group–Loch Eil Group boundary at the highest pelite unit or at the granite gneiss boundary. Thus, the psammite units of the Loch Loyne–Loch Cluanie areas were tentatively attributed to the Glenfinnan Group. However, to the south these psammites patently correlate with the Lower Garry Psammite of the Loch Eil Group and possibly also with the Garry Banded Formation. The 'Cluanie' psammites contain some pebbly layers, locally spectacular cross-bedding, magnetite-rich heavy-mineral bands and abundant calc-silicate lenticles. They are partly gneissose and are interlayered with subsidiary semipelite and pelite, which in places form discrete units (Roberts *et al.*, 1987; Peacock *et al.*, 1992). A similar problem occurs with the rocks that occupy the core of the F3 Glendessarry/Gleouraich Synform, which stretches some 40 km NNE from Glen Dessarry to Glen Affric. Surrounding the Glendessarry Syenite in the south are the psammites of the Loch Arkaig Psammite Formation, interpreted by Roberts *et al.* (1984) as the lower member of the Loch Eil Group. Farther north, between Loch Quoich and Glen Affric, the thick Easter Glen Quoich Psammite Formation occurs in the same synform. It consists of feldspathic and micaceous psammite with subsidiary semipelite and pelite units. Quartzite layers are common and calc-silicate lenses are found in parts. In Glen Affric, a prominent quartzite is developed at the base. Although correlations have been made with the Loch Eil Group, the lithologies of the Easter Glen Quoich Psammite are atypical and show more similarites with the Glenfinnan Group sequence. The structure is complex with possible early (D1?) shear-zone dislocations, D2 and D3 thrusting and folding; in concert with sedimentary facies changes these may be responsible for the occurrence of the Glenfinnan Group psammites within the synform.

Neoproterozoic intrusive rocks

Several suites of intrusive rocks are found in the Moine (South) area, notably members of the West Highland Granite Gneiss Suite and metadolerites and metagabbros. Their distribution is shown in Figure 8.1. These intrusive sheets and dykes were emplaced prior to the earliest deformation, and U-Pb zircon age dating has shown that both granitic and mafic bodies were intruded at *c.* 873 Ma (Friend *et al.*, 1997; Millar, 1999).

West Highland Granite Gneiss Suite

In the Moine (South) area thick sheets of deformed and locally migmatitic granitic gneiss, collectively known as the 'West Highland Granite Gneiss Suite', form disconnected but clearly related outcrops (Johnstone and Mykura, 1989). The sheets are concentrated along the Quoich Line around the Glenfinnan Group–Loch Eil Group boundary. Individual occurrences are termed the 'Ardgour (Sgurr Domhaill)', 'Sgùrr Mhurlagain', 'Quoich', 'Glen Doe' and 'Fort Augustus' granite gneisses. Its occurrence is described in the **Fassfern to Lochailort Road Cuttings**, **Quoich Spillway** and **Glen Doe** GCR site reports (this chapter). Sheets vary in thickness from < 1 m to over 1.4 km for the main Ardgour Granite Gneiss body. The granitic gneiss normally shows sharp contacts with the adjacent Moine rocks and locally contains metasedimentary xenoliths. The sheets are normally concordant with the bedding and main foliation, but its mapped outcrop shows that regionally it cuts across parts of the Moine stratigraphy (Figure 8.1). Granite gneiss sheets are commonly interleaved on a metre-scale with the Moine metasedimentary lithologies, particularly around the margins of the thicker sheets, for example west of Ceannacroc Lodge at NH 202 106. Examples of cross-cutting relationships occur in Glen Garry at NH 134 028 (Peacock *et al.*, 1992).

The granite gneiss is a monzogranite consisting essentially of quartz, plagioclase feldspar (oligoclase), potash feldspar (perthitic microcline) and biotite, with minor garnets (< 0.5 mm) and muscovite and accessory apatite, zircon, titanite and magnetite/ilmenite (May and Highton, 1997). Veins of leucogranite and quartz-feldspar pegmatite are present locally. There are abundant quartz, quartz-feldspar and granitic segregation veins with marginal biotite selvedges. These veins, together with aligned biotite and mafic aggregates, define an S1 gneissose foliation. This is folded by tight to isoclinal F2 folds, which also affect the larger sheets of granitic gneiss. The gneiss generally also contains a locally strong S2 foliation, which is typically composite with the earlier S1. The granite gneiss represents an early sheeted intrusion into the Moine succession that predated the main deformation and metamorphic episodes.

The geochemistry of the West Highland Granite Gneiss Suite classifies it as an S-type peraluminous granite, consistent with derivation by partial melting of semipelitic Moine rocks at deeper crustal levels (e.g. Gould, 1966; Barr *et al.*, 1985; May and Highton, 1997). U-Pb zircon SHRIMP and TIMS studies have determined an emplacement age of the Ardgour and Fort Augustus granite gneiss bodies at 873 ± 7 Ma (Friend *et al.*, 1997) and 870 ± 30 Ma (Rogers *et al.*, 2001) respectively. Rogers *et al.* (2001) also obtained a 470 ± 2 Ma titanite age from the Fort Augustus body, interpreted as reflecting a Grampian metamorphic overprint.

Metadolerites and metagabbros

As in the northern and central Moine areas, mafic dykes or sheets, intruded prior to deformation and metamorphism, are locally common and form swarms in parts of the Moine (South) area. They are now largely amphibolites but were originally mainly dolerite sheets. Rarely, the mafic bodies still show doleritic textures. Particular concentrations occur along the Quoich Line, and in the eastern outcrop of the Loch Eil Group outcrop (May and Highton, 1997). Amphibolite lenses are also scattered throughout the Glenfinnan Group outcrop. They are generally schistose and garnetiferous, typically with biotite-rich margins, particularly in the pelitic lithologies.

In thin section the amphibolites consist of green-brown to blue-green hornblende, plagioclase (oligoclase to andesine) and quartz, with subsidiary titanite, epidote, biotite, garnet and ilmenite. Garnets locally range up to several centimetres across and tend to overgrow the earlier fabrics in the amphibolites. In parts the amphibolites are retrogressed to biotite-rich mafic schist.

Metagabbros typically form pods and lenticular sheets from < 1 m to some 20 m thick. They are only abundant in Glen Doe in upper Glen Moriston, where they intrude the Glen Doe Granite Gneiss. The critical relationships between the granite gneiss and the several distinct intrusive phases of the metagabbro and metadolerite are described in detail in the **Glen Doe** GCR site report (this chapter). The geochemistry of the metagabbros and metadolerites shows that they are tholeiitic and overlap with Mid-Ocean Ridge Basalts (Peacock *et al.*, 1992; Millar, 1999). The metagabbros also show evidence of contamination by granite or metasedimentary rocks (Millar, 1999). Zircons from the metagabbro have been dated by U-Pb TIMS method at *c.* 873 Ma (Millar, 1999). Although it is possible that the zircons originated from the nearby granite gneiss, the date is interpreted as an emplacement date of the metagabbro, implying that the protoliths of granite gneiss and the metagabbro were intruded essentially contemporaneously. This is supported by field relationships at **Glen Doe** (see GCR site report, this chapter) and at **Quoich Spillway**, where a xenolith of Moine metasedimentary rock in the Quoich Granite Gneiss contains hornblende schist. If the 873 Ma age obtained from zircons from the metamorphic segregations in the granite gneiss at Glenfinnan also reflects the formation of the main foliation (Barr *et al.*, 1985; Friend *et al.*, 1997), then a metamorphic event must have occurred immediately following emplacement of the granite and mafic bodies.

Pegmatites

Pegmatite bodies are abundant within semipelitic and pelitic rocks of the Morar Group and Glenfinnan Group. They range from single pegmatitic granite veins (e.g. at Ardnish peninsula, Loch Ailort), to zones of pegmatite pods as at **Knoydart Mica Mine** (see GCR site report, this chapter), and areas of extensive pegmatite veining (e.g. Sgurr Breac, North Morar). Although pegmatite generation undoubtedly related to several different orogenic events, early isotopic dating by Giletti *et al.* (1961) and Long and Lambert (1963) showed that several of the pegmatites were of Precambrian age. Rb-Sr muscovite ages of 690–750 Ma from these pegmatites were interpreted as indicating the age of metamorphism in the Moine rocks. Isotopic dating using the Rb-Sr mica and U-Pb zircon and monazite systems has confirmed their Neoproterozoic age and suggested that the pegmatites are mostly related to a Knoydartian tectonometamorphic event (van Breemen *et al.*, 1974; Powell *et al.*, 1983; Rogers *et al.*, 1998). Rogers *et al.* (1998) obtained U-Pb TIMS monazite ages of 827 ± 2 Ma and 784 ± 1 Ma from the Ardnish and Sgurr Breac pegmatites respectively. These ages appear to link to Sm-Nd garnet ages of 820–790 Ma that Vance *et al.* (1998) obtained from the Morar Pelite Formation.

Notable Neoproterozoic pegmatite occurrences have been described at Knoydart, Sgurr Breac, Kinloch Hourn, Ardnish and Loch Eilt in the Moine (South) area, and except for Ardnish they are described in the relevant GCR site reports. Although these larger pegmatite bodies are granitic, the more-abundant smaller segregation veins are commonly leucotonalitic (formely termed 'trondhjemite'). Johnstone and Mykura (1989) assigned these pegmatitic leucotonalite bodies to the Loch Shiel Migmatite Complex and showed that they related to their parent lithology and reflected the metamorphic grade of the host rocks. Prominent large masses occur immediately east and south-east of the head of Loch Morar (NM 880 903); on Beinn Gharbh and Sgurr an Ursainn (NM 880 870); on Meall a' Choire Dhuibh (NM 923 984) at the head of Loch Quoich; and on Beinn Odhar Mor

(NM 851 791), south-west of Glenfinnan (Figure 8.1). Some of these segregation veins and related larger pegmatitic leucotonalite bodies may be of Neoproterozoic age, but most are probably of Ordovician age. They relate spatially to the zone of sillimanite-grade metamorphism that accompanied the Grampian Event in the Glenfinnan Group and upper Morar Group rocks of the 'Steep Belt'.

Caledonian intrusions

Caledonian intrusions range from major plutons to dyke swarms and from mafic to felsic; some were deformed during the Caledonian Orogeny, others are undeformed. The structures in the igneous bodies, their mutual relationships, and their emplacement ages, allow documentation of the different stages of the Caledonian Orogeny in the North-west Highlands. The distribution of the major plutons, granitic vein-complexes, and microdiorite and porphyritic microgranodiorite (the 'Main Felsic Porphyrites') dykes and sheets is shown on Figure 8.5. Johnstone and Mykura (1989) give good summaries of the different intrusive elements, and Strachan *et al.* (2002a) provide a more-recent review. Stephenson *et al.* (1999) described some of the major intrusions in the GCR Volume *Caledonian Igneous Rocks of Great Britain*, and Smith (1979) provided a summary of the minor intrusions of the Northern Highlands.

Major intrusions

The Glendessarry Syenite has been dated at 456 ± 5 Ma (U-Pb zircon, van Breemen *et al.*, 1979b). It consists of an outer mafic syenite and a younger, inner felsic syenite (Richardson, 1968; Fowler, 1992). The syenite has a strong, steeply SW-plunging lineation (L3). There are several large pelite and metalimestone xenoliths in the syenite and patches of pegmatitic granite. The pelitic xenoliths locally contain sillimanite and kyanite. Other xenoliths contain tight minor folds. The xenoliths cannot be matched with the surrounding psammite envelope, which was assigned by Roberts *et al.* (1984) to the Loch Arkaig Formation (Loch Eil Group). The intrusion is interpreted as an original sheet-like body now occupying the core of a curvilinear F3 synform (Roberts *et al.*, 1984; Johnstone and Mykura, 1989).

The Glen Scaddle Intrusion and petrologically related Glen Loy intrusions together with the Clunes Tonalite, lie adjacent to the Great Glen. The Glen Scaddle (6.5 km × 3 km) and adjacent Glen Muic intrusions in Ardgour consist of gabbros and subsidiary diorites with varying degrees of amphibolitization (Drever, 1940). The lithologies are locally appinitic and have transitional complex marginal phases. They are variably sheared with fine-grained amphibolite developed in the shear zones. Loch Eil Group gneissose feldspathic psammite and semipelite surround the intrusions with transitional igneous-sedimentary 'hybrid' rocks commonly present. The intrusions contain xenoliths of graphitic pelite, psammite, metalimestone and calc-silicate rock with some small pods of serpentinite (Johnstone and Mykura, 1989). Stoker (1983) noted that the intrusion lay in the core of the Glen Scaddle Synform and its internal foliation generally lay sub-parallel to local 'F2' fold axial planes. However, the accompanying coarse lineation lay consistently at a high angle to 'F2' fold axes and related 'L2' lineations in the adjacent Moine rocks. Stoker agreed with Drever (1940) that contact metamorphic diopside, sillimanite and cordierite in the country rocks overprint the regional metamorphic mineralogy, which he attributed to a 'D1' episode. Thus, Stoker (1983) interpreted the intrusions as pre-'D2' in age. However, the intrusions appear to have only undergone partial structural and metamorphic modification internally, and a U-Pb TIMS zircon age of 426 ± 3.2 Ma for the intrusion of the Glen Scaddle metagabbro obtained by Strachan and Evans (2008) suggests that the deformation and metamorphism were coeval with major movements along the Great Glen Fault and may relate to the Scandian Event. Hence, emplacement appears to post-date the main D2 deformation and metamorphic events seen elsewhere in the Moine outcrop. Strachan and Evans (2008) propose that the deformation in the intrusion relates to the main upright 'Steep Belt' folding, normally termed 'D3', and that this event is Scandian in age.

The Glen Loy Complex (5 km × 3.5 km) lies farther north in Lochaber and consists of hornblende gabbro, with appinitic and dioritic variants (Johnstone and Mykura, 1989). The gabbro body is unfoliated and shows igneous compositional layering. Rarely xenoliths of hornfelsed garnet-cordierite-staurolite-bearing pelite are present. The surrounding Loch Eil Group psammites are veined, hornfelsed, metasomatized and locally contain sillimanite.

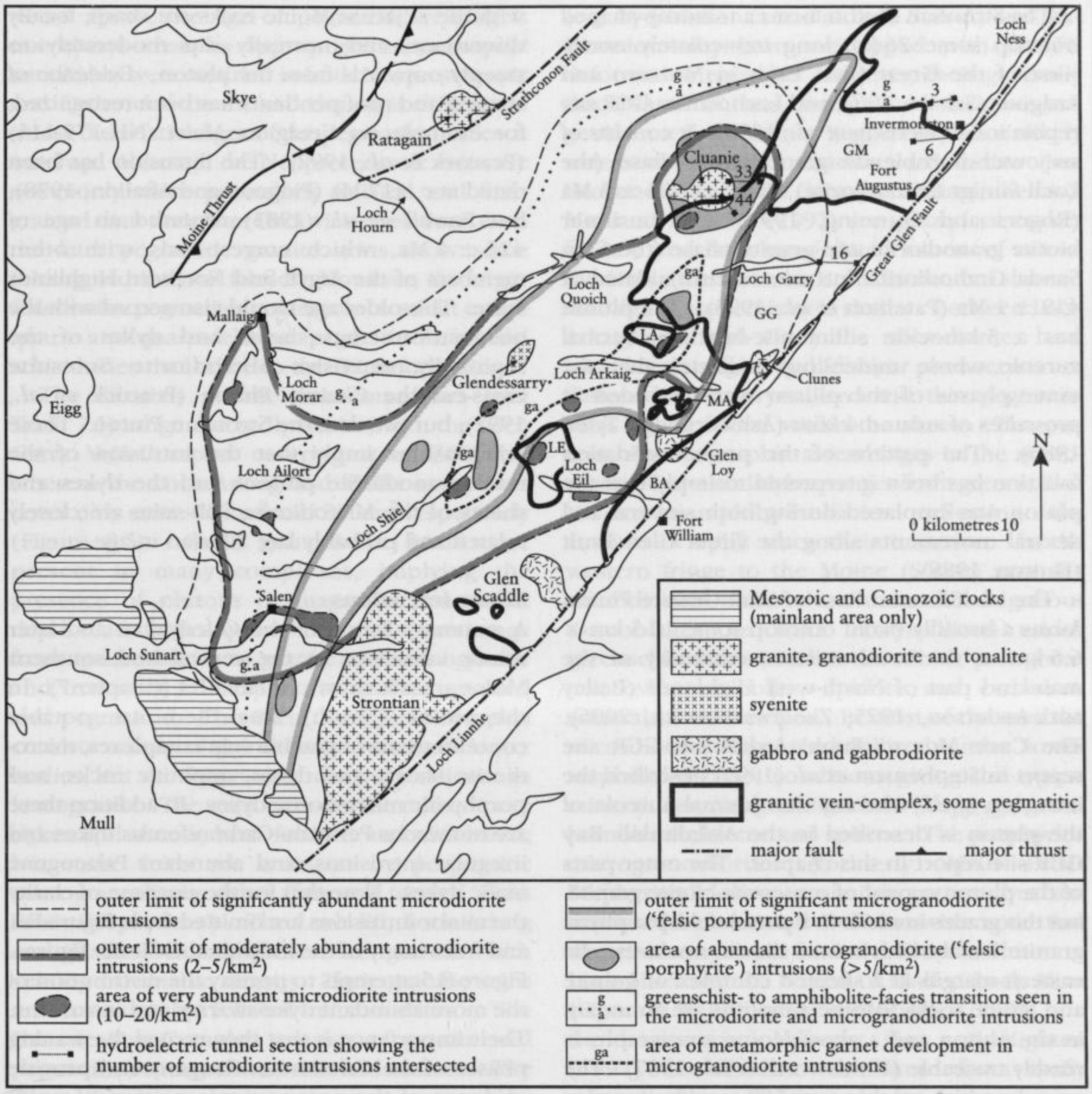


Figure 8.5 Map showing the Caledonian major and minor intrusions. Granitic vein-complexes: Ba – Banavie; GG – Glen Garry; GM – Glen Moriston; LA – Loch Arkaig; LE – Loch Eil; MA – Mallie.

Thick masses of pegmatitic granite cross-cut the southern part of the gabbro and the adjacent psammites. Dykes and sheets of the late Silurian Microdiorite Sub-suite and granitic veins of the Banavie Vein-Complex both transect the Glen Loy Complex. Regional dips in the adjacent Loch Eil Group psammites suggest that the complex lies in a synform. No age dating has yet been undertaken on this body.

The Clunes Tonalite forms a roughly triangular-shaped body (4 km × 2.3 km) above Loch Lochy, adjacent to the Great Glen Fault. The tonalite is generally homogeneous, but with variable biotite and hornblende content. Where biotite-rich, a steep SW-dipping planar foliation is dominant; where hornblende is present, plagioclase and hornblende form the prominent shallow NW- or SE-plunging lineation. Stewart *et al.* (2001) interpreted the internal fabrics to result from deformation during emplacement, linked to sinistral movements on the Great Glen Fault. They obtained a U-Pb zircon TIMS age of 427.8 ± 1.9 Ma, which they interpreted as dating emplacement of the intrusion.

The Strontian Pluton forms a teardrop-shaped outcrop some 26 km long immediately north-west of the Great Glen Fault in Morvern and Ardgour (Sabine, 1963, and Loch Sunart GCR site report in Stephenson *et al.*, 1999). It consists of an outer hornblende granodiorite phase (the Loch Sunart Granodiorite), dated at 425 ± 3 Ma (Rogers and Dunning, 1991) and an inner biotite granodiorite and granite phase (the Glen Sanda Granodiorite Intrusion-swarm), dated at 418 ± 1 Ma (Paterson *et al.*, 1993). The pluton has a 3 km-wide sillimanite-bearing thermal aureole whose mineralogy indicates that the outer phases of the pluton were intruded at pressures of around 4 kbar (Ashworth and Tyler, 1983). The pattern of the pre-consolidation foliation has been interpreted to imply that the pluton was emplaced during both sinistral and dextral movements along the Great Glen Fault (Hutton, 1988).

The undeformed Ross of Mull Granite Pluton forms a broadly ovoid outcrop some 10.5 km × 6.5 km at the south-western extremity of the mainland part of North-west Highlands (Bailey and Anderson, 1925; Zaniewski *et al.*, 2006). The Cnoc Mor to Rubh' Ardalanish GCR site report in Stephenson *et al.* (1999) described the intrusion itself, whereas the thermal aureole of the pluton is described in the **Ardalanish Bay** GCR site report in this chapter. The outer parts of the pluton consist of muscovite-biotite granite, but this grades inwards to a potash-feldspar-phyric granite locally with minor diorite enclaves. Its eastern margin is a sheeted complex of granite and Moine rocks. Moine xenoliths are abundant in the pluton and a ghost Moine stratigraphy is readily traceable (Holdsworth *et al.*, 1987). The aureole, which reaches over 500 m wide, contains all three aluminosilicates, but not all at the same locality. Halliday *et al.* (1979) obtained an Rb-Sr mineral–whole-rock age of 414 ± 3 Ma for the outer biotite granite, but this is thought to date uplift rather than emplacement.

The Cluanie Granodiorite Pluton is an undeformed, 'keyhole-shaped' pluton some 7 km long and 4 km wide, centred on the eastern part of Loch Cluanie (Figure 8.5). It consists essentially of hornblende granodiorite with varying amounts of megacrystic potash feldspar. Non-megacrystic granodiorite occurs marginal to the eastern and southern contacts. Along the eastern contact, aplitic granite, leucogranite and quartz-feldspar pegmatite veins are abundant (Leedal, 1952; Peacock *et al.*, 1992). The contacts with the adjacent Moine rocks are sharp, locally discordant, and normally dip moderately to steeply outwards from the pluton. Evidence of stoping and roof pendants has been recognized, for example on Creag na Mairt (NH 175 115) (Peacock *et al.*, 1992). The intrusion has been dated at *c.* 417 Ma (Pidgeon and Aftalion, 1978), but Powell *et al.* (1983) reported an age of 425 ± 4 Ma, which corresponds with other members of the Argyll and Northern Highlands Suite. This older age would also accord with the observations that sheets and dykes of the regionally extensive Microdiorite Sub-suite cross-cut the Cluanie Pluton (Peacock *et al.*, 1992), but pre-date the Strontian Pluton. These relationships imply that the intrusion of the main granodiorite plutons and the dykes and sheets of the Microdiorite Sub-suite are closely related and probably late Silurian in age.

Minor intrusions

A summary listing of the Caledonian and later minor intrusions in the central and southern Moine areas is shown in Table 7.1 (Chapter 7). In the Moine (South) area there are notable concentrations of granitic vein-complexes, micro-diorite sheets and dykes, appinitic rocks, and porphyritic microdiorite dykes. In addition there are numerous Permian–Carboniferous dykes and irregular intrusions, and abundant Palaeogene mafic dykes. Note that for the purpose of clarity the minor intrusions are omitted from Figure 8.1 and from many of the individual GCR site figures. Figure 8.5 attempts to portray the distribution of the more-abundant dyke-swarms and intrusions. Their importance is that they record the waning phases of the Caledonian Orogeny and provide evidence of the post-orogenic pattern of uplift (see Table 7.1, Chapter 7).

Within the gneissose to migmatitic semipelitic and pelitic units of the Moine succession, quartz and quartz-feldspar pegmatite veining is normally developed. The veins and pods are mainly leucotonalite (quartz-oligoclase feldspar-biotite), although locally they are granitic. In parts of the Glenfinnan Group, the veining forms lit-par-lit migmatites (see Johnstone and Mykura, 1989), and locally areas of pegmatitic leucotonalite veining are extensive (e.g. in Ile Choire at the head of Loch Morar). The occurrence of leuco-tonalite veining clearly reflects the middle amphibolite-facies metamorphic grade and semi-pelitic nature of the host Moine rocks and relates to the penetrative D2 and D3 deformations. As noted above, the age of pegmatitic veining is not always clear as appropriate metamorphic conditions were attained in both Neoproterozoic and Ordovician times, and thus it is difficult to assess the relative ages of the pegmatite bodies at outcrop. Although the Neoproterozoic veins are commonly more pervasively foliated and finer grained than their later Ordovician relatives, even the later pegmatitic granite veins show some folding and internal fabrics. However, the larger Caledonian pegmatites commonly cross-cut earlier quartz and quartz-feldspar pegmatite veins and schistosities that relate to the D2 deformation.

The Silurian granite vein-complexes (see Table 7.1) range markedly in size, with the Glen Garry Vein-Complex covering some 300 km^2, whereas the Loch Arkaig and Mallie complexes cover only some 40 km^2 and 20 km^2 respectively (Figure 8.5). Small granodiorite bodies are present in many complexes, implying the presence of plutons or magmatic sources at depth. Lithologically the veins and sheets range from quartz-diorite to granite and leucogranite and texturally from aplitic to medium-grained and pegmatitic. The Glen Garry Vein-Complex consists mainly of granodiorite veins and larger bodies, but shows a range from quartz-diorite to leucogranite. The veins cross-cut the microdiorite dykes and sheets, both foliated and unfoliated, but some veins are cross-cut by porphyritic microgranodiorite dykes (formerly termed 'Main Felsic Porphyrites'). The Loch Eil, Loch Arkaig and Mallie vein-complexes are granitic with veining of variable density. Their granitic veins are cross-cut by foliated microdiorites. The Banavie Vein-Complex consists of granite and pegmatitic leucogranite veins and masses. The pegmatitic leucogranite veins are cross-cut by microdiorite sheets and dykes and may well be an extension of the Loch Eil or Loch Arkaig complexes. In contrast the red granite veins are later as they cross-cut the microdiorites.

Intrusions of the Microdiorite Sub-suite are wide-ranging in the Cluanie and Glen Moriston area and farther south (Smith, 1979). They form generally SE-dipping sheets, and their igneous mineralogy consists of zoned andesine and hornblende (commonly forming phenocrysts) with biotite and subordinate interstitial quartz and potash feldspar. They cross-cut the Cluanie Pluton, but are commonly sheared and carry a strong marginal or at times penetrative schistosity or foliation. Talbot (1983) suggested that some earlier members of the sub-suite were folded (e.g. by Glenfinnan and at Loch Sunart) and that intrusion may have overlapped with the F3 deformation episode. However, their generally discordant contacts, fine-grained margins and geochemical coherence suggest that is unlikely unless the D3 deformation is Scandian (see 'Metamorphism and isotopic dating', below). May and Highton (1997) recognized an earlier foliated and later non-foliated swarm of microdiorites in the Invermoriston district, but showed that their geochemistry is similar. Between Loch Arkaig and Loch Garry the microdiorites have crenulated margins and feldspar phenocrysts are flattened and recrystallized and thin pegmatite veins tightly folded within the sheets. The pattern of metamorphic assemblages in the microdiorite sheets and dykes ranges from greenschist- to lower-amphibolite-facies reflecting the amount of uplift since their intrusion. In the western fringe to the Moine (South) area the microdiorites either show unmodified igneous assemblages, or have recrystallized under greenschist-facies conditions. Albite, pale-green muscovite, actinolite, epidote and carbonate minerals are developed. In most of the area the microdiorites have recrystallized under lower amphibolite-facies conditions giving the typical mineral assemblage: oligoclase (An_{20-30}), green hornblende, biotite and sphene. The porphyritic microgranodiorites (formerly 'Main 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 to Loch Shiel and the Sound of Mull at Loch Aline (Figure 8.5; Johnstone and Mykura, 1989). In the Invermoriston district May and Highton (1997) described a continuum from mafic microdiorites dominated by green-brown hornblende with rare relict clinopyroxene through to granodiorites dominated by andesine and oligoclase.

The Appinite Suite has petrological and geochemical affinities with the Microdiorite Sub-suite, but the main concentrations of appinitic diorite and related ultramafic bodies apparently relate to the Strontian and Cluanie plutons. Fowler and Henney (1996) interpreted the suite to represent a primary shoshonitic magma of mantle derivation, linked closely to the calc-alkaline plutons. In places appinites cluster near major faults or are associated with breccia pipes, for example in Glen Garry (May and Highton, 1997).

Dykes of the Lamprophyre Sub-Suite (formerly 'Minette Suite') trend predominantly east–west and consist mainly of minette with augite and biotite phenocrysts. The southern edge of the Ratagain Dioritic-syenitic Pluton extends south into Knoydart and prominent individual dykes are found on the Ardnish peninsula (Loch Ailort) and in Moidart. The lamprophyres cut the Strontian and Ross of Mull plutons and are an important marker in the structural sequence.

Quartz-dolerite dykes and small bosses of Permo–Carboniferous age occur locally in the southern Moine area. More abundant are similar-age camptonite and subsidiary monchiquite dykes that Rock (1983) separated into three major swarms (Morar, Eil–Arkaig, and Ardgour) and a minor swarm (Iona–Ross of Mull). Basalt and dolerite dykes of the North British Palaeogene Dyke Suite are also common. These dykes are typically up to 10 m wide and normally trend north-west; the majority belong to the Mull, Muck–Ardnamurchan, and Skye swarms.

Structure

Structural models for the southern Moine area divide the overall Moine succession into three major nappes, the Moine, Knoydart and Sgurr Beag nappes in structurally ascending order (Barr *et al.*, 1986). The Sgurr Beag Nappe can be divided into a western 'Steep Belt', where the structural pattern is dominated by upright F3 folding, and an eastern 'Flat Belt', where D3 deformation is generally much weaker and the overall bedding and foliation are normally gently dipping. The 'Steep Belt' corresponds roughly with the outcrop of Glenfinnan Group rocks and the 'Flat Belt' with the outcrop of Loch Eil Group rocks.

Although structural patterns have been mapped and structural chronologies recognized widely across the Moine outcrop, it is not a simple matter to translate the structural picture from one area to another. Powell (1974) correlated his stratigraphy and structure from the Morar–Loch Eilt area with that from the Kinloch Hourn (Tanner, 1971) and Moidart–Ardgour (Brown *et al.*, 1970) areas, showing that there was broad agreement on the nature of the main deformation phases D1, D2 and D3. However, even with the acquisition of considerable geochronological data over the past 30 years the age and tectonic significance of the different deformation phases still remain unclear. The main D2 phase has been variously ascribed to the Knoydartian (720–800 Ma), or Grampian (490–450 Ma) events. Similarly, the D3 phase has been attributed to either the Grampian Event or the Scandian (440–420 Ma) Event (see Strachan *et al.*, 2002a for recent summary).

D1 deformation

As in the Moine rocks farther north, this episode is manifest mainly as a bedding-parallel foliation. Tight to isoclinal, minor F1 folds have only been confirmed where they are refolded by F2, resulting in F1–F2 fold interference patterns. However, D1 is deemed partially responsible for interleaving of Lewisianoid basement and Moine cover rocks in the Morar region. Although thrust structures of D2 age can be identified readily in parts of the southern Moine area, D2 structures are locally seen to fold Lewisianoid–Moine contacts or pre-existing tight to isoclinal folds. In these circumstances the Lewisianoid rocks have been portrayed either as thrust sheets of basement or as isoclinal F1 fold cores. The best examples occur in the Morar Antiform and farther east around Ardnamurrach (see **North Morar** GCR site report, this chapter). Powell (1974) noted that if the Lewisianoid rocks at Ardnamurrach do lie in a fold core, this core is itself isoclinally folded and the whole structure refolded by D2 folds. This seems unlikely and a combination of D1 thrusting and localized F1 and F2 folding would explain the observed relationships somewhat better. Similarly, the presence of shear zones in the Morar Antiform would explain the primary basement–cover interleaving more simply. However, farther north by Attadale on Loch Hourn, Ramsay (1957b) described the extensive refolding of early F1 isoclines involving Lewisianoid basement and Moine cover (see **Rubha Camas na Cailinn** GCR site report, Chapter 7). O'Brien (1981) also described tight to isoclinal F1 folds and associated muscovite-rich platy zones from low-strain areas in psammitic units of the Morar Group in Ardnamurchan.

In other areas the D1 event does not seem to have resulted in major folding, but it probably marks a time of movement along some of the main shear-zones in the Moine succession, particularly in the Glenfinnan Group rocks. The accompanying metamorphic conditions are difficult to ascertain; in the Morar area they probably attained upper-greenschist or lower-amphibolite facies (see 'Metamorphism and isotopic dating', below).

D2 deformation and the Sgurr Beag Thrust

As in the Moine (North) and Moine (Central) areas, the D2 deformation phase resulted in the most pervasive structures in the Moine and Lewisianoid rocks. Minor and major folds, related mineral lineations, and a prominent foliation are all common. Peak-metamorphic minerals define the foliation and commonly the L2 lineation, which is generally parallel to F2 minor fold axes. Hence the D2 deformation and main metamorphic mineralogy appear to be closely related. Quartz, quartzofeldspathic and leucotonalite veins have been generated widely during the D2 deformation episode.

Generally, F2 folds are tight with a well-developed axial-planar foliation (S2), and range in amplitude and wavelength from a few millimetres to several kilometres. Although they are the most significant and abundant structures in the area, the overall outcrop pattern is normally strongly controlled by F3 folds. The S2 foliation is typically a penetrative cleavage or schistosity, in most F2 fold hinges it is manifest as a new discordant mica fabric. However, in some pelitic rocks S2 forms a crenulation cleavage affecting S1 and the bedding fabric. S2 mostly dips moderately to steeply east to south-east, except where refolded by F3 or later folding (Brown *et al.*, 1970; Powell, 1974). In Morar and in the 'Flat Belt', S2 dips are typically gentle and F2 fold-axis orientations are variable but mostly plunge gently to moderately northwards and southwards, dependent on later folding. F2 folds in the 'Steep Belt' are commonly reclined and their axial orientations are very variable. Around Kinloch Hourn, F2 axes consistently plunge to the south-east and SSE.

D1–D2 relationships are well seen at **Glen Doe** (see GCR site report, this chapter), where amphibolitic mafic sheets have intruded the Glen Doe Granite Gneiss. F2 recumbent folds, with a prominent axial-planar penetrative schistosity (S2), fold an earlier S1 foliation in the gneissose granite and S1 schistosity in the amphibolites (Millar, 1999).

The main thrusts, such as the Sgurr Beag Thrust and the Knoydart Thrust are attributed primarily to D2. The largest structural dislocation in the southern Moine area is the Sgurr Beag Thrust, originally recognized and mapped by Tanner (1971) in the Kinloch Hourn area and featured in the **Kinloch Hourn** and **Lochailort** GCR sites. The thrust consistently separates Morar Group rocks in the footwall from Glenfinnan Group rocks in the hangingwall, and over considerable distances its trace is parallel to stratigraphical boundaries. Locally, however, formations are truncated, such as the Reidh Psammite Formation in the hangingwall south of Kinloch Hourn. As noted above, near Loch Sunart the Salen Pelite and Resipol Striped formations in the footwall appear also to be truncated by a lateral ramp of the Sgurr Beag Thrust (Roberts *et al.*, 1987).

The Sgurr Beag Thrust is marked by a zone of increasing ductile strain, tens to hundreds of metres wide (Rathbone and Harris, 1979), and by Kinloch Hourn small lenses of Lewisianoid gneisses mark its position. Both major and minor F3 folds fold the trace of the Sgurr Beag Thrust, most notably the Glenshian Synform and Loch Eilt Antiform in the Loch Eilt–Loch Morar area. Although the Sgurr Beag Thrust is contiguous with minor D2 structures and is generally regarded as a dominantly D2 structure, Powell *et al.* (1981) showed that the regional metamorphic zonation was disrupted by late-stage (i.e. Caledonian) translation across the thrust and attributed this movement to the regional D3 episode. Baird (1982) documented the F3 fold pattern around Lochailort and showed that the thrust appeared to relate to D3 strain patterns and F3 fold geometry. However, he also noted that the thrust truncated the axial planes of significant F3 folds (e.g. the Ranochan Synform), and suggested that thrust movement outlasted the D3 event. Structural and metamorphic considerations suggest that thrust movement must have occurred along a relatively low-angle structure that dipped gently eastwards (Powell *et al.*, 1981; Barr *et al.*, 1986). The age of the Sgurr Beag Thrust and its relationship to peak metamorphism has long been a contentious issue. The thrust has been inferred to have been generated before (Tanner, 1971), coeval with (Powell *et al.*, 1981; Tanner and Evans, 2003), or after (Baird, 1982; Rathbone *et al.*, 1983) peak metamorphism. Its age has been variously interpreted to be Caledonian (Barr *et al.*, 1986) or Knoydartian (Piasecki and van Breemen, 1983; Tanner and Evans, 2003). It seems clear that the Sgurr Beag Thrust is the site of early ductile displacement of considerable magnitude followed by more-defined ductile thrusting that relates to the Caledonian deformation episodes.

The Knoydart Thrust emplaces higher metamorphic grade rocks over lower-grade rocks, but the Morar Group stratigraphy can be matched across the structure, implying that only a moderate amount of translation has occurred (Barr *et al.*, 1986). The trace of the Knoydart Thrust south of Loch nan Uamh is somewhat speculative, but further discrete thrusts are present in the underlying Moine Nappe in **North Morar** (see GCR site report, this chapter), and thrusts or dislocations also occur in the Morar Group succession farther south in Moidart and Ardnamurchan (O'Brien, 1981). In the Moine (Central) area, large Lewisianoid inliers commonly occur in the hangingwall of the main thrusts. However, except along the Sgurr Beag Thrust by Kinloch Hourn and in the Morar Antiform, Lewisianoid inliers are absent from the Moine (South) area.

D3 deformation

F3 structures vary from centimetre- to kilometre-scale, open to tight folds that control much of the overall outcrop pattern of the Moine succession. Locally, a penetrative or crenulation cleavage (S3) is developed, best seen in fold hinge zones, dependent on the degree of D3 strain and the lithology. D3 structures formed under lower- to upper-amphibolite-facies conditions, commonly accompanied by formation of quartz-feldspar pegmatite segregations, locally emplaced preferentially along F3 fold axial planes. In places, F3 folds are associated with shear zones, but in most areas the F3 structures fold the major D2 shear-zones, at least locally. Brown *et al.* (1970) showed a western front of F3 major folding stretching north from the western end of Loch Moidart to Loch Ailort. Examples of D2 structures folded by F3 folds are abundant throughout the area. Good examples of D2–D3 fold interference patterns are described and illustrated in the **Kinloch Hourn**, **North Morar**, and **Fassfern to Lochailort Road Cuttings** GCR site reports (this chapter). F3 fold axes are locally curvilinear on a small- to medium-scale, reflecting D3 strain variations and the complex F2 and earlier geometry.

The large-scale periclinal Morar Antiform dominates the structural pattern in the Morar area (see **North Morar** GCR site report, this chapter). The antiform folds the lower part of the Morar Group succession and the inthrust and folded lenticular Lewisianoid gneiss inliers. Regionally, the antiform appears to be a simple structure but in reality it has a complex profile. Normally it has been interpreted as a major F3 fold (Poole and Spring, 1974), but Powell (1974) attributed its formation to D2 on the basis of its associated minor structures and the overall structural geometry, whereas Tanner (1971) attributed related folds to F4 (although confusingly, he termed them 'F3'). Kennedy (1955) documented the main lineation pattern (L2), which apparently pre-dates the antiform. Although most authors have interpreted the overall periclinal Morar Antiform as an F3 structure, the presence of thrust and folded Lewisianoid rocks suggests that it may also represent an earlier structural culmination. Corresponding synforms (Ladhar Bheinn/Ben Sgriol Synform) and antiforms occur to the east, and offset antiformal structures lie to the north (Loch Hourn Antiform) and to the south.

D4 and later phases

Within the Moine succession are identifiable phases of late-stage open to close folds, commonly termed 'F4'. The folding and related cleavages and lineations are variably developed and confined to specific areas. In some semi-pelitic and pelitic units, S4 crenulation cleavages are developed. Biotite has recrystallized in the S4 cleavages, suggesting that metamorphic conditions were at least at greenschist facies. Powell (1974) recognized a phase of open folding with related subvertical crenulation cleavage development in Knoydart, Morar and Lochailort, here tentatively re-assigned to D4. Note that Powell (1974) correlated his F4 folds with the similarly orientated NNW-trending F3 folds of Tanner (1971) around Kinloch Hourn. In Ardnamurchan, conjugate sets of F4 folds occur (Powell, 1974; O'Brien, 1985).

Brown *et al.* (1970) described F4 open folding and localized S4 crenulation cleavage development in the 'Steep Belt' near Loch Shiel, but F4 folds are difficult to distinguish here as they are effectively coplanar with the F3 and earlier structures. In contrast, Strachan (1985) recognized open to close F4 folds with subvertical N-trending axial planes in Loch Eil Group rocks around Loch Eil itself. Here the F4 folds refold earlier F3 folds and control the outcrop pattern in the Loch Eil Group rocks of the 'Flat Belt'.

NW-trending open F4 folds and related crenulation cleavages in pelitic lithologies occur close to the Cluanie Pluton and possibly relate to its intrusion (Peacock *et al.*, 1992). Steeply dipping ENE- and E-trending open F4 folds, locally associated with a prominent S4 crenulation cleavage, also refold D3 and earlier structures in Glen Affric.

Strachan (1985) also recognized a later set of NW-trending open F5 folds that warp and refold earlier structures near Kinlocheil. The fold axes plunge gently east or south-east and have sub-vertical axial planes that trend north-west. Only minor local late-stage monoclines, box folds and kink bands are recorded in the platy psammitic Moine rocks of the Ross of Mull (Holdsworth *et al.*, 1987). No obvious mineral growth is associated with these structures.

Metamorphism and isotopic dating

In their summaries of the metamorphic facies in the Moine succession, Winchester (1974) and Fettes *et al.* (1985) showed that the metamorphic pattern in the Moine outcrop is complex, both in time and space. The metamorphic grade has been determined either by Barrovian index minerals in the relatively sparsely distributed pelitic lithologies (e.g. garnet, kyanite, sillimanite) or by the mineralogy of calc-silicate lithologies (Kennedy, 1949; Tanner and Evans, 2003). Although several distinct phases of metamorphism are superimposed (Lambert *et al.*, 1969; Powell *et al.*, 1981), in general the metamorphic grade increases from greenschist facies in the west to middle- and locally upper-amphibolite facies in the central and eastern parts of the Moine (South) area (Figure 8.6). The lowest-grade, greenschist-facies metamorphic rocks occur in the south-western part of Ardnamurchan. Most of Morar, western Knoydart, and western Ardnamurchan lie in the epidote-amphibolite facies (garnet, biotite grade). Farther east are lower- and middle-amphibolite-facies rocks (kyanite grade), with distinct jumps in metamorphic grade apparently corresponding to the Knoydart and Sgurr Beag thrusts (Powell *et al.*, 1981; Barr *et al.*, 1986). The highest grades are reached in the Glenfinnan–Ardgour area where middle amphibolite-facies assemblages (sillimanite grade) and gneissose pelites are present. The metamorphic grade falls off again eastwards over much of the 'Flat Belt', but this appears to be a result of late-stage retrogression superimposed on earlier higher-grade assemblages.

Isotopic age dating of metamorphic minerals and detailed microprobe studies has only recently revealed a clearer picture of the metamorphic history. Vance *et al.* (1998) obtained Sm-Nd ages from zoned garnets in schistose pelites in the Morar–Lochailort area. The garnet cores gave ages of 814–823 Ma and the middle zone of a large garnet from Polnish gave an age of 788 ± 4 Ma. Unfortunately, they were unable to date the narrow outermost garnet zone. Vance *et al.* (1998) used geobarometry to conclude that garnet growth commenced between D1 and D2 under pressures of 5 kbar and temperatures of 540° C, with pressures eventually rising to over 11 kbar and temperatures to over 700° C.

In large garnets from the 'big garnet' rock from the Glenfinnan Group in Glen Doe, Zeh and Millar (2001) recognized four distinct compositional phases, each containing varied mineral inclusions. Detailed studies of the garnet and included mineral compositions revealed a complex P–T history. The data suggested that the P and T conditions for the four phases were 4–6 kbar, 550°–560° C; 6–8.5 kbar, 560°–575° C; 5–8 kbar, 640° C; and 5 kbar at 670° C. The oldest, relatively low-pressure phase is compatible with crustal extension or contact metamorphism and may relate to the *c.* 870 Ma intrusion of the West Highland Granite Gneiss Suite. The higher-pressure phase 2 implies crustal stacking and rotational strain and probably relates to the D2 deformation phase. Phase 3, again compressional, followed a cooling and uplift event and the last stage showed final heating. The Caledonian late-stage retrogression is recorded only as crack infillings in the garnet. Epidote, chlorite, calcite, plagioclase and magnetite are recorded as inclusion phases in the garnet.

Tanner and Evans (2003) dated metamorphic titanites from calc-silicate layers in the Morar Pelite Formation near Loch Eilt at 737 ± 5 Ma and 751 ± 14 Ma (U-Pb TIMS). They argued that the titanite was part of the peak metamorphic assemblage in the Morar Group rocks immediately beneath the Sgurr Beag Thrust. The bytownite/anorthite + hornblende assemblages in these rocks formed under middle amphibolite-facies conditions (moderate P, T of *c.* 660° C). Together with ages of pegmatites from Loch Eilt (van Breemen *et al.*, 1978), Sgurr Breac and Knoydart (Rogers *et al.*, 1998), these ages imply that the main metamorphic episode in the Moine rocks of Morar occurred around 750 Ma. Later Grampian and possible Scandian

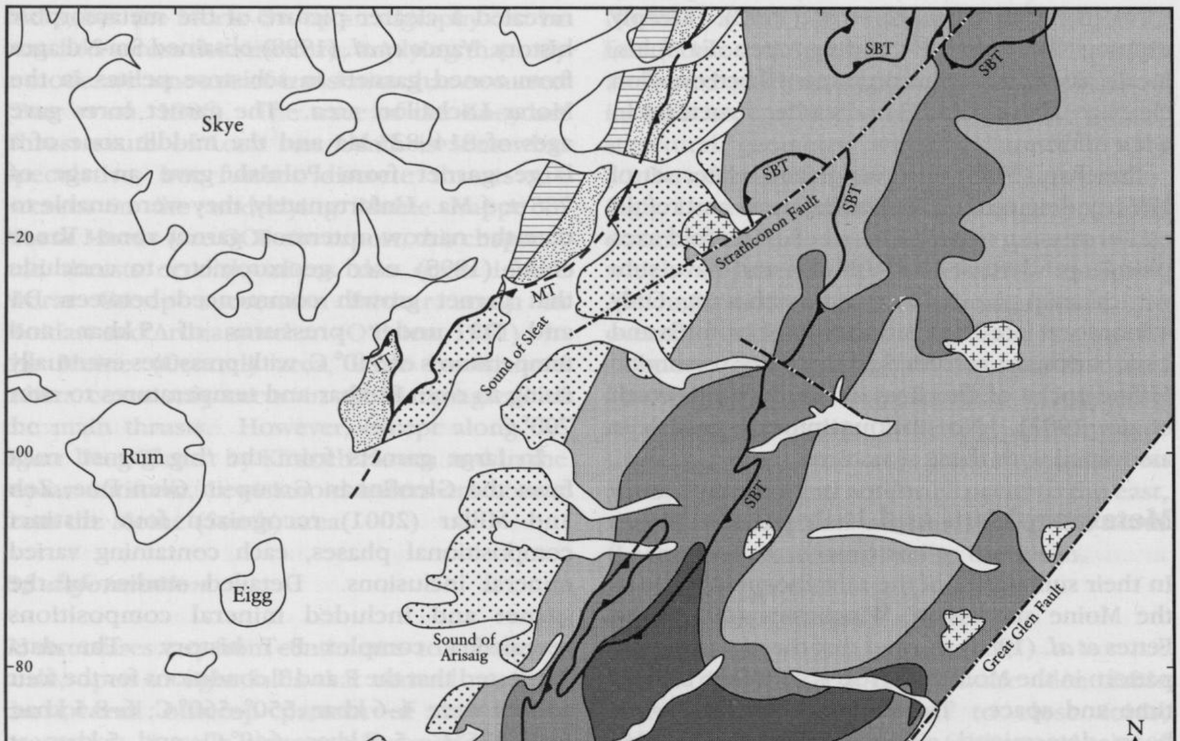


Figure 8.6 Map of the metamorphic zones of the Moine (South) and Moine (Central) areas. After Fettes *et al.* (1985).

metamorphic events are superimposed on this earlier pattern. The garnet studies of Zeh and Millar (2001) and a zircon U-Pb TIMS age date of 727 ± 6 Ma from migmatitic rocks in Glen Urquhart (Emery *et al.*, 2004) suggest that this event also affected Glenfinnan Group and Loch Eil Group rocks.

Grampian metamorphic events are signified by a U-Pb titanite age of 470 ± 2 Ma from the Fort Augustus Granite Gneiss at Torr a' Choiltreich (Rogers *et al.*, 2001) and a U-Pb monazite age of 455 ± 3 Ma from the corresponding Ardgour Granite Gneiss at Glenfinnan (Aftalion and van Breemen, 1980). The *c.* 456 Ma Glendessarry

Syenite (van Breemen *et al.*, 1979b) was intruded just prior to D3 deformation. Rb-Sr mica and U-Pb zircon ages from pegmatites around Loch Eilt also give Ordovician ages ranging from 445–470 Ma (van Breemen *et al.*, 1974).

Strachan *et al.* (2002a) has argued that by analogy with the Northern Highlands, where penetrative Scandian deformation strongly affects rocks west of the Naver Thurst Zone, the D3 deformation in the 'Steep Belt' is also Scandian in age (440–425 Ma). This would also agree with Barr *et al.* (1986) who envisaged the internal deformation of the Moine succession and the main thrusting along the Moine Thrust Belt as coeval. However, the current geochronological data in the Moine (South) area favour a Grampian age for the D3 deformation with possibly a localized Scandian deformational and metamorphic overprint. This problem is discussed more fully in the 'Introduction' to Chapter 7 and in the **Meall an t-Sithe and Creag Rainich** GCR site report (Chapter 7).

The Silurian-age microdiorite sheets provide information about the last phase of metamorphism. Igneous mineralogies and greeschist-facies mineralogies (albite-green mica-actinolite-epidote + carbonate) are present in western Morar, but east of a line from Salen to Kinloch Hourn, lower amphibolite-facies mineralogies (oligoclase-green hornblende-biotite-titanite) are preserved in the deformed microdiorite sheets. Hornblende + biotite fabrics accompanied normally by a down-dip lineation are present in these deformed sheets, and locally, a crenulation cleavage is developed (Smith, 1979). Talbot (1983) described their locally folded nature in parts of the 'Steep Belt', and concluded that the earliest members were emplaced prior to the conclusion of D3 deformation. However, most microdiorite sheets undoubtedly cross-cut the F3 folds and record only the waning phases of the Scandian deformation and metamorphism.

GLEN DOE (NH 209 128–NH 220 125)

I.L. Millar

Introduction

The Glen Doe river section shows the relationships between the Glen Doe Granite Gneiss and the metagabbro and metadolerite intrusions, all of which were emplaced at an early stage in the tectonometamorphic history of the Moine succession. Regionally discordant granite sheets, now represented by granite gneiss, were emplaced into psammitic and pelitic metasediments that lie around the Glenfinnan Group–Loch Eil Group boundary, during Neoproterozoic deformation and amphibolite-facies metamorphism. The granite gneiss in Glen Doe forms part of the most northerly large body of the West Highland Granite Gneiss Suite. Unlike some of the more southerly granite gneiss bodies (see **Quoich Spillway** and **Fassfern to Lochailort Road Cuttings** GCR site reports, this chapter), the Glen Doe body lies to the east of the Loch Quoich Line, and has escaped strong Caledonian reworking. Rock *et al.* (1985) demonstrated the tholeiitic nature of the Glen Doe mafic rocks, and Peacock *et al.* (1992) noted that they formed part of a widespread mafic suite. Millar (1990, 1999) showed that the earlier-formed metagabbros and later metadolerites were geochemically related, but were texturally, mineralogically and geochemically distinct. The metadolerites are comparable with intrusions found widely elsewhere in the Moine succession (see **Comrie** GCR site report, Chapter 6). The rocks in Glen Doe are generally highly deformed by pre-Caledonian structures, but primary igneous intrusive relationships and textures are locally preserved in the mafic bodies.

Peacock (1977) first described the Glen Doe section and interpreted the metagabbro-metadolerite-granite gneiss relationships to infer that two separate generations of mafic rocks were present and that the granite gneiss predated their emplacement (see also Peacock *et al.*, 1992). This work suggested that the granite and early amphibolitic mafic rocks were foliated and metamorphosed during a D1 event, prior to metagabbro intrusion. Soper and Harris (1997) and Millar (1999) rejected this interpretation and attributed the observed relationships to the variable deformation of the different components dependent on their competency and the prevailing metamorphic conditions. They argued for emplacement of the granite gneiss followed closely by intrusion of the metadolerites and metagabbros.

Early geochonological work suggested that the Moine succession had been affected by Grenville orogenesis at around 1000 Ma (e.g.

Brook *et al.*, 1976; Brewer *et al.*, 1979; Aftalion and van Breemen, 1980), and Millar (1990) interpreted the Glen Doe metabasic rocks as having been emplaced during this event. However, more-recent U-Pb zircon dating has shown that emplacement of the granite gneiss took place at 873 ± 7 Ma (Friend *et al.*, 1997), and zircons from the metagabbros in Glen Doe similarly date their intrusion at 873 ± 6 Ma (Millar, 1999).

Description

The River Doe section exposes the granite gneiss and mafic rocks at a number of readily accessible localities between NN 209 128 and NH 225 120 (Figure 8.7). Two distinct types of mafic rocks intrude the granite gneiss here; older coarse-grained metagabbros and later finer-grained metadolerites. Throughout much of the section, both types can be represented by tight to isoclinally folded, pervasively recrystallized hornblende schists (e.g. Locality 'A', Figure 8.7). However, at some low-strain localities, original intrusive relationships are well preserved in relatively undeformed mafic intrusions.

The best examples of the mafic rocks occur at NH 2184 1259, where five intrusive phases can be observed in a weakly deformed body exposed in the river bed for some 80 m (Locality 'B', Figure 8.7). The bulk of the intrusion is a coarse-grained, hornblende-plagioclase metagabbro (Metagabbro 1) with a relict sub-ophitic texture and locally rhythmic layering on a 5 cm scale. In its central part, the metagabbro contains metre-scale xenoliths of partially melted, unfoliated granite, containing coarse, partly resorbed quartz and feldspar phenocrysts. The xenoliths have similar chemical and isotopic characteristics to the local granite gneiss country rocks. Their lack of foliation implies that they were incorporated into the gabbroic melt before the onset of deformation. The metagabbro shows considerable contamination for several metres around the xenoliths with decreased modal amphibole at the expense of plagioclase and biotite, and local development of garnet. Within the zone of granitic xenoliths, SiO_2 shows an increase from 48% to > 55%, Rb and Ba show elevated values, whereas Sr, Y and Zr are depleted (Peacock *et al.*, 1992; Millar, 1999). A later phase of metagabbro (Metagabbro 2) shows chilled margins against the main body and encloses a xenolith of undeformed, rhythmically layered metagabbro with a well-preserved sub-ophitic texture.

Upstream between Metagabbro 2 and the metabasic–granitic gneiss contact is a zone of complex mixing, where gabbroic rocks pass into irregular masses of quartz-plagioclase-biotite-garnet-hornblende schist. As the contact is approached granitic veinlets derived from local melting of the country rocks are common, and a strong foliation is developed parallel to that in the adjacent granite gneiss. Xenoliths within the mixed zone also carry this fabric, but show no evidence of earlier fabrics. The downstream contact of the metabasic body is faulted but poorly exposed.

A 10 m-thick composite metadolerite dyke, (metadolerites 1 and 2) cuts the metagabbro lithologies described above. The dyke shows chilled fine-grained contact zones against the metagabbro, and dips at 60° towards the south-east, near-perpendicular to the layering in the gabbro. Where an offshoot of the dyke approaches the upstream contact of the mafic body, it also develops a strong foliation, parallel to that in the surrounding metagabbroic rocks (Locality 'B', Figure 8.7).

Just upstream from the main metagabbro body, a large boulder and associated outcrops show an undeformed mafic intrusion with finer-grained margins cross-cutting the granite gneiss foliation. Peacock (1977) interpreted the mafic rock to be a metagabbro, thus requiring an additional phase of deformation in the granite gneiss, prior to emplacement of the metagabbro suite. However, thin sections from the 'later metagabbro' show it is a biotite-hornblende microdiorite, a member of the late Caledonian Microdiorite Sub-suite (Millar, 1990).

A number of deformed mafic bodies are exposed in the river section 20–50 m west of the main mafic body described above. These bodies fall into two distinct groups; the majority are fine-grained, garnet-free hornblende schists, chemically and isotopically similar to the undeformed metadolerites (Millar, 1990); less abundant are coarsely foliated, garnetiferous hornblende schists, commonly with a distinctive augen texture, that represent the metagabbros. A typical deformed metagabbro is exposed at NH 2182 1261. Peacock (1977) termed these bodies 'rodded hornblende schists' and interpreted them as an early phase of metabasite intrusion, pre-dating emplacement of the undeformed metagabbros and metadolerites.

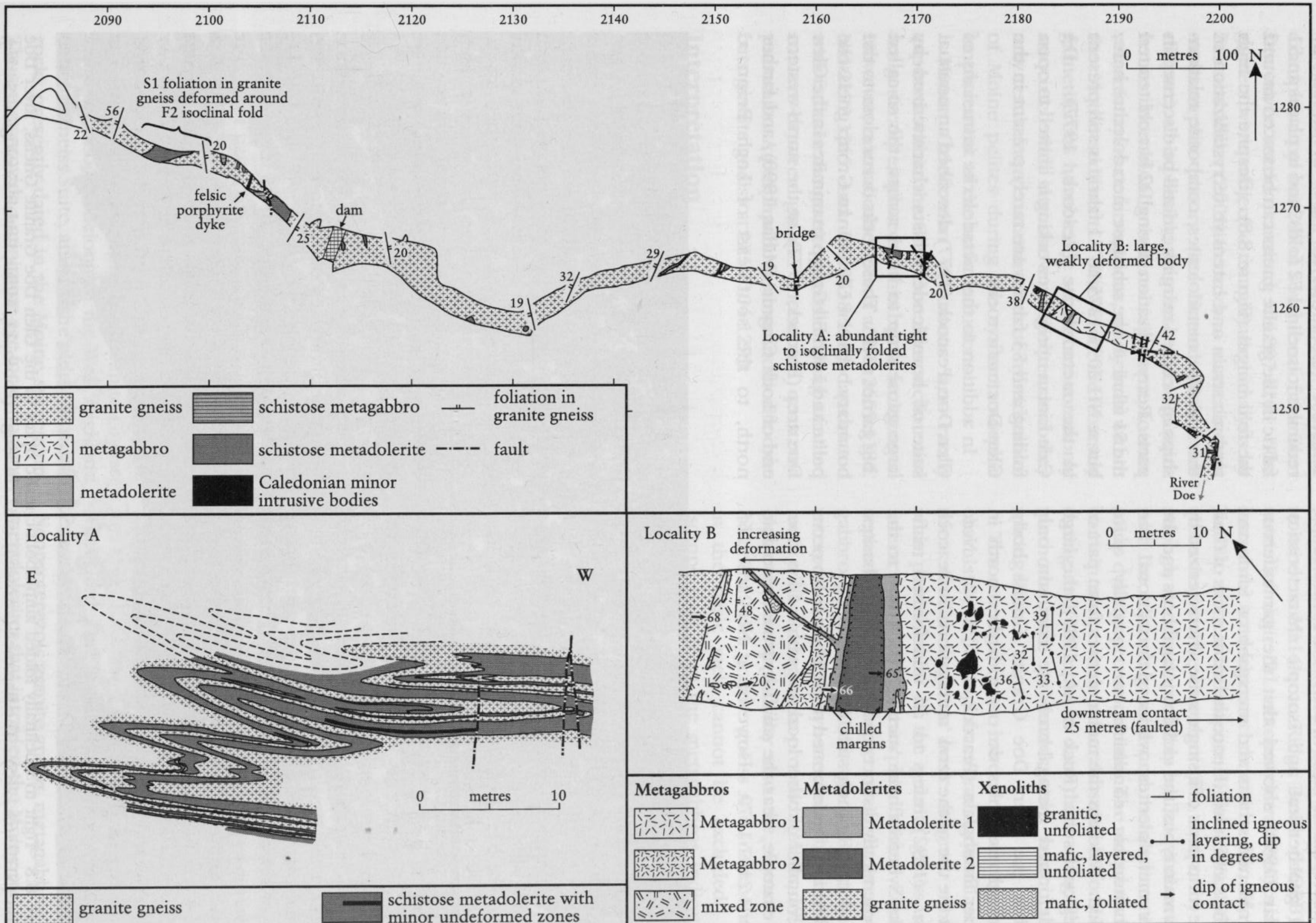


Figure 8.7 Map of the Glen Doe GCR site. (1) Inset Locality A – detail of tight to isoclinally folded amphibolitic mafic dykes. (2) Inset Locality B – detailed map, showing field relationships between different generations of metagabbro, metadolerite and granite gneiss.

However, on the basis of their field relationships, and geochemical and isotopic characteristics, Millar (1990) showed that the garnetiferous hornblende schists and metagabbros form part of the same suite. Hence the mafic rocks of Glen Doe form parts of a single suite, characterized by two main types, the earlier metagabbros and the later metadolerites, whose deformational and metamorphic condition are spatially quite varied. Whereas the metadolerites form part of a regional suite (Rock *et al.*, 1985), the large undeformed metagabbros are common only within the Glen Doe Granite Gneiss body, although examples do occur farther north in upper Strathglass (Peacock *et al.*, 1992). Note that the use of the term 'metagabbro' in Peacock *et al.* (1992) refers to all undeformed mafic rocks, whereas here 'metagabbro' refers to the geochemically distinct coarse-grained metabasites, irrespective of their state of deformation.

Relatively undeformed mafic bodies also occur at a number of other localities within Glen Doe, for example, near the small hydro-electric dam at NH 2107 1270. However, at NH 2169 1265 schistose metadolerites are deformed by recumbent isoclinal F2 folds, and in places an S1 fabric in the granite gneiss can be traced around the fold hinges (Figure 8.8). Despite the high tectonic strain and extensive recrystallization of the schistose metadolerites, composite relationships and chilled margins can still be discerned in parts. Recrystallization during D2 has obliterated the S1 fabric in the schistose metadolerites here, but at NH 2095 1275 an S1 fabric is still present in the metadolerite (Peacock, 1977). D3 Caledonian upright reworking is limited to open folding and S3 fabrics are rarely present in the Glen Doe mafic rocks.

In addition to the metadolerite intrusions of Glen Doe, Peacock (1977) described an unusual suite of hornblende schists characterized by large garnets up to 4 cm across, the so-called 'big garnet rock'. These rocks occur close to the boundary between Glenfinnan Group gneissose pelite and Loch Eil Group psammites in the Glen Doe area (Peacock, 1977), at the north-western end of Loch Cluanie (Millar, 1990), and farther north, to the south-east of Loch Beinn a'

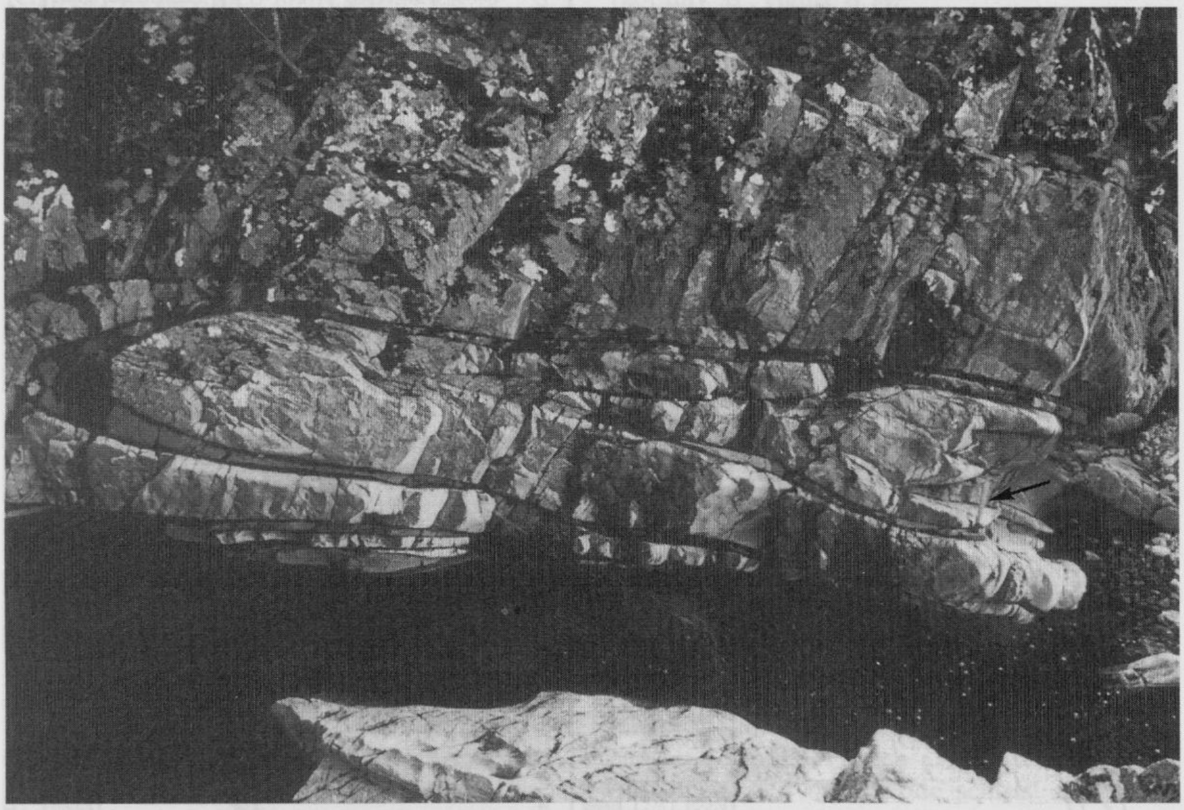


Figure 8.8 Tight to isoclinally folded amphibolitic mafic dykes in the Glen Doe Granite Gneiss, River Doe section (NH 2169 1265). The hammer (arrowed) is 32 cm long. (Photo: I.L. Millar, British Geological Survey, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Mheadhoin (Peacock *et al.*, 1992). Typical examples crop out 200 m south-east of the Glen Doe river section, around NH 207 126. The garnets were subjected to a detailed analysis by Zeh and Millar (2001) in order to ascertain their metamorphic history (see 'Introduction', this chapter). It is possible that these coarse garnetiferous hornblende schists represent former volcanic layers or ferruginous, marly beds within the Moine sediments. However, the coarsely garnetiferous hornblende schists are commonly associated with intrusive amphibolites, and they may result from contamination or hybridization of Moine pelites during the syn-metamorphic emplacement of the mafic intrusions.

Minor Caledonian intrusions are rarely exposed within the Glen Doe river section and are generally emplaced within brittle fault-zones. However, microdiorites occur at NH 2659 1181, NH 2172 1265 and NH 2158 1263, associated with faults in the granite gneiss or along a faulted contact between granite gneiss and quartzose psammite. A porphyritic microgranodiorite dyke cuts granite gneiss at NH 2104 1273.

Interpretation

The field relationships of the mafic intrusive bodies and granite gneiss at Glen Doe are particularly well displayed owing to the low Caledonian strain in this area. The sequence of intrusive events that pre-date the onset of deformation is as follows:

- Emplacement of granite sheets – protolith of the Glen Doe Granite Gneiss.
- Emplacement of gabbro in multiple pulses, incorporating undeformed xenoliths of granite and earlier gabbro pulses. Melting of adjacent country rocks and xenoliths.
- Emplacement of dolerite in multiple pulses.

Emplacement of the Ardgour Granite Gneiss precursor has been dated at 873 ± 7 Ma by the U-Pb TIMS zircon method (Friend *et al.*, 1997) from samples near Glenfinnan. Rogers *et al.* (2001) obtained a similar intrusive age of 870 ± 30 Ma using U-Pb SHRIMP analyses of zircons from the Fort Augustus Granite Gneiss. These two bodies belong to the West Highland Granite Gneiss Suite, and are the oldest intrusive rocks presently dated in the Moine succession. Thus, they provide a minimum age for deposition of this sedimentary sequence.

The metadolerites are geochemically similar to modern Mid-Ocean Ridge Basalt (MORB) in terms of their Nd isotope characteristics and immobile trace-element chemistry (Th, Zr, Hf, Ta, Nb, rare-earth-elements; Millar 1990, 1999). However, mobile elements (Rb, K, Ba, Sr) are strongly enriched, probably by fluid interaction with the adjacent granitic and metasedimentary rocks during metamorphism. The metadolerites contain no primary minerals suitable for U-Pb dating and attempts to date them using Rb-Sr methods have produced only meaningless mixing lines.

The metagabbros have a more-evolved chemistry, reflecting fractional crystallization of a similar tholeiitic basic magma, mixing with partial melts of the granite gneiss, and interaction with metamorphic fluids. Zircons separated from a sample of schistose metagabbro give a U-Pb TIMS age of 873 ± 6 Ma, interpreted as dating syn-metamorphic emplacement of the metagabbro protolith (Millar, 1999). However, the possibility that the zircons are inherited from granite gneiss and incorporated in the basic melt cannot be excluded. Sr isotope data from the metagabbros indicate a major isotopic disturbance at a later date (Millar 1990).

The field evidence implies emplacement of metagabbro and metadolerite suites occurred shortly after emplacement of the granite gneiss, but prior to the onset of deformation. The data suggest that the mafic suite and granite gneiss suite were emplaced during a single geological event. The MORB-like chemistry of the mafic rocks supports the hypothesis that this bimodal magmatism occurred during a Neoproterozoic extensional event at *c.* 870 Ma. Dalziel and Soper (2001) suggested that such an event may mark the start of the break-up of the Rodinia supercontinent. However, the evidence for a Knoydartian orogenic event (see 'Introduction', this chapter, Strachan *et al.*, 2002a, and Tanner and Evans, 2003) implies that extensional events were followed by orogenic compression and crustal stacking at around 750 Ma.

Conclusions

The Glen Doe GCR site contains unrivalled exposures of the relationships between Neoproterozoic granite gneiss, metagabbros and metadolerites that intruded the Moine metasedimentary rocks prior to the onset of orogenic deformation. These relationships are critical to the understanding of the early intrusive, tectonic and metamorphic history of the Moine. The MORB-like geochemical characteristics of the abundant metadolerite dykes are of particular importance, as they suggest emplacement in an extensional environment. Field and geochronological evidence support emplacement of the metabasic rocks at *c.* 870 Ma, effectively coeval with intrusion of the granitic protolith of the West Highland Granite Gneiss Suite. The basic magmatism resulted in high-grade metamorphism and melting of the Moine metasediments at depth that led to formation of the granitic intrusions followed by the development of early metamorphic fabrics. No major fold structures are associated with this early metamorphism in the Glen Doe area: the age of the major isoclinal folds that deform the granite gneiss, the mafic bodies, and the early schistosity remains unconstrained. The Glen Doe GCR site provides evidence for an early attempted break-up of the Rodinia supercontinent and is therefore of international importance.

KINLOCH HOURN (NG 944 069)

E.K. Hyslop

Introduction

The GCR site at Kinloch Hourn is the type locality for the Sgurr Beag Thrust, one of the most significant tectonic structures within the Moine succession. The site incorporates a wide zone of ductile shearing of Moine psammites and pelites, which encloses lenticular bodies of Lewisianoid gneisses.

Tanner (1971) identified two distinct metasedimentary sequences in the Moine rocks of the Kinloch Hourn area, separated by a narrow linear psammitic zone containing pods of Lewisianoid rocks. Despite the apparent continuity of structural history across this zone the two sequences differ in terms of metamorphic facies. The overlying assemblage to the east is gneissose and migmatitic, whilst the western sequence appears lower grade and contains well-preserved sedimentary structures. This led Tanner to postulate the presence of a tectonic break, which he termed the 'Sgurr Beag Slide', along the western edge of the Lewisianoid rocks. Rocks of the western sequence were attributed to a different sedimentary and tectonic succession to those in the east, the two divisions subsequently being recognized as the Morar Group and Glenfinnan Group respectively (Holdsworth *et al.*, 1994; see **Fassfern to Lochailort Road Cuttings** GCR site report, this chapter).

Following the recognition of the 'Sgurr Beag Slide' at Kinloch Hourn, the structure was traced both to the north (see **Fannich** GCR site report, Chapter 7) and to the south, and became established as a major regional tectonic boundary with a lateral extent of over 150 km. In recent times, it is realized that the shear zone has an overall westward thrust movement and it is generally termed the 'Sgurr Beag Thrust'. Deformation was mainly ductile, and apparently contemporaneous with the local D2 deformation and folding. Although on outcrop scale the thrust zone appears concordant with the lithological layering, on a more-regional scale stratigraphical units are cut out.

Description

Kinloch Hourn lies at the head of the remote sea loch of Loch Hourn, a roughly E–W-trending fjord that extends inland for almost 20 km. The Sgurr Beag Thrust passes in a NNE–SSW direction only a few hundred metres from the end of the loch (see Figure 8.9). The rocks are well exposed on the southern shore where a footpath provides access.

Glenfinnan Group rocks with a steep easterly dip lie to the east of the Sgurr Beag Thrust. The lowest unit, the Reidh Psammite, varies from siliceous and coarse-grained to feldspathic and migmatitic, and contains abundant quartz-feldspar lenses. The overlying Sgurr Beag Pelite (Figure 8.3), correlated with the Lochailort Pelite of Powell (1974), is a highly garnetiferous and gneissose rock, commonly containing early quartz-feldspar migmatitic leucosomes. Psammitic layers are common, locally giving the rock a ribbed appearance. No sedimentary structures are seen in these rocks.

Westwards towards the Sgurr Beag Thrust the contact between the Sgurr Beag Pelite and the Reidh Psammite is repeated by a series of S-plunging, tight F3 folds. As the Sgurr Beag Thrust is approached an intense planar fabric obscures the transitional contact between the two units. Early-formed leucosomes, quartz

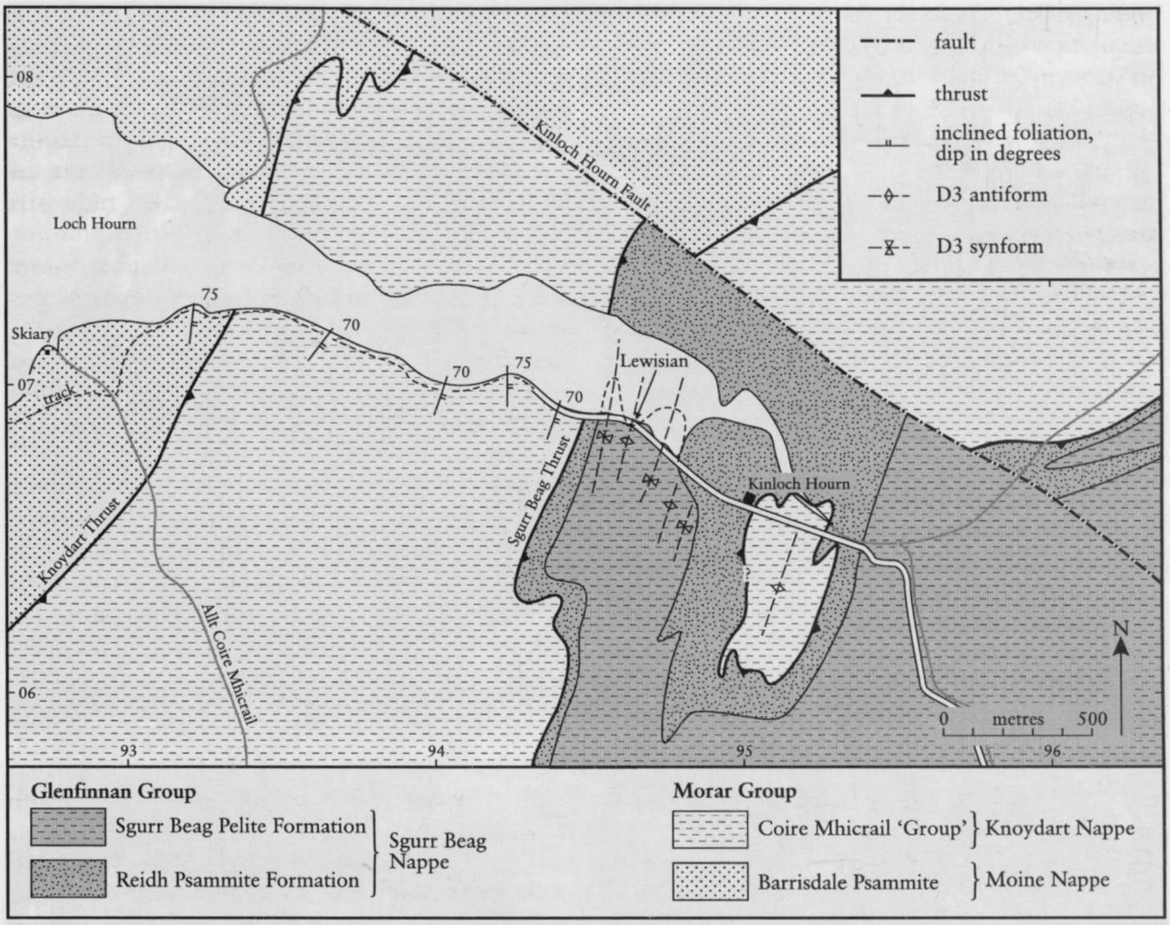


Figure 8.9 Map of Kinloch Hourn GCR site and surroundings. After Roberts and Barr (1988).

veins and pegmatite lenses become intensely deformed and 'shredded', with porphyroblasts wrapped by a quartz ribbon fabric.

At the shoreline on the south side of Loch Hourn at NG 9462 0688 a small lenticular pod of Lewisianoid gneisses is present near the thrust contact. It consists mostly of layered hornblende schist with boudins of more-uniform amphibolite, but grades into felsic gneisses on its eastern side (Figure 8.10). Much of the hornblende is replaced by biotite, and epidote is common, unlike in most Moine lithologies. The Lewisianoid body is enclosed to the south and west (near an F3 fold closure) by migmatitic Reidh Psammite, with a sharp contact separating the two lithologies. Tanner (1971) interpreted this body as a Lewisianoid inlier, one of several lenticular fragments of a once larger sheet that lay along the Sgurr Beag Thrust. A similar body is exposed at the same stratigraphical level in Coire Shubh, about 3 km to the south, and more-extensive gneiss outcrops occur some 7–10 km to the NNE in Glen Shiel (Rathbone and Harris, 1979). Although subsequent work has extended the Sgurr Beag Thrust throughout Inverness-shire and Ross-shire where thicker Lewisianoid inliers are present (Tanner *et al.*, 1970; Powell, 1974), no Lewisianoid slices are found associated with the thrust in the Lochailort area to the south.

On the west side of the Sgurr Beag Thrust is a psammite and semipelite unit, the Coire Mhicrail 'Group' (Tanner, 1971), that represents the Morar Pelite–Upper Morar Psammite transition (see 'Introduction'). The Sgurr Beag Thrust is defined by the contact between the western-most outcrop of Reidh Psammite and the Coire Mhicrail 'Group'. An intense foliation is developed in a narrow zone either side of the contact. F2 axial planes are parallel to this foliation, and minor F2 folds tighten and become sheared out as it is approached. The

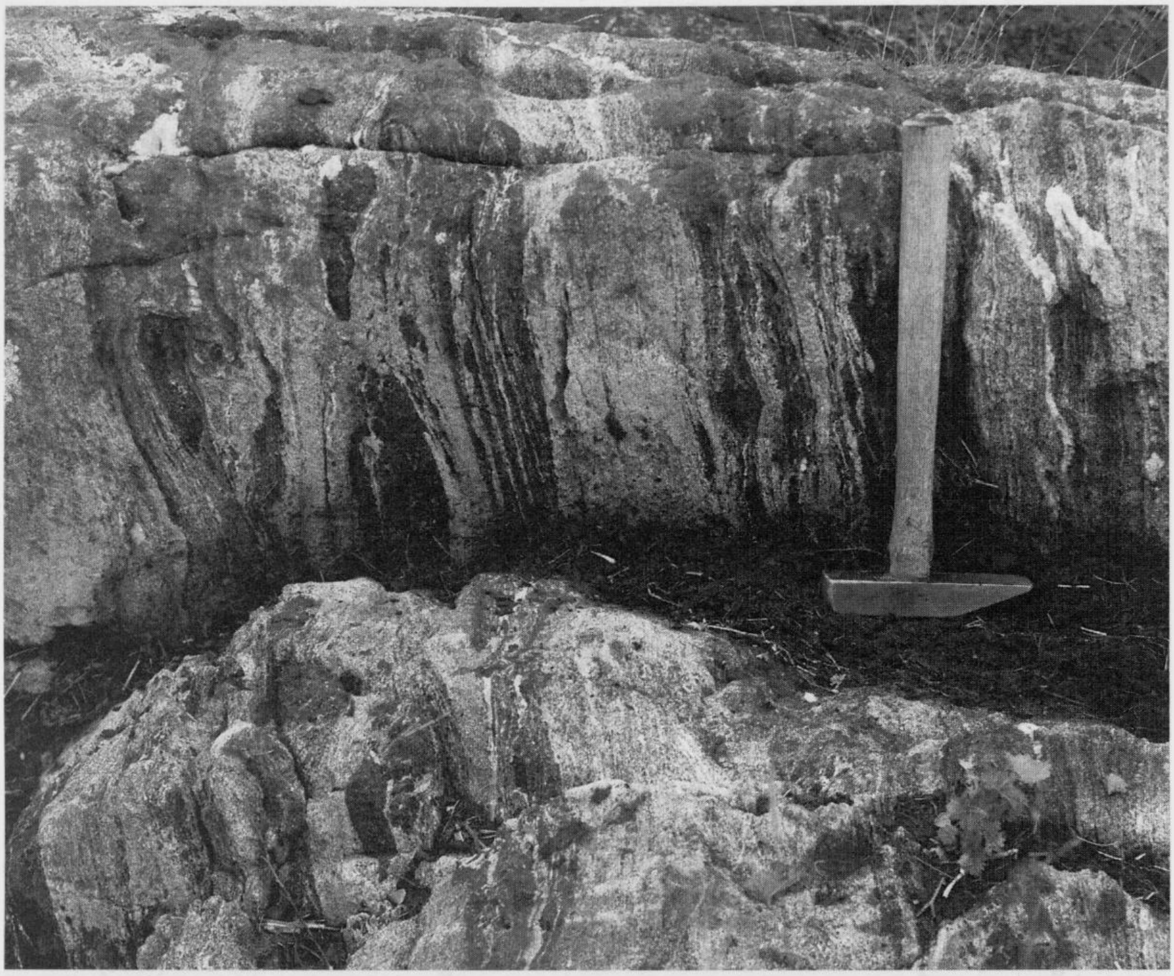


Figure 8.10 Photograph of layered hornblende gneisses with small boudins of amphibolite from Lewisianoid rocks in the Sgurr Beag Slide at Kinloch Hourn. The hammer is 37 cm long. (Photo: British Geological Survey, No. P218788, reproduced with the permission of the Director, British Geological Survey, © NERC.)

shear plane is concordant with the compositional layering on the local scale, though on a larger scale (> 100 m) there is attenuation of fold limbs and the Coire Mhicrail 'Group' is regionally cut out against the Reidh Psammite to the north. The shear zone strikes NNE with a steep dip to the east but is itself affected by F3 folds. Despite their attenuated appearance, in thin section the shear-zone rocks show no obvious indication of mylonitization or significant grain-size reduction, implying that widespread recrystallization and grain recovery has occurred.

Immediately west of the thrust zone the Coire Mhicrail 'Group' retains an intense planar fabric, lacking any angular features such as cross-cutting veins or cross-bedding. However, over several hundred metres the lithology becomes more psammitic, and tight F2 folds of quartz veins, pegmatites and calc-silicate ribs are apparent, indicating a reduction in ductile strain. Psammitic layers carry a strong mica fabric, apparently related to the Sgurr Beag Thrust, as well as an earlier oblique S1 schistosity, showing that the Sgurr Beag Thrust is primarily a D2 structure (Roberts and Barr, 1988). Approximately 200 m to the west of the shear plane, deformed sedimentary structures can be seen in the psammites, and a further hundred metres west the psammites are little deformed and young towards the east.

Interpretation

At Kinloch Hourn the boundary between the distinct Morar Group and Glenfinnan Group rocks has been interpreted as a major tectonic break termed the 'Sgurr Beag Thrust'. The thrust is the most important of the regional NNE-trending ductile dislocations that affect the Moine succession. It represents an early ductile thrust, probably with a displacement comparable to the Moine Thrust, which together with the Knoydart Thrust cuts up-section to the NNW, forming part of a series of regionally extensive thrust nappes (Barr *et al.*, 1986).

Elsewhere in the Moine outcrop, the Sgurr Beag Thrust forms a several hundred metres wide ductile high-strain zone, (Rathbone and Harris, 1979; Kelley and Powell, 1985; see also **Fannich** GCR site report, Chapter 7). However, at Kinloch Hourn it lies within a narrow zone of concentrated strain. The presence of lenses of Lewisianoid gneisses (upon which the Glenfinnan Group Moine is considered to have been deposited) is significant, and suggests significant movement along the thrust. The continuity of the geometry of F2 fold structures across the thrust, limited grain-size reduction, and absence of mylonitization, suggests that thrusting occurred under amphibolite-facies conditions during regional D2 deformation and metamorphism.

The age of the Sgurr Beag Thrust and its relationship to peak metamorphism has long been a contentious issue. The main translation on the thrust has been inferred to occur before (Tanner, 1971), coeval with (Powell *et al.*, 1981; Tanner and Evans, 2003), or after (Baird, 1982; Rathbone *et al.*, 1983) peak metamorphism. This movement has been interpreted to be Caledonian (Barr *et al.*, 1986) or Knoydartian (Piasecki and van Breemen, 1983; Tanner and Evans, 2003) in age. Piasecki and van Breemen (1983) obtained a Rb-Sr age of 755 ± 19 Ma from muscovite in a coarse-grained quartz-feldspar-muscovite pegmatite lens from the Reidh Psammite, about 80 m east of the Sgurr Beag Thrust at Kinloch Hourn. They interpreted this early pegmatitic lens as part of a regional syn-tectonic Knoydartian/Morarian pegmatite suite, developed during Neoproterozoic ductile thrusting, (see Rogers *et al.*, 1998). However, Barr (1985) included such bodies in the regional migmatitic leucosome suite, and suggested that their isotopic age represents partial resetting of an even earlier (possibly Grenvillian) metamorphic event during Caledonian movements on the Sgurr Beag Thrust. Soper *et al.* (1998) rejected the evidence for a Knoydartian orogeny and suggested that the 'slide zone' may have had an earlier history, possibly as an extensional low-angle fault, and was then reactivated as a ductile thrust during Caledonian D2 and D3 events.

Conclusions

On the shore section at Kinloch Hourn, slivers of Lewisianoid gneiss are present within a narrow ductile high-strain zone, the Sgurr Beag Thrust. This structure was first recognized at Kinloch Hourn and is one of the most significant, regional, large-scale tectonic boundaries in the Moine succession, separating the Morar and Glenfinnan groups. Muscovite age dates from pegmatites at Kinloch Hourn suggest that the Sgurr Beag Thrust was originally a Knoydartian structure, providing further evidence of pre-Caledonian orogenic activity in Scotland. The site is of international significance as it is one of the major ductile structures in the Moine outcrop of Scotland and one of the first such structures to have been recognized.

QUOICH SPILLWAY (NH 071 024)

R.A. Strachan

Introduction

The Quoich Spillway GCR site, situated at the eastern end of Loch Quoich, provides a *c*. 175 m-long continuously exposed section across the Quoich Granite Gneiss and adjacent Moine metasedimentary rocks. The rocks dip steeply to the ESE and lie at the eastern margin of the 'Steep Belt' on what is termed the 'Quoich Line' (Clifford, 1957; Johnstone *et al.*, 1969; Roberts and Harris, 1983). This structural feature marks a change from steeply dipping, tightly folded, dominantly Glenfinnan Group pelites, semipelites and psammites to the west, to more gently dipping, open to tightly folded, Loch Eil Group psammites to the east. The Quoich Granite Gneiss is part of the West Highland Granite Gneiss Suite, which outcrops over a wide area in Inverness-shire between Strontian in the south and Glen Affric and Fort Augustus in the north. The suite comprises six major granite gneiss bodies and numerous smaller sheets, mostly intruded close to the boundary between the Glenfinnan and Loch Eil groups (Johnstone *et al.*, 1969; Johnstone, 1975; see also **Fassfern to**

Lochailort Road Cuttings GCR site report, this chapter). U-Pb zircon isotopic data indicate a *c.* 870 Ma, Neoproterozoic age for the granite gneiss suite (Friend *et al.*, 1997). The Quoich Spillway site enables evaluation of the geological setting of the West Highland Granite Gneiss Suite and its role in the early tectonothermal evolution of the Moine Supergroup.

The Quoich Dam area was mapped by A.L. Harris for the Geological Survey in 1961, but more-detailed work was undertaken by A.M. Roberts as part of a PhD study of the stratigraphical and structural significance of the Quoich Line (Roberts and Harris, 1983; Roberts, 1984).

Description

The spillway at the Loch Quoich Dam exposes Moine rocks of the Lower Garry Psammite and the Garry Banded formations separated by a sheet of Quoich Granite Gneiss (Figure 8.11). The bedding and foliation are steeply inclined to subvertical. The upper, western 100 m of the spillway expose mainly psammites and quartzites of the Lower Garry Psammite Formation. Roberts and Harris (1983) interpreted this unit as a transitional lithology marking the Glenfinnan Group–Loch Eil Group boundary, but here it is assigned to the Loch Eil Group (see 'Introduction', this chapter, and Figure 8.3). The rocks display a uniform, centimetre-scale lithological layering suggestive of high tectonic strain, although locally a few highly deformed cross-beds can still be discerned. Two sets of folds are apparent: an early set of small-scale, steeply plunging, tight to isoclinal folds, and a later set of gently plunging, tight, asymmetrical folds which verge to the west. These fold sets have been assigned, respectively, to D2 and D3 deformation phases in this part of the Moine outcrop (Roberts and Harris, 1983; Roberts and Barr, 1988). Biotite and muscovite define a penetrative schistosity which is axial planar to the D2 folds. A 1 m-thick migmatitic pelite separates these psammites from the Quoich Granite Gneiss, which crops out in the lower 75 m of exposure in the spillway (Figure 8.11a,b). The Garry Banded Formation crops out to the south-east of the granite gneiss and comprises psammite and gneissose pelite interlayered on a centimetre-scale. Within the pelitic layers, quartzofeldspathic migmatitic segregations and veins are common and some veins are

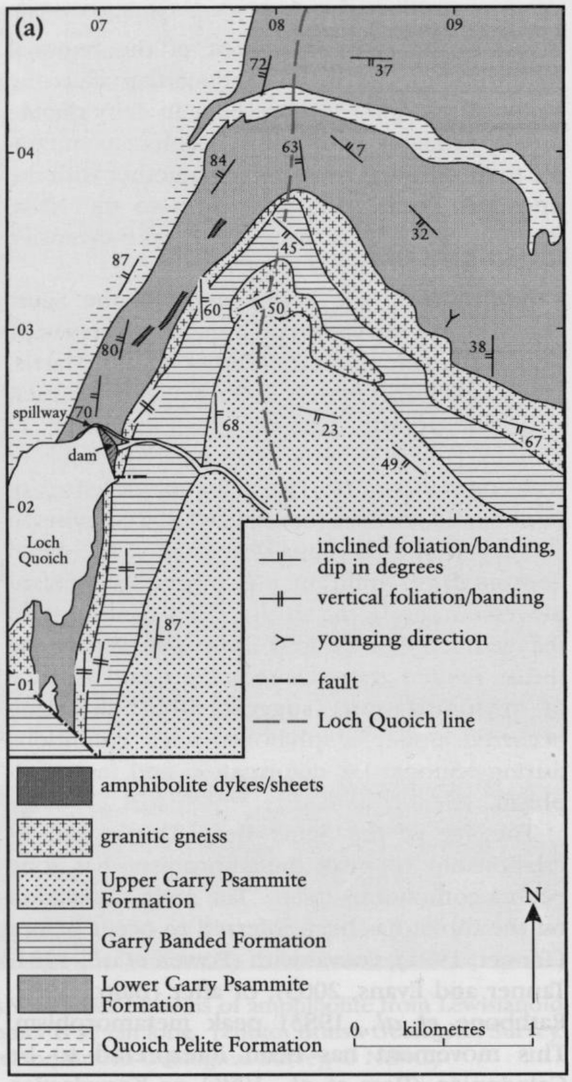


Figure 8.11 (a) Map of the Quoich Spillway GCR site and surrounding area (after Roberts and Barr, 1988). ***Continued opposite.***

isoclinally folded, possibly by D2 structures. Roberts and Harris (1983) again interpreted these rocks as transitional between the Glenfinnan Group and the Loch Eil Group. The Upper Garry Psammite Formation, which consists of more-typical Loch Eil Group psammites, outcrops *c.* 500 m farther east (Roberts and Harris, 1983; Roberts and Barr, 1988).

The Quoich Granite Gneiss is a pale-pink to grey, foliated, medium-grained rock composed mostly of K-feldspar, plagioclase (oligoclase) and quartz with subsidiary biotite. Minor muscovite, garnet, ilmenite, pyrite and epidote also occur. The ubiquitous coarse gneissic foliation is

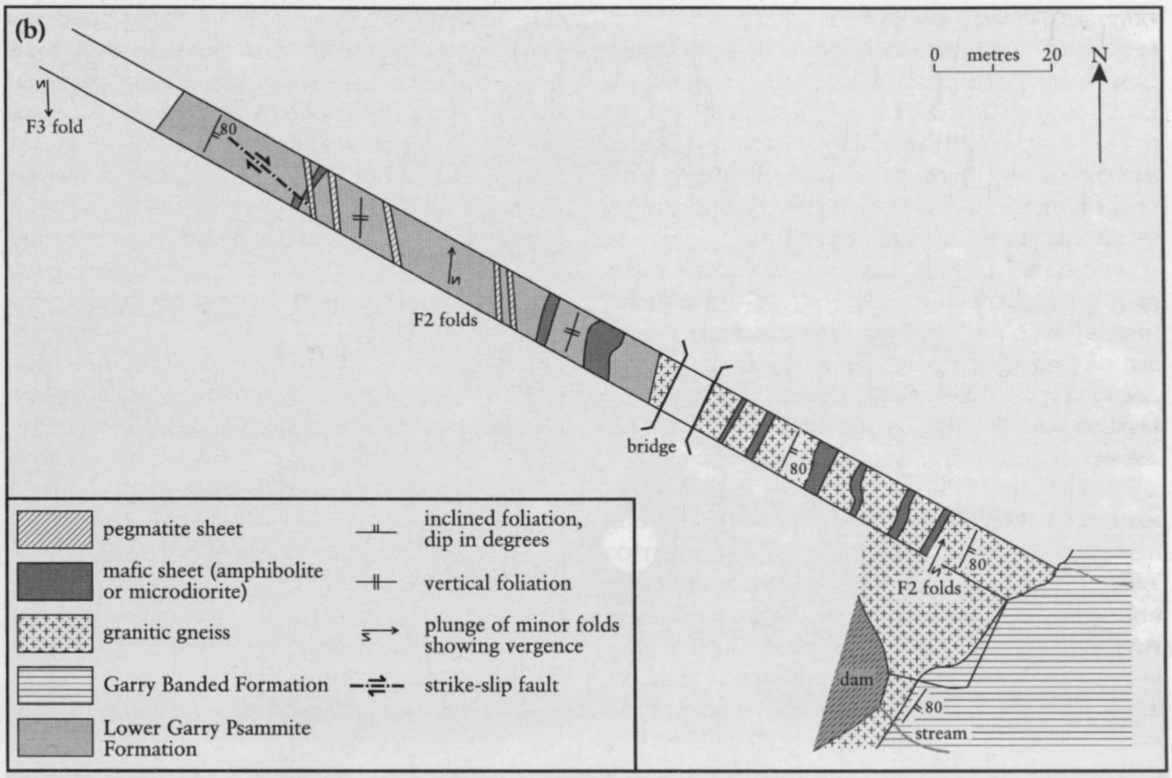


Figure 8.11 – *continued*. (b) The local geological setting of the Quoich Spillway section (after Roberts and Barr, 1988).

defined by discontinuous biotite foliae and lenticular migmatitic quartz-feldspar segregations (Figure 8.12). Mafic selvedges around the segregations suggest that these probably formed *in situ* by partial melting. F2 and F3 folds both deform the gneissic foliation. Contacts with the Moine rocks are sharp and concordant with the foliation, and there is no discernable increase in tectonic strain associated with either contact. Two metasedimentary enclaves, composed of psammite and quartzite with concordant hornblende schist, occur within the granite gneiss near its eastern boundary. Both enclaves are deformed by F2 folds. The foliation is locally re-orientated in a number of NW-trending sinistral shear-zones, notably in the central part of the granite gneiss outcrop (Figure 8.12). Some of these shear zones contain pegmatitic veins which apparently formed by localized segregation coeval with the shearing (Barr, 1985).

Concordant to slightly discordant sheets of hornblende schist, up to 4 m thick, occur within the Moine rocks and the granite gneiss (Figure 8.11b). The hornblende schists are interpreted as deformed and metamorphosed mafic intrusions and several xenoliths of granite gneiss are seen in one sheet. In Coir' an t-Seasgaich, *c.* 1200 m ENE of the spillway, markedly discordant amphibolite dykes are seen cutting bedding in the Lower Garry Psammite Formation. These occur in the low-strain hinge zone of a large-scale F3 fold (Figure 8.11). Where F2 folds deform the hornblende schists, an S2 axial-planar fabric is produced.

The grade of metamorphism is difficult to evaluate because of the lack of aluminosilicate indicator minerals, but the presence of migmatitic segregations and possibly localized partial-melting suggests that middle- or upper-amphibolite-facies metamorphic conditions prevailed prior to D2 deformation. The presence of aligned hornblendes within the S2 fabric, and segregations within the later cross-cutting shear-zones indicates that amphibolite-facies conditions persisted during and after D2 deformation (Barr, 1985).

Within the Lower Garry Psammite Formation in the spillway section, several undeformed, N-trending pegmatites cut F2 folds, but are deformed by late kink-bands. The pegmatites

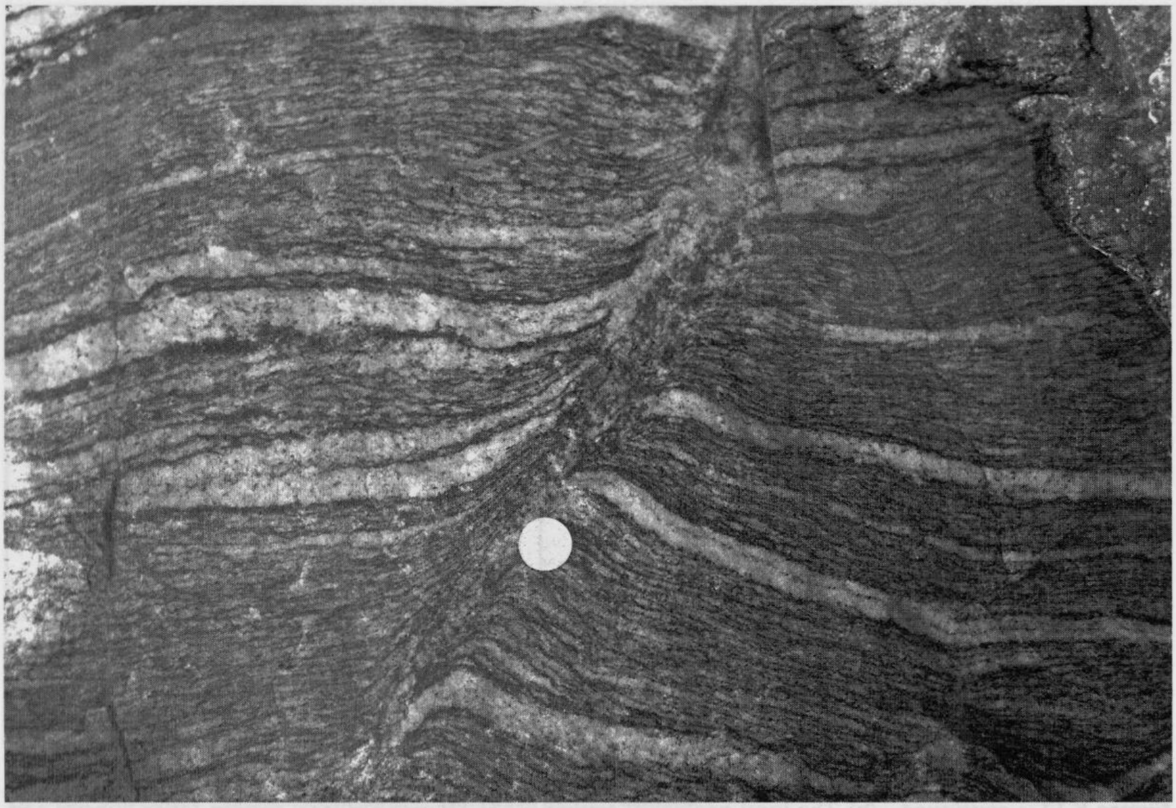


Figure 8.12 Typical aspect of the Quoich Granite Gneiss at the site, showing the gneissose foliation and migmatitic segregations deformed by a sinistral ductile shear-zone. The coin is 2.4 cm in diameter. (Photo: A.M. Roberts.)

were probably emplaced at a late stage of the Caledonian Orogeny. In addition, several 1–2 m-thick, NE-trending microdiorite sheets, here largely undeformed, cut discordantly across the Moine rocks, the granite gneiss, and the amphibolites. They are members of the Silurian-age late Caledonian Microdiorite Sub-suite (Smith, 1979). Although their original igneous mineralogy has partially recrystallized under greenschist- and/or epidote-amphibolite-facies conditions, relict igneous features are typically preserved in their central parts. The sheets normally have coarse-grained central zones and marginal more-foliated zones, with biotite developed.

Interpretation

The significance of the site lies in the excellent exposure of a member of the West Highland Granite Gneiss Suite, intruded into lithological units that straddle the transition from Glenfinnan Group to Loch Eil Group rocks (Roberts and Harris, 1983). The main outcrop of the Glenfinnan Group comprises migmatitic, gneissose semipelite, pelite and micaceous and feldspathic psammite. In contrast the Loch Eil Group consists mainly of psammite and subordinate quartzite. The general lack of migmatization in the Loch Eil Group psammites is attributed to its relatively quartz-rich composition. The Moine sedimentary rocks were probably deposited in a variety of marine sub-environments (Strachan *et al.*, 1988), although primary sedimentary structures are generally absent around the Quoich Spillway, probably reflecting the high tectonic strain and extensive recrystallization.

The origin of the West Highland Granite Gneiss Suite has been controversial. Bailey and Maufe (1916) interpreted the southernmost body, the Ardgour Granite Gneiss, as a deformed, pre-metamorphic intrusion. Harry (1954) and Dalziel (1966) subsequently concluded that the Ardgour body formed *in situ* as a result of K-metasomatism of Moine (Glenfinnan Group) sediments during high-grade metamorphism. On the basis of limited chemical data, Mercy (1963) suggested that the Ardgour Granite Gneiss could have been magmatic in origin. Gould (1966), on the basis of a larger geochemical database, concluded that it has a uniform granitic composition, distinct from that of the adjacent Moine metasediments. However, he accepted Dalziel's field and petrographic evidence and suggested intrusion of an Al-undersaturated magma in order to retain a metasedimentary component in the bulk gneiss. To explain the presence of granite gneiss in areas of apparent low metamorphic grade, Harris (in discussion of Winchester, 1974) suggested that it could be a slice of pre-existing granitic basement tectonically emplaced into the Moine.

Barr *et al.* (1985) re-investigated the granite gneiss occurrences in the North-west Highlands and concluded that they represent a series of deformed and metamorphosed intrusive granite sheets. This is consistent with the absence of transitional metasedimentary rock–granite gneiss contacts, the overall homogeneity of the granite gneisses, and its appearance as a weakly deformed granite in low-strain zones within the larger bodies. The granite gneisses record all the deformation and metamorphic episodes apparent in the adjacent Moine rocks, and hence their igneous precursors must have been intruded either prior to or during D1. The lack of any thermal aureole suggested to Barr *et al.* (1985) that the granites were intruded into Moine rocks that were already undergoing high-grade metamorphism, thus indicating a syn-D1 rather than pre-D1 origin. The major-element and limited trace-element geochemical data are consistent with an origin by partial melting of Moine metasediments at a deeper structural level. The emplacement of the granite gneiss suite may have been controlled by the lithological contrast between the Glenfinnan and Loch Eil groups. Alternatively it may reflect a deep lineament in the basement to the Moine succession. The location of the granite gneisses within the Moine succession, rather than at its base, and their homogeneous character compared to the Lewisianoid inliers, shows that they cannot represent pre-Moine basement. Furthermore, granite gneiss–metasedimentary rock contacts lack the very high ductile strains that generally accompany proven allochthonous basement slices in the Moine (cf. Rathbone and Harris, 1979).

Isotopic data have consistently indicated a Neoproterozoic age for the high-grade tectonothermal event, which resulted in formation of the granite gneiss suite (e.g. Brook *et al.*, 1976; Piasecki and van Breemen, 1979a). Recent high-precision U-Pb SHRIMP and TIMS dating of single zircon grains from both the Ardgour and Fort Augustus granite gneisses indicated an age of *c.* 870 Ma (Friend *et al.*, 1997, Rogers *et al.*, 2001). This is currently regarded as the most reliable age of intrusion of the granite gneisses.

The age of D2 deformation in and around the granite gneiss is uncertain. D3 structures correspond to a phase of tight upright Caledonian folding, which resulted in the formation of the 'Steep Belt' (Roberts and Harris, 1983). The centimetre-scale lithological layering, notably flattened D3 fold style, and steep foliation attitude are characteristic structural features of the highly strained rocks within the 'Steep Belt'.

Conclusions

At the Quoich Spillway GCR site are excellent exposures of the Quoich Granite Gneiss, a member of the West Highland Granite Gneiss Suite, and its contacts with the host Moine metasedimentary rocks. The Quoich Granite Gneiss was intruded as a granite sheet into transitional psammite and semipelite units that straddle the Glenfinnan Group–Loch Eil Group boundary. U-Pb zircon isotopic dating indicates a Neoproterozoic age (*c.* 870 million years) for emplacement of the West Highland Granite Gneiss Suite, and clarification of its geological setting is crucial for understanding the early history of the Moine Supergroup. The contact relationships of the granite gneiss at the site are consistent with the view that it represents deformed and metamorphosed thick granite sheets, emplaced into the Moine rocks prior to or during earliest D1 deformation, accompanied by amphibolite-facies metamorphism and migmatization. The granite gneiss suite places important constraints on the age of deposition of the Moine Supergroup and the early D1 and D2 tectonothermal events; thus the Quoich Spillway GCR site is of international importance.

KNOYDART MICA MINE (NM 797 961)

E.K. Hyslop

Introduction

The Knoydart Mica Mine, north of Loch Nevis in a remote part of the Knoydart peninsula, is one of the sample sites used in a pioneering geochronological study of metamorphic rocks from the Scottish Highlands by Giletti *et al.* (1961). Large muscovite crystals were obtained from a thick pegmatite in the Ladhar Bheinn Pelite Formation, part of the Morar Group succession (Figure 7.3, Chapter 7). The muscovites provided Rb-Sr isotopic ages of 705–765 Ma, the first evidence for a Neoproterozoic tectonometamorphic event in the Moine rocks. These ages stimulated a long-running and still continuing debate on the geological history of the Scottish Highlands.

The Knoydart Mica Mine was one of the few sources of coarse mica in Britain, and it remains the most important source of beryl. Muscovite books and beryl crystals over 30 cm in size have been described. A single beryl crystal weighing over 4 kg collected from the mine dumps is in the possession of the Natural History Museum in London.

W.Q. Kennedy first mapped the Knoydart area for the Geological Survey in 1938 and delineated the prospective pegmatite veins (Figure 8.13; see also Figure 8.15, **North Morar** GCR site report, this chapter). The overall geology was summarized by Kennedy (1955) as part of his wider synthesis of the Morar Antiform. In the 1960s the Moine and Lewisianoid rocks of Knoydart and Morar to the south were subject to further detailed mapping and related structural and metamorphic investigations. This work has been fundamental to advancing the understanding of geology in the Northern Highlands (Poole and Spring, 1974; Powell, 1974). The overall geology is described more fully in the succeeding **North Morar** GCR site report, which covers a wider area south of Loch Nevis.

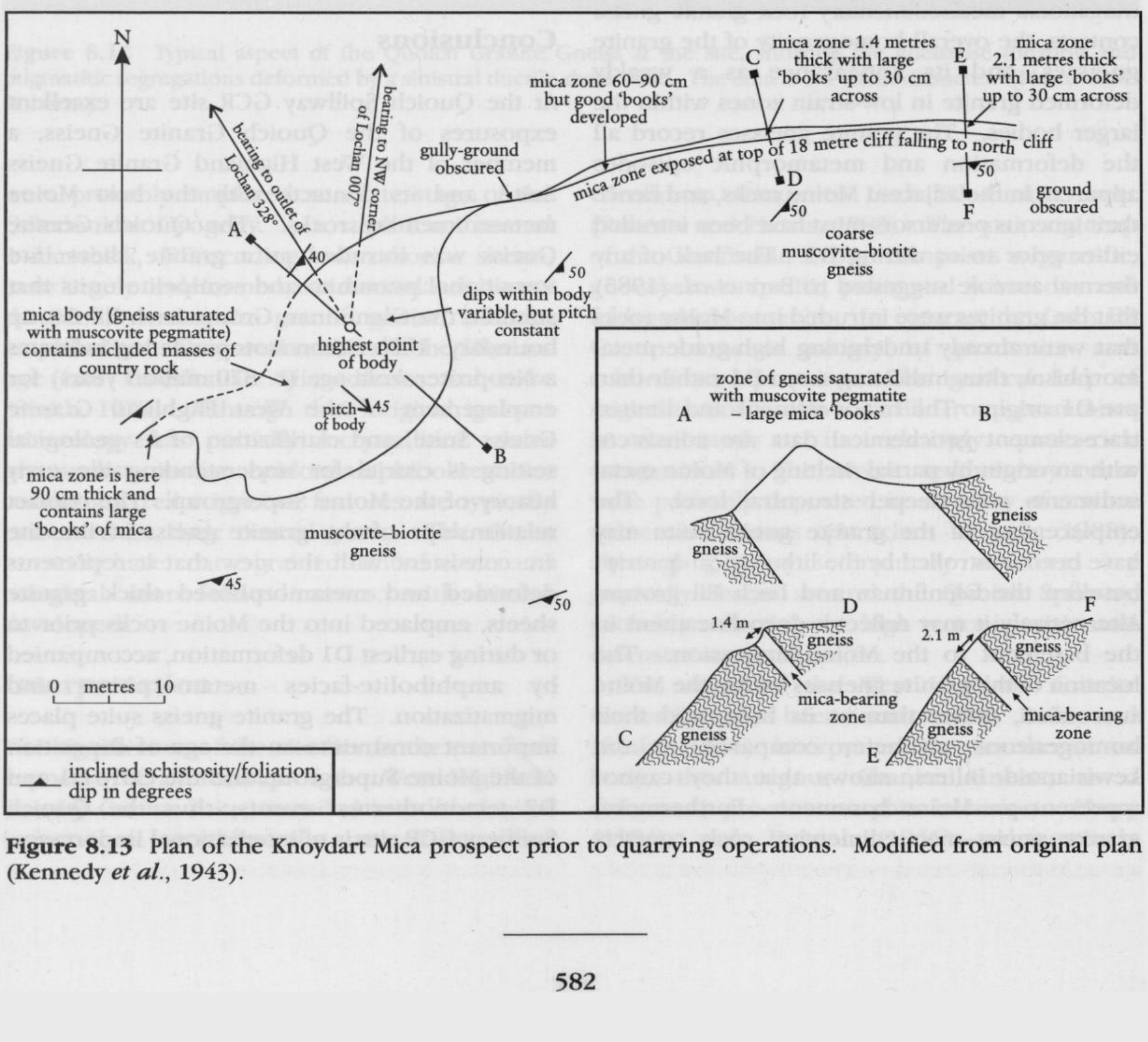


Figure 8.13 Plan of the Knoydart Mica prospect prior to quarrying operations. Modified from original plan (Kennedy *et al.*, 1943).

Description

The Knoydart Mica Mine is situated on the north side of Loch Nevis on the southern flank of Sgurr Coire nan Gobhar, at an altitude of 560 m. Kennedy *et al.* (1943) documented the mine area as part of a wartime evaluation of sources of mica in Scotland. Large muscovite books of high optical quality were described from a suite of pegmatites within the gneissose Moine pelites. As a result of extensive quarrying most of the larger pegmatite bodies have been removed, leaving sizeable spoil heaps. Smaller pegmatite veins remain ***in situ*** as clues to the original nature of the site. The Knoydart mine was worked as a source of sheet mica between 1943 and 1944; some 3600 tons of rock were processed yielding 33.3 tons of good quality mica.

The original description by Kennedy *et al.* (1943) is important as it provides the only detailed information on the site prior to quarrying (Figure 8.13). The quartz-rich muscovite pegmatites occurred as a series of concordant veins within a SW–NE-trending lens of 'saturated gneiss', some 30 m in length and 15 m in width. At its eastern end, a thin pegmatite-bearing sheet of gneiss extends for a further 30 m towards the north-east.

The zone of pegmatization lies within the Ladhar Bheinn Pelite Formation, the lateral equivalent to the Morar Pelite Formation (Holdsworth *et al.*, 1994), in a northern extension of the Morar Antiform (see **North Morar** GCR site report, this chapter). The formation here consists of interlayered gneissose pelite and psammite, with the lithological layering and foliation generally dipping steeply to the east. The gneissose pelite contains stromatic migmatitic leucosomes typically up to about 1 cm thick, bounded by thin biotite selvedges. Garnet porphyroblasts in the pelite show evidence of a complex tectonic history with an inner core retaining a discordant, relict early fabric surrounded by an outer inclusion-free rim, which in turn is wrapped by the main schistosity (Figure 8.14). The pegmatites that remain today are dominated by quartz, feldspar, muscovite and garnet, with mantles of biotite and garnet in the host rock. They are concordant with the layering and foliation, and vary from a few

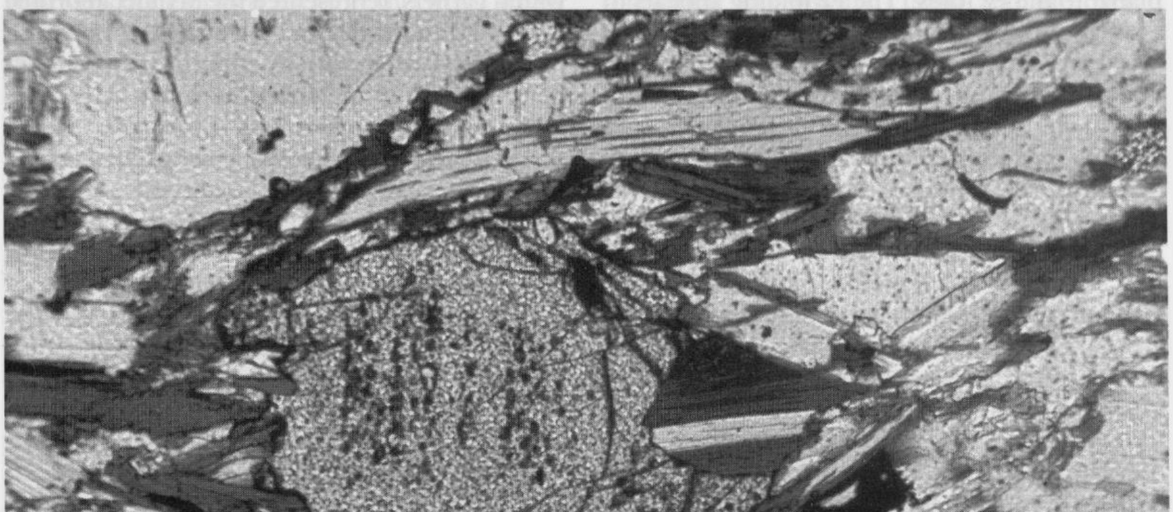


Figure 8.14 Photomicrograph showing garnet within pelitic host rock to Knoydart pegmatites. Garnet core contains fine-grained inclusions aligned to give a planar fabric perpendicular to the main fabric, surrounded by a broad inclusion-free rim. The garnet is *c.* 1 mm across. (Photo: E.K. Hyslop, thin section N4940.)

centimetres up to *c.* 1 m in length and up to *c.* 30 cm thick. Muscovite is abundant, with large individual or intergrown books up to 30 cm long and about 10 cm thick. Large books occur even within small pegmatites that are only 10 cm thick. Muscovite is normally developed with its basal cleavage aligned parallel to the pegmatite margins, and is typically remarkably fresh, clear and undeformed with a distinctive smoky colouration. Garnet occurs as small euhedral crystals up to *c.* 1 cm across, and beryl is abundant as euhedral crystals several centimetres long. Material in the surrounding spoil heaps suggests that the quarried pegmatites were mineralogically similar, although large individual feldspar crystals > 30 cm in size imply that some of the pegmatite bodies were several metres in length.

The pegmatites have been deformed into boudins on the limbs of tight to isoclinal folds whose axes plunge steeply to the south-east, consistent with the F2 folds of the area (James, 1977). They are also clearly folded by the later upright, open F3 folds. In the psammites a penetrative schistosity, defined by muscovite and abundant quartz veinlets, is developed axial planar to the F2 folds. The F2 folding appears to be that referred to by Kennedy *et al.* (1943) as 'contemporaneous' with the pegmatites, as the bodies are rarely folded around hinges and appear to be generally axial planar to F2. Locally, pegmatite bodies are also rodded, parallel to the F2 axes.

Interpretation

The pioneering Rb-Sr isotopic age dates of 705–765 Ma obtained by Giletti *et al.* (1961), subsequently revised by Long and Lambert (1963) to 680–745 Ma, were used as evidence for a discrete Neoproterozoic orogenic event in the Moine assemblage, termed 'Knoydartian' (Bowes, 1968) or 'Morarian' (Lambert, 1969). Further isotopic evidence was provided by K-Ar dating of muscovite from the Knoydart Mica Mine by Fitch *et al.* (1969), which gave a cooling age of 744 ± 10 Ma. Since this time, other isotopic ages of *c.* 750–800 Ma have been reported widely from the Moine outcrop and also the Scottish Central Highlands (e.g. van Breemen *et al.*, 1974; Piasecki and van Breemen, 1983; Powell *et al.*, 1983; Noble *et al.*, 1996; Rogers *et al.*, 1998; Vance *et al.*, 1998). Much debate has taken place as to the significance of these dates and the nature, cause and even occurrence of Neoproterozoic orogenesis in the Moine. This Neoproterozoic event, first revealed at Knoydart Mica Mine, has remained one of the most controversial aspects of Highland geology (see Tanner and Bluck (1999) and Oliver (2002) for recent summaries).

On the basis of the initial Sr ratios, Long and Lambert (1963) proposed that the pegmatites were locally derived from their surrounding Moine host rocks. This supports the conclusions of Kennedy *et al.* (1943) who noted that the pegmatites occur in a 'saturated' zone where the gneisses are particularly biotite rich, with strong mafic selvedges at the margins of the pegmatites. These features are consistent with the pegmatites having formed by in-situ segregation or partial melting.

In a detailed structural study of the area, James (1977) interpreted the Knoydart pegmatites as being post-D1, and either pre- or syn-D2 in age, and correlated the first recognizable metamorphism (M1) with the Neoproterozoic Knoydartian event. MacQueen and Powell (1977) demonstrated that the early high-strain fabrics, preserved as internal inclusion trails within garnets, represented the M1 metamorphic event, which overlapped D1 and D2. However, the fabrics were typically deformed by the D2 deformation. In the gneissose pelitic rocks, the high-strain fabrics have been destroyed by the coeval migmatization, which generated pegmatitic segregations axial planar to the F2 structures (Dalziel and Johnson, 1963). Recent pressure–temperature calculations based on the mineralogy and Sm-Nd ages of 820–790 Ma for garnets in the Morar Group have been taken to indicate an episode of crustal thickening in the western Moine during the Neoproterozoic (Vance *et al.*, 1998). Indeed, there is now substantial evidence to support the proposal, first identified at Knoydart, that a Neoproterozoic 'Knoydartian' tectonometamorphic or 'orogenic' event affected these rocks at *c.* 750–800 Ma.

Conclusions

The Knoydart Mica Mine marks the occurrence of a suite of muscovite- and beryl-rich quartz-feldspar pegmatites, which have been of fundamental importance to the development of understanding the geological history of the Scottish Highlands. Samples from the site were used in a pioneering geochronological study in 1961 that obtained Rb-Sr mica ages of *c.* 750 Ma and provided the first evidence of a Neoproterozoic, Knoydartian tectonometamorphic event in Scotland. The character of this event is still being researched and debated. The site is of national importance. It is also of historical significance as one of the few sites of limited commercial muscovite exploitation in the United Kingdom, and it remains the most significant resource of beryl in Britain.

NORTH MORAR (NM 668 933, NM 682 922, NM 703 927, NM 718 936, NM 731 924–NM 872 915)

J.R. Mendum

Introduction

The North Morar GCR site provides a cross-section through the Morar Group metasedimentary succession in its type area. It also documents the transition from low-grade, relatively undeformed rocks in the west, across the Morar Antiform, to high-grade, highly deformed rocks in the interior of the Caledonian Orogen.

The GCR site is large and extends from west of the Mallaig road (A830) eastwards as far as Kinlochmorar, encompassing the hills that separate Loch Morar from Loch Nevis. However, much of the north-western part of this North Morar area is excluded from the GCR site. The approximately N–S-trending, domal Morar Antiform, is the dominant structure of the western part of the area. The antiform exposes Lewisianoid inliers as sheets within the Moine succession and also repeats the Morar Group succession on its flanks (Figure 8.15). The lower contacts of the Lewisianoid rocks are ductile shear-zones. Farther east, other structurally higher shear-zones dominate the overall structural pattern, notably the Knoydart Thrust (Poole and Spring, 1974), the complex zone of ductile thrusting around Ardnamurach, and the Sgurr Beag Thrust (Johnstone and Mykura, 1989). These D2 shear-zones and related folds have been refolded by a later D3 phase; for instance the Sgurr Beag Thrust at Sgurr Breac is folded by the F3 Glenshian Synform (Powell, 1974). Metamorphic grade ranges from epidote-amphibolite facies in the west to middle- and locally upper-amphibolite facies in the east.

The Geological Survey mapped much of the North Morar area between 1935 and 1938, but gaps in the mapping meant that work continued into the 1960s, and Sheet 61 (Arisaig) was only published in 1971 (Institute of Geological Sciences, 1971). Richey and Kennedy (1939) summarized the overall stratigraphy, emphasizing the sedimentary features of the Lower Morar Psammite and Upper Morar Psammite formations. Subsequently Glendinning (1988) carried out detailed work on the sedimentological features of the Morar Group psammites, notably the Upper Morar Psammite. Other field studies in the adjacent areas of Knoydart (Ramsay and Spring, 1962), Mallaigmore (Lambert and Poole, 1964), and Lochailort (Powell, 1964, 1966) have been summarized by Poole and Spring (1974) and Powell (1974). These latter two papers both used the Sheet 61 geological map to re-interpret the major structures of Knoydart and Morar. The stratigraphical and structural terminology of Powell is preferred here. The regional structure of the area is summarized by Johnstone and Mykura (1989) and the overall Moine stratigraphy shown in Figure 8.3 (after Holdsworth *et al.*, 1994).

Description

The North Morar GCR site extends from east to west for some 20 km and ranges in width from 6 km down to *c.* 2 km at Tarbet (NM 792 923). It is bounded to the south by Loch Morar, the deepest freshwater loch in Europe, and to the north by Loch Nevis. It consists of rugged rocky and grassy hills with numerous clean rock exposures present in the area.

The oldest rocks in the area are the Lewisianoid gneisses that form lenticular sheets whose contacts are now approximately conformable with the overall bedding in the underlying and overlying Moine rocks. The gneisses consist of interlayered feldspathic acid gneiss with abundant amphibolitic mafic layers and lenses. In parts the hornblende is extensively retrograded to biotite or chlorite and secondary epidote. Even where highly deformed, the pyrite and epidote content of the felsic and mafic gneisses confirm their Lewisianoid origin. Excellent exposures of white and green-black, layered felsic and mafic gneiss with rare discordant basic sheets

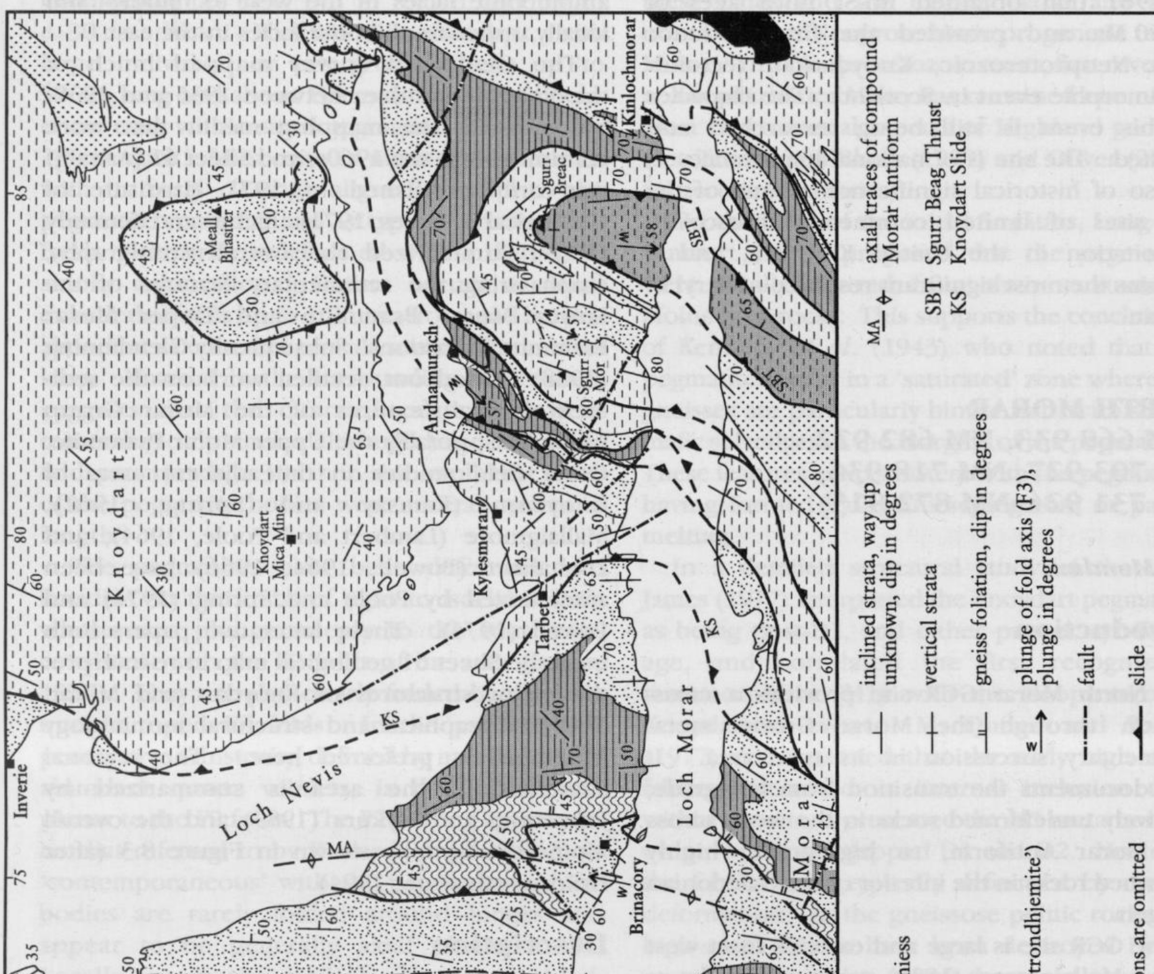


Figure 8.15 Geology of the North Morar GCR site and surrounding area. Compiled from 1:63 360-scale Sheet 61 (Arisaig) (Institute of Geological Sciences, 1971), and Powell (1974).

occur at Rubh' Àird na Murrach (NM 8261 9375) (Figure 8.16). The compositional layering in the Lewisianoid inliers ranges from less than 1 mm to over 1 m thick, dependent on the amount of later tectonic reworking. Where thickly layered, the lenticular and gneissose nature of the rock, and locally discordant nature of some of the mafic sheets and dykes is evident. A good section is seen near Brinacory between NM 758 912 and NM 762 910, where the sheared contact between hornblende-bearing Lewisianoid gneisses and Moine psammites and minor semipelites (Lower Morar Psammite) is exposed. The sheared Lewisianoid rocks contain abundant epidote, biotite, pyrite and chlorite. Within 50 m of the contact they generally regain their coarser gneissose aspect, with some tonalitic gneiss units up to 1 m thick. Farther east the amphibolitic mafic sheets and lenses thicken to several metres and mafic sheets discordant to the overall layering are seen. The upper contact shows no evidence of attenuation and the immediately overlying semipelites and psammites of the Basal Pelite Formation still show recognizable sedimentary structures, suggesting this contact is a structurally modified unconformity.

The Moine rocks have a well-defined stratigraphy in North Morar, which is summarized in Table 8.1 (see also Figure 8.3; Richey and Kennedy, 1939; Holdsworth *et al.*, 1994).

The Basal Pelite Formation generally overlies the Lewisianoid gneisses, and although there is now little evidence of angular unconformity, east of Brinacory the contact appears to be sharp and show no evidence of subsequent shearing. The formation is variable both in lithology and thickness, and consists of interbedded semipelite, coarse pelite, micaceous and feldspathic psammite, with minor gritty quartzose psammite units. The rocks are commonly epidotic. Graded units are seen, but cross-bedding is rare, and calc-silicate lenses are typically absent. In places the formation contains psammitic lenses at the base and the top (Ramsay and Spring, 1962). Quartz and subsidiary quartz-feldspar veins and lenses are locally abundant, especially

Figure 8.16 Attenuated and folded Lewisianoid felsic and mafic gneisses at Rubh' Àird na Murrach (NM 8661 9374), Loch Nevis. The prominent open to close folds are F3 and in parts refold earlier very tight F2 folds: an example can be seen to the top right. The hammer is 28 cm long. (Photo: G.S. Johnstone, BGS No. P254880, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Table 8.1 Moine Stratigraphy in North Morar.

Glenfinnan Group	
Lochailort Pelite Formation	Gneissose pelite and semipelite with subordinate psammite and quartzite beds. Amphibolite sheets and calc-silicate lenses.
Morar Group	
Upper Morar Psammite Formation	Feldspathic and siliceous psammite and subsidiary semipelite. Excellent cross-bedding and loading structures. Calc-silicate layers and lenses.
Morar Striped and Pelitic Schist Formation	Dark-grey fine-grained semipelite and striped pelite–psammite units with abundant calc-silicate layers and lenses.
Lower Morar Psammite Formation	Siliceous to micaceous psammite, commonly arkosic, with pebbly and gritty beds. Heavy-mineral bands common. Interbedded pelitic units.
Basal Pelite Formation	Mixed, thinly bedded, schistose pelite, semipelite, and micaceous to feldspathic psammite.

where the unit is sheared. Richey and Kennedy (1939) interpreted these veined and sheared rocks as part of a 'Sub-Moine Series', as discussed below.

The Lower Morar Psammite Formation is exposed in the core of the Morar Antiform in North Morar, where typically it is a pale, blocky to massive, feldspathic to micaceous psammite with thin coarsely schistose pelite and semipelite interbeds. Calc-silicate lenses occur rarely and are concentrated in the upper, more-semipelitic part of the formation. Bedding is commonly lenticular, with channel features seen on Creag Mhòr Bhrinicoire (NM 743 919). The formation also contains examples of cross-bedding, heavy-mineral bands, gritty lenses, loading structures and slump folds, testifying to its rapid deposition and relatively proximal nature. On the southern flank of Sgurr Mòr around NM 831 919 feldspathic and quartzose psammites with subsidiary micaceous psammites and thin semi-pelite interbeds are tightly folded. The bedding is nebulous in the main F2 hinge zone, but elsewhere, early tight folds, confined to individual beds are seen. These are interpreted either as slump folds or D1 folds. Powell (1974) assigned these beds to the Lower Morar Psammite Formation. This formation is also mapped below and within the Ardnamurach Shear Zone, and farther east where it links northwards to the Arnisdale Psammite of Ramsay and Spring (1962). The unit becomes generally thinner to the east and contains a greater proportion of pelitic material, reflecting its more-distal nature.

The Morar Pelite Formation, formerly termed the 'Striped and Pelitic Group' (Richey and Kennedy, 1939), comprises three lithologically distinctive units. Interlayered semipelite and psammite units sandwich a central garnetiferous pelite and semipelite unit, as exposed around the estuary of the River Morar, east of Tarbet at NM 804 931, and on Sgurr Mòr. To the north in Knoydart, Ramsay and Spring (1962) termed the equivalent unit the 'Ladhar Bheinn Pelitic Group'. The boundary with the underlying Lower Morar Psammite Formation is transitional, marked by mid-grey micaceous psammites and semipelites with feldspathic and siliceous psammite interbeds. Calc-silicate ribs are present but become more abundant in the higher parts of the pelite formation. The central pelitic schist is a dark-grey, garnetiferous, biotite-rich pelite and semipelite with a penetrative schistosity. The semipelitic and minor micaceous psammite interbeds define the bedding. The upper striped unit consists of thinly bedded, grey, micaceous and feldspathic psammites and garnetiferous, biotite + muscovite-bearing semipelites with abundant thick calc-silicate ribs and lenticular layers. Biotite-rich amphibolite pods are present and locally show discordant relationships with the bedding. Around Sgurr Breac the semipelitic units become gneissose in parts.

The overlying Upper Morar Psammite Formation is composed mainly of medium-bedded feldspathic psammite with abundant sedimentary structures, notably tabular and trough cross-bedding, ripple marks, and dewatering and loading structures. The formation is at least 5 km thick in its western outcrop, where it has been interpreted as a proximal marine sand sequence, derived from the west and south-west and dominated by N-flowing tidal currents (Glendinning, 1988). The sequence thins rapidly to *c.* 1.5 km thick on the east side of the Morar Antiform and the minor semipelite element found in the west becomes more significant. In North Morar, the formation is not well represented on the eastern side of the Morar Antiform. Only the lower parts of the formation occur in small fold outliers on the southern slopes of Sgurr Breac where they consist of thin- to medium-bedded, siliceous to micaceous psammites and minor semipelites with abundant calc-silicate ribs.

The Lochailort Pelite Formation is the basal unit of the Glenfinnan Group, and is separated from the underlying Morar Group succession by the Sgurr Beag Thrust. The pelite crops out in the central part of the Glenshian Synform that crops out on the southern slopes of Sgurr Breac, where it consists of massive gneissose muscovite-biotite pelite, commonly garnetiferous, with subsidiary semipelite and minor thin micaceous and feldspathic psammite interbeds. The pelite contains abundant quartz and quartz-feldspar segregation veins and pods, in parts with prominent biotite selvedges. Lenticular calc-silicate beds and small lenses are locally common and an excellent example displaying interference fold patterns is seen at NM 839 907. Garnetiferous biotite-hornblende metabasic pods and sheets, locally discordant to the lithological layering, are present in the Lochailort Pelite here.

Foliated garnet-muscovite-bearing pegmatites are found in the eastern, higher metamorphic grade areas, notably between Sgurr Mòr and Sgurr Breac, and on Sgurr Breac itself. They mainly intrude the Morar Pelite and Upper Morar Psammite formations. A particularly large pegmatite at NM 836 924 is locally discordant to the lithological layering but is strongly foliated parallel to the S2 schistosity in the surrounding semipelite–psammite sequence. In the eastern margin of the area pegmatitic leucotonalite ('trondhjemite') forms large white masses and vein networks. This is coincident with the overall increase in metamorphic grade and migmatization eastwards. Such masses are of Caledonian age.

There are numerous minor intrusions in the North Morar area, including late Caledonian microdiorite and lamprophyre dykes, Permo–Carboniferous quartz-dolerite plugs and E–W-trending camptonite dykes, and Palaeogene basalt and dolerite dykes of the Skye swarm.

Structure

The Moine succession has been affected by two main penetrative deformation phases, termed 'D2' and 'D3' (Powell, 1974). Prior to their development, D1 is recognized as resulting in a bedding-parallel schistosity and minor tight to isoclinal folding. These are mainly slump folds and convolute bedding structures, largely resulting from sediment loading. Powell (1974), following the work of Ramsay and Spring (1962) in the Glenelg area to the north (see **Rubha Camas na Cailinn** GCR site report, Chapter 7), postulated that the Lewisianoid inliers in Morar formed the cores of early F1 isoclinal folds, termed the 'Morar and Ardnamurach Isoclines'. This hypothesis is rejected here as on the east flank of the Morar Antiform the sedimentary structures clearly show that the Moine succession youngs upwards on both sides of the Lewisianoid gneiss inlier, and the lower contact of the inlier is strongly sheared.

The D2 event resulted in the development of a pervasive S2 cleavage and large- and small-scale, generally tight F2 folds in both Moine and Lewisianoid rocks. F2 fold axes plunge gently north-east in the broad hinge zone of the Morar Antiform, but on its eastern flank they plunge steeply to the south and south-west, and on its western flank they plunge gently to steeply north. The relatively open hinge of the D2 Knoydart Antiform crops out immediately east of Tarbet, where it dips very steeply to the south (Poole and Spring, 1974). An F2 hinge zone is also exposed on Sgurr Mòr near NM 832 918, where the bedding becomes nebulous, and prominent quartz rodding in low-strain psammites plunges steeply to the south-west. In this area later more-upright D3 folds refold large-scale tight F2 folds. Excellent examples of small-scale F2–F3 fold interference patterns occur in Moine rocks on the north shore of Loch Morar at NM 839 907 and in Lewisianoid gneisses at Rubh' Àird na Murrach (NM 826 938).

D2 shear-zones occur as narrow planar zones of highly attenuated rock, typically < 50 m wide. Their overall geometry and orientation suggests that they stack up the sequence towards the WNW. On Creag Mhòr Bhrinicoire at NM 745 920 lenses of indurated and partly silicified, millimetre-striped, Lewisianoid gneisses are included in and interfolded with highly sheared psammites over some 10 m in a shear zone. This Lewisianoid–Moine boundary is folded by minor, close to tight F3 folds. The underlying footwall Lower Morar Psammite Formation consists of feldspathic psammites, and thin, coarsely schistose semipelite layers with quartz-feldspar segregations and quartz veins. Immediately below the contact zone they contain a strong penetrative fabric (S2), generally sub-parallel to bedding, with related close to tight F2 folds. In parts attenuated cross-bedding structures can be seen and these become less deformed in psammites some 50 m below the contact. Both at Brinacory and farther west on Creag Mhòr Bhrinicoire at NM 743 919, where cross-bedding, load structures, channel forms and slump folds are present, the sedimentary structures show that the Moine psammites young upwards towards the Lewisianoid rocks. Hence, a D2 ductile thrust has emplaced Lewisianoid gneisses and the unconformably overlying Morar Group cover sequence towards the WNW over the Lower Morar Psammite.

A 650 m-wide zone of interleaved, sheared and tightly folded Morar Group metasediments and Lewisianoid gneisses, the Ardnamurach Thrust Zone, occurs on the south shore of Loch Nevis east of Creag Cruachain at NM 817 936. To the west are subvertical, highly strained, interbedded micaceous psammites and semipelites with quartz and quartz-feldspar veins, assigned to the Basal Pelite Formation. The beds are attenuated and boudinaged and contain tight to isoclinal folds with sheared and disrupted limbs. Within the thrust zone are highly strained feldspathic and siliceous psammites, cut by discordant thick quartz veins. At the eastern edge of the zone, by the ruins of Ardnamurach (NM 828 936) are highly sheared micaceous psammites, which have also been assigned to the Basal Pelite Formation (Powell, 1974). The rocks possess a pervasive S2 schistosity sub-parallel to bedding, and strongly boudinaged quartz pods. Tight F2 minor folds occur in low-strain zones.

A further zone of strongly attenuated platy psammite marks the boundary of the Lochailort Pelite Formation with bedding, veining and internal structures all strongly aligned parallel to the compositional layering giving the rocks a so-called 'tramline' appearance (Rathbone and Harris, 1979). This is the Sgurr Beag Thrust that here juxtaposes the Glenfinnan Group Lochailort Pelite against various units of the Morar Group succession (see also **Lochailort** and **Kinloch Hourn** GCR site reports, this chapter). The thrust and related D2 fabrics and minor structures are refolded by the F3 Glenshian Synform (Powell *et al.*, 1981) (Figure 8.15).

The D3 deformation resulted in kilometre-scale upright to W- or WNW-verging folds. Associated cleavage development is variable, dependent on lithology and metamorphic grade; it is more strongly developed in the pelitic lithologies. The general effect of D3 structures in North Morar is to steepen and locally refold the earlier D2 structures. The F3 Morar Antiform dominates the structure in the western part of North Morar. This forms a large domal or periclinal antiform whose hinge zone is subhorizontal in North Morar, but whose axial plunge steepens considerably to the north and south. In the Mallaig–Morar area, its western limb is vertical and the antiform refolds the D2 ductile thrust at the base of the Lewisianoid gneiss inliers. Tight F3 folds in the thrust zone suggest localized reactivation of thrusting during D3. Farther east in Knoydart the F2 Knoydart Antiform is refolded by the F3 Ladhar Bheinn Synform and also folded over the Meall Bhasiter dome (Powell, 1974).

South of Sgurr Breac at around NM 847 925 the steeply S-plunging F3 Glenshian Synform refolds the Sgurr Beag Thrust. Small-scale examples of F2–F3 refold patterns are common in mixed lithologies on the limbs of this structure. In the fold core the prominent S3 mica fabric varies from a crenulation cleavage to a coarse penetrative schistosity and is axial planar to open to tight F3 minor folds. An intersection lineation, L3, plunges steeply south. In the gneissose pelites and semipelites, D3 deformation, folding and cleavages attenuate and refold the already segregated and veined, foliated rocks giving rise to very complex structural patterns. D3 strain increases towards the boundary of the Lochailort Pelite showing that the Sgurr Beag Thrust was reactivated during D3. Farther east F3 folds become tighter, and metamorphic grade increases giving rise to a coarse S3 schistosity and complex medium-scale F2–F3 fold interference patterns.

Later folding is also present but generally no related cleavages are developed. Powell (1974) showed that later open folding along NNW-trending axes is common south of Loch Morar and these fold axes swing to trend WNW in

North Morar to the west of Tarbet. They are well seen on Creag Mhòr Bhrinicoire (NM 743 923) and adjacent cliffs where they locally control the dip of the bedding and the trace of the D2 shear-zone. Within the Lochailort Pelite and the Morar Pelite formations, later, open to close, kink-folds with axial planes at a high angle to S2 and S3 are seen. These structures and the more-open folds may be assigned to D4 (Powell, 1974) but as they are local in extent and variable in trend, correlation with fold sequences elsewhere is problematical.

Metamorphism

The rocks range in grade from epidote-amphibolite facies in the west to middle-amphibolite facies in the east. Concomitant with this eastward increase in grade is the incoming of abundant quartz and quartz-feldspar segregations in semipelitic and pelitic lithologies, as seen just east of Sgurr Mòr, and followed farther eastwards by the incoming of abundant large transgressive pegmatite veins. The large leucotonalite body at the eastern end of Loch Morar on An Stac and Sron a' Choin, represents the acme of this pegmatitic activity. There are two distinct stages of pegmatite generation, coeval with the D2 and D3 deformation events.

The pelitic rocks in the western part of North Morar contain abundant garnets that show evidence of two distinct phases of growth; the earlier phase pre-dating D2 deformation, and the later phase overlapping with D2 (MacQueen and Powell, 1977). Farther east staurolite, kyanite and sillimanite (fibrolite) occur progressively in the pelitic lithologies. In the extreme east, sillimanite + potash feldspar is recorded in pelitic rocks, and plagioclase compositions in calc-silicate rocks lie in the range An_{60} to An_{90}. The peak of metamorphism appears to have been synchronous with, or at least overlapped, the D2 deformation. The later D3 event was associated with a greenschist- to lower-amphibolite-grade metamorphism that again increased in grade eastwards. Work on the mineralogy of calc-silicate lenses from the Lochailort area to the south (Powell *et al.*, 1981) showed that the Sgurr Beag Thrust is coincident with a sharp break in the overall metamorphic profile, implying westward thrusting post-dating the metamorphic peak.

Interpretation

The North Morar GCR site shows a profile from low-grade, moderately deformed Moine metasedimentary rocks in the west, to higher-grade, partly gneissose, pegmatite-veined, complex thrust and folded Moine rocks in the east.

Richey and Kennedy (1939) originally interpreted the metasedimentary rocks in the core of the Morar Antiform as an older more-deformed sequence, the 'Sub-Moine Series', lying unconformably beneath the Morar Group succession. Following work by MacGregor (1948), Kennedy (1955) re-interpreted the 'Sub-Moine Series' as more-deformed relatives of the lower part of the Morar Group, namely the Basal Pelite and Lower Morar Psammite formations. Kennedy's revised interpretation postulated that the Lewisianoid gneiss inliers were thrust into the succession, and that the bulk of the overlying structural sequence lay within a Morar Nappe. The base of the nappe was drawn below the outcrop of the Lower Morar Psammite, overlying all the Basal Pelite Formation and Lewisianoid inliers in the Morar Antiform. The antiform was envisaged as a structural window into a lower, more-deformed sequence with lesser-deformed Morar Group rocks occuring higher in the structural succession. There was much discussion of Kennedy's presentation, with many geologists doubting the identification of the gneissose inliers as Lewisianoid, preferring them to be part of the Moine succession. Subsequent work has shown the concept of the Morar Nappe to be incorrect, but Ramsay's (1957b) studies on the Moine–Lewisianoid relationships at Glenelg (see Chapter 7) dispelled the doubts about Kennedy's interpretation of the Lewisianoid gneiss inliers.

Ramsay and Spring (1962) concluded that in the Glenelg–Arnisdale and Knoydart areas the Lewisianoid gneisses were disposed in isoclinal fold closures, (see **Rubha Camas na Cailinn** GCR site report, Chapter 7). Most subsequent workers followed this interpretation in North Morar (e.g. the Morar and Ardnamurach Isoclines of Powell, 1974). However, the North Morar folds cannot be convincingly substantiated in the field, and as D2 strain and deformation are notably high around several of the Lewisianoid–Moine contacts, the smaller Lewisianoid inliers are interpreted here as being underlain by D2 shear-zones. Lewisianoid gneisses also occur in synformal inliers in North Morar (Lambert and Poole, 1964), for example near Mallaigmore and immediately NNE of Creag Mhòr Bhrinicoire (NM 745 920), but these folds are D3 in the regional context.

Isotopic age data for the rocks of Morar have been critical in discussions of the structural and metamorphic history for over 20 years. The pegmatites of Knoydart (see **Knoydart Mica Mine** GCR site report, this chapter) and Loch Eilt give Rb-Sr, U-Pb and K-Ar ages in the range 680–745 Ma (Long and Lambert, 1963; Fitch *et al.*, 1969; van Breemen *et al.*, 1974). Latterly, Hyslop (1992) showed on the basis of field and geochemical studies that the pegmatites at Knoydart, Sgurr Breac and Ardnish formed under amphibolite-facies conditions essentially *in situ*, related to zones of high D2 strain. Rogers *et al.* (1998) obtained U-Pb TIMS ages of 784 ± 1 Ma and 827 ± 2 Ma from single monazites from the Sgurr Breac and Ardnish pegmatites respectively and a discordant (upper intercept) zircon age of 815 ± 30 Ma from the Sgurr Breac pegmatite. Vance *et al.* (1998) put forward evidence of an earlier metamorphic event, based on Sm-Nd ages of 813–822 Ma from garnet cores from the Morar Pelite at Polnish in western Morar. The rims on the garnet gave a Sm-Nd age of 788 ± 4 Ma. Vance *et al.* (1998) showed that the mineral compositions were compatible with a prograde P–T path that implied nappe-scale folding. Peak pressures of 12.5–14.5 kbar and temperatures of *c.* 650°–700° C were inferred from the mineralogy. Hence, the isotopic data and correlation with the metamorphic and structural history of these rocks suggest that a Neoproterozoic Knoydartian orogenic event or series of events affected the Moine succession in the period 840–750 Ma.

Conclusions

The North Morar GCR site provides a traverse from the western Moine Morar Group rocks, which show evidence of only moderate deformation and metamorphism at lowermost amphibolite facies, through Archaean-age Lewisianoid inliers to highly deformed and middle amphibolite-facies Moine rocks in the interior of the orogenic belt. Relationships between mineral growth and deformation episodes have been defined in the epidote-amphibolite-facies rocks in the west; these can then be traced eastwards to higher-grade areas where relationships are more complex. The Lewisianoid inliers represent parts of the gneissose basement to the Moine metasedimentary succession and their lower contacts with the Moine rocks are ductile thrust zones, which formed during the main D2 deformation and metamorphic event. Glenfinnan Group rocks occur in the hangingwall of the D2 Sgurr Beag Thrust in the eastern part of the site. D2 is currently thought to be Neoproterozoic in age in the Morar area.

Early-formed garnets have been isotopically dated at *c.* 820–790 Ma. Later pegmatitic granite bodies were intruded into the strongly deformed and higher metamorphic grade parts of the section at *c.* 780 Ma. Caledonian folding (F3) is responsible for the formation of the domal Morar Antiform that dominates the structure of western Morar. In the eastern part of the area, more-pervasive Caledonian folding and metamorphism, dated at around 470–455 Ma, is widely recognized. The F3 folds refold the earlier F2 structures and the D2 shear-zones, including the Sgurr Beag Thrust.

The North Morar site is of international significance as it provides a well-exposed cross-section across *c.* 20 km of the western part of the Caledonian Orogen, and contains many of the elements that can be found in the Moine rocks of north-west Scotland. It was the first area in which sedimentary structures were used to elucidate the succession in such high-grade rocks, and has formed a natural 'laboratory' for the testing of numerous ideas about the nature and timing of the Caledonian and putative Knoydartian orogenies. It remains an area of significant importance for future studies.

DRUIMINDARROCH (NM 684 838–NM 690 844)

J.R. Mendum

Introduction

The Druimindarroch GCR site provides a representative section through the psammites and subsidiary semipelites of the Lower Morar Psammite Formation. Sedimentary structures, mainly cross-bedding and convolute bedding, are locally well seen. In addition, good examples of minor fold structures are displayed. The semipelites in the north-east part of the site contain well-developed microcline feldspar porphyroblasts whose relationship to the minor structures and related cleavages was studied by Smith and Harris (1972).

The Morar District was initially mapped by J.E. Richey for the Geological Survey in the mid-1930s. Richey and Kennedy (1939) divided the rocks into two main units, the 'Moine' and 'Sub-Moine Series'. They proposed that the underlying 'Sub-Moine' rocks had experienced a more-complex structural history and higher metamorphic grades than the overlying 'Moine' rocks. The largely right-way-up 'Moine' sequence mantles the large-scale periclinal Morar Antiform (Figure 8.4). Richey and Kennedy also noted the sedimentary features in the 'Moine' rocks on the western flank of the Morar Antiform. On its eastern flank metamorphic grade is higher and locally migmatites are developed in the semipelitic and pelitic lithologies. Later work in the area has shown that the psammites and semipelites of the 'Sub-Moine Series' form the basal units of the flanking succession of 'Moine' rocks (MacGregor, 1948; Lambert, 1958; Powell, 1964). These basal pelites, semipelites and siliceous psammites, and underlying Lewisianoid gneisses were tightly interfolded and thrust westwards, prior to the formation of the Morar Antiform. Although Richey and Kennedy's Moine–Sub-Moine hypothesis is now rejected, the 'Moine' stratigraphy is still largely correct (Figure 8.3).

Powell (1974) carried out a detailed analysis of the regional structure in the Morar–Knoydart district and recognized four separate deformation phases. His terminology is used in this account.

Description

The rocky peninsula of Rubh' Aird Mhòir by Druimindarroch consists mainly of SE-dipping, flaggy to blocky, feldspathic and micaceous psammites of the Lower Morar Psammite Formation. The psammites are well exposed on a clean-washed rock platform adjacent to Loch Nan Uamh and on rocky crags immediately inland. The Druimindarroch GCR site lies immediately west of the hinge region of the large-scale Morar Antiform and hence bedding dips are low to moderate, with open folding of probable F3 age (Figure 8.17).

The psammites range from laminated to medium-bedded and are interbedded with subsidiary dark-grey, finely cleaved, semipelite units. Cross-bedding is seen locally and some of the units show grading from siliceous bases to micaceous tops. North of the stone pier, ovoid white microcline porphyroblasts up to 5 mm across are locally abundant in the semipelite units (Smith and Harris, 1972) (Figure 8.18).

A NNE-trending fault separates more-deformed siliceous psammite and semipelite on Rubh' Aird Ghamhsgail from the upper part of the Lower Morar Psammite that is exposed in the Druimindarroch area (Figure 8.17). This boundary was originally interpreted by Richey and Kennedy (1939) as the Moine–Sub-Moine boundary, but is now recognized as the tectonic junction between the highly deformed lower part of the Lower Morar Psammite and underlying Basal Pelite, and the overlying less-deformed Morar Group succession. Lewisianoid inliers occur farther north in the deformed lower sequence.

Powell (1974) recognized four separate deformation phases in the Morar–Knoydart district. Broadly, D1 folds and shear-zones duplicate the stratigraphy and the underlying Lewisianoid gneisses. The upright Morar Antiform, which dominates the overall structural pattern in this district, was assigned to D2. At Druimindarroch, D1 structures are represented by tight minor F1 folds preserved in hinge zones of F2 folds, for instance in thinly bedded psammites and semipelites at NM 690 842. A related penetrative cleavage (S1) is developed here. Both D1 and D2 structures have associated cleavages or schistosities; S1 invariably lies sub-parallel to bedding, and S2 also lies close to bedding except in F2 hinges. In the semipelitic units S2 is manifest as a pervasive crenulation cleavage, but normally forms only a weak fabric in the psammites. F2 folds are commonly tight and verge to the south-east, with S2 normally axial planar. At Druimindarroch, steeply dipping and locally inverted minor folded zones separate the predominant, gently SE-dipping, right-way-up parts of the Moine sequence. Both tight minor folds (F2) and more-upright open structures (F3) are present, with the latter structures largely responsible for the rolling nature of the bedding. F2 and F3 fold axes are generally coaxial and plunge gently to the south-west, co-linear with the locally strong quartz rodding lineation (mainly L2). East of the Morar Antiform both major and minor F3 folds occur (Powell, 1974), but only minor open to tight F3 folds occur to the

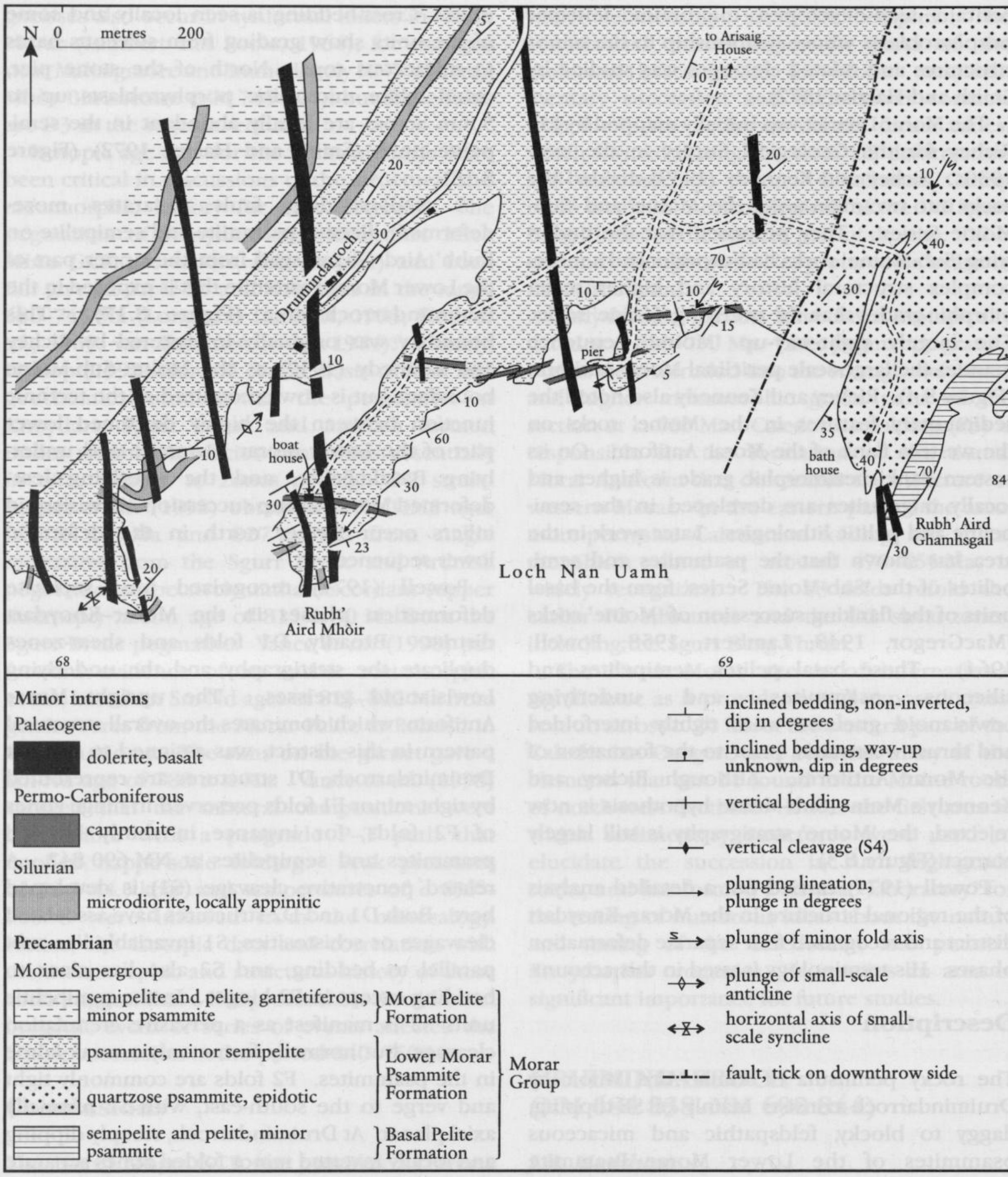


Figure 8.17 Map of Druimindarroch GCR site and surrounding area (from BGS field maps).

west. Locally they have an associated crenulation cleavage (S3). Upright F4 folds form small- and large-scale open folds, typically manifest as swings in the regional strike of the bedding and traces of the earlier axial planes. Semipelites locally show a weak SSE-trending subvertical S4 crenulation cleavage.

Smith and Harris (1972) showed that microcline porphyroblasts are generally flattened in S2 and have been partially replaced by quartz, epidote and white mica. These relict 'microcline augen' lie in a matrix of quartz, muscovite and biotite, with the micas showing a strong preferred orientation defining S2. In the field

Figure 8.18 F2 fold in psammites and semipelites of the Lower Morar Psammite Formation. The psammites are locally cross-bedded. Microcline porphyroblasts are abundant in the semipelite. North side of pier (NM 6884 8420). The compass is 18 cm long. (Photo: J.R. Mendum, British Geological Survey, reproduced with the permission of the Director, British Geological Survey, © NERC.)

the porphyroblasts occur both as flattened and aligned forms and unmodified non-aligned crystals (Figure 8.18). These latter porphyroblasts retain their initial form and consist mainly of single crystals of microcline. Smith and Harris (1972) argued that these feldspars crystallized subsequent to D2 deformation under lower amphibolite-facies conditions, and that they overgrow the S2 fabric. Some of the porphyroblasts were reported to contain a central zone of strongly orientated fine inclusions and a marginal zone of coarser inclusions, suggesting either two phases of growth or that porphyroblast growth continued after D2 deformation had ceased. The later D4 deformation has resulted in some rotation of the 'microcline augen', the generation of microfolds of the S2 mica fabric, and locally formation of a rudimentary crenulation cleavage.

Two 1 m-thick sheets of grey-green microdiorite, locally appinitic with coarse hornblende, intrude the Moine succession near the south-west end of the peninsula. These intrusions belong to the Silurian-age, late Caledonian Microdiorite Sub-suite and have been metamorphosed, here under greenschist-facies conditions. In a small bay (NM 687 842) west of the pier, a camptonite dyke cuts an additional thin microdiorite sheet. Several camptonite dykes are present on the peninsula. They range from 0.5 m to 3.5 m thick and form part of the regional, E–W-trending, Permo–Carboniferous alkali-basalt camptonite-monchiquite swarm. They are cut in turn by several brown-weathering Palaeocene basalt dykes of the Skye swarm that form very marked features on the coastal section. These dykes range up to 13 m thick and in this area consistently trend 350° (Figure 8.17).

Interpretation

The Druimindarroch site lies immediately west of the hinge region of the regional Morar Antiform. The psammitic Moine sequence is locally tightly folded here, but overall the beds dip gently to moderately to the south-east. The psammites, which form the upper part of the

Lower Morar Psammite Formation, show sedimentary features indicative of their shallow-water origin.

The microcline porphyroblasts found in some of the semipelite units formed both before the development of the main S2 cleavage, and after D2 deformation but prior to the D3 deformation (Smith and Harris, 1972).

Conclusions

The Druimindarroch area contains a well-exposed rocky coastal section that shows the Neoproterozoic Moine psammites of the Lower Morar Psammite Formation, a prominent unit in the lower part of the Morar Group. These are mainly psammites but include subsidiary semipelites. At the site sedimentary grading and cross-bedding are still readily recognizable, yet the rocks show two main phases of open to tight minor folding and related cleavages. In the semipelites metamorphic porphyroblasts of microcline feldspar are present in places. These Moine rocks lie just to the west of the complex hinge zone of the Morar Antiform, a regional structure that controls the outcrop pattern in the Morar district. On the peninsula Silurian microdiorite sheets, Permo–Carboniferous camptonite dykes, and Palaeogene basalt and dolerite dykes intrude the Moine metasedimentary rocks. The Druimindarroch site remains an excellent area to study the effects of the various deformation phases that are present in this part of the Moine succession and their relationship to the lower amphibolite-facies metamorphism.

FASSFERN TO LOCHAILORT ROAD CUTTINGS (A830) (NN 047 784–NM 769 827)

R.A. Strachan

Introduction

The road cuttings between Fassfern and Lochailort on the Fort William to Mallaig road (A830) provide a comprehensive profile across the Neoproterozoic Moine Supergroup, its associated meta-igneous and igneous intrusions, and the Caledonian and earlier structures that typify this part of the orogenic belt. The 27 km-long section includes numerous localities that in their own right would merit GCR status; when put together as a coherent traverse they provide the definitive section across the Moine Supergroup (Figure 8.19). In the east, psammites and quartzites of the Loch Eil Group pass transitionally westwards into underlying pelitic and psammitic gneisses of the Glenfinnan Group (Dalziel, 1966; Brown *et al.*, 1970; Baird, 1982; Strachan, 1985; Powell *et al.*, 1988; Strachan *et al.*, 1988). Lithological layering in the Loch Eil Group is typically subhorizontal to gently inclined (the 'Flat Belt') in contrast to the Glenfinnan Group where it is typically steeply inclined to subvertical (the 'Steep Belt'). The junction between these two domains was initially termed the 'Loch Quoich Line' by Clifford (1957) (here abbreviated to the 'Quoich Line'). The structural contrast between the domains results from the varying intensity of upright folding during the Caledonian Orogeny (Roberts and Harris, 1983). A suite of deformed and metamorphosed granites, known collectively as the 'West Highland Granite Gneiss' (Johnstone, 1975), occurs approximately along the Glenfinnan Group–Loch Eil Group boundary. A cross-section through the southernmost member of the suite, the Ardgour Granite Gneiss, is exposed east of Glenfinnan. Recent U-Pb isotopic dating of zircons from the gneiss indicates that granite sheets were emplaced at *c.* 873 Ma (Friend *et al.*, 1997; Rogers *et al.*, 2001) (see 'Introduction', this chapter). The abundant segregation pegmatite veining in the granite gneiss possibly also formed at this time under middle amphibolite-facies metamorphic conditions. In the vicinity of Loch Eilt and Lochailort, the Glenfinnan Group is tightly interfolded with psammites and semipelites of the underlying Morar Group. The junction between the two groups was for many years interpreted as a stratigraphical boundary (Powell, 1964, 1966), but is now generally thought to be a major ductile shear-zone, the Sgurr Beag Thrust (Powell *et al.*, 1981). Morar Group rocks at Loch Eilt are intruded by pegmatites (Figure 8.20), which have yielded isotopic ages of *c.* 740 Ma (van Breemen *et al.*, 1974). In addition, U-Pb isotopic dating of titanite from calc-silicate rocks by Loch Eilt implies that the main metamorphic event occurred at *c.* 735 Ma (Tanner and Evans, 2003). All three Moine groups were intruded by a variety of mafic and felsic igneous rocks during the Ordovician–Silurian Caledonian Orogeny (van Breemen *et al.*, 1974; Fettes and MacDonald, 1978; Smith, 1979; Talbot, 1983). They are also cross-cut by Permian–Carboniferous camptonite dykes and by Palaeogene dolerites and basalt dykes of the Skye swarm.

Description

The east to west traverse from Fassfern to Lochailort follows the A830 and includes road cuts and outcrops on the adjacent rocky hills (Figure 8.2). It crosses the Loch Eil, Glenfinnan and Morar groups of the Moine Supergroup (Figure 8.19) and it was in this region that this basic division of the Moine rocks was first defined (Johnstone *et al.*, 1969).

The easternmost road cuttings around Fassfern and west to Kinlocheil are dominated by generally subhorizontal to gently inclined psammites and quartzites of the Loch Eil Group (Strachan, 1985). Within the psammites, micaceous laminae locally define cross-lamination that indicates that the rocks are normally right-way-up and young eastwards. The psammites commonly contain abundant small lenses of calc-silicate rock, which formed during diagenesis. The grade of metamorphism is difficult to establish because of the lack of metamorphic indicator minerals such as staurolite, kyanite and sillimanite and the widespread retrogression of the rocks. The co-existence of hornblende and garnet within the calc-silicates is broadly indicative of at least lower amphibolite-facies metamorphism. The Loch Eil Group rocks are deformed by metre-scale, recumbent, tight to isoclinal folds. Good examples are exposed in road cuts at NN 043 785, 2 km east of Fassfern. Here, a weak axial-planar fabric is developed in micaceous layers in the fold hinges and a poorly developed mineral and extension lineation parallel to the N–S-trending fold hinge lines is locally discernable. The axial-planar fabric can be seen in places to be a crenulation of a pre-existing mica schistosity, S1, that is attributed to the first episode of deformation (D1), with the recumbent folds related to the second deformation (D2). Late upright, open to gentle folds with N–S-trending axes constitute evidence for a third (D3) period of deformation.

The road cuttings between the west end of Loch Eil and the east end of Loch Eilt (Figure 8.19) mainly expose metasedimentary rocks of the Glenfinnan Group. Unlike the Loch Eil Group they contain a high proportion of semi-pelites and pelites that are thinly interlayered with psammites and quartzites. Although metamorphic index minerals are not abundant, pelitic rocks locally contain sillimanite, kyanite and staurolite and in many places develop migmatitic quartz-feldspar segregations. These segregations formed *in situ*, possibly as a result of partial melting under middle- to upper-amphibolite-facies conditions. Sedimentary structures are generally absent in this section, in part due to widespread recrystallization and high tectonic strain of the dominantly pelitic lithologies.

The easternmost outcrops of the Glenfinnan Group immediately west of Loch Eil display a well-developed gneissic S1 foliation, which dips gently eastwards and is deformed by recumbent, tight to isoclinal F2 folds. Westwards from Glenfinnan, the gneissosity is steep and commonly subvertical, typical of the 'Steep Belt'. The rocks are highly strained and display evidence of a more-complex structural history. The S1 foliation and F2 folds are deformed by at least one and possibly two subsequent phases of upright, close to isoclinal, NNE-trending folds (D3–D4; Baird, 1982; Powell *et al.*, 1988). These have curved hinges that plunge gently to steeply to the NNE and SSW. A strong lineation defined by quartz, feldspar and mica plunges very steeply down-dip. An inlier of Loch Eil Group psammites located within the 'Steep Belt' south of Glenfinnan (Figure 8.19) occupies the core of a kilometre-scale composite F3/F4 synform (Dalziel, 1966). The characteristic fold structures of the 'Steep Belt' are spectacularly well exposed on flat glaciated surfaces located above the road cuttings at The Muidhe (NM 857 815) (see Figure 8.2). Open to tight, F3 and F4 asymmetrical minor folds, whose axes mainly plunge to the north-east, dominate the outcrops. The folds are accompanied by tight crenulations that refold the migmatitic fabric in the pelitic and semipelitic horizons. There are numerous examples of coaxial, type-3 fold interference patterns (*sensu* Ramsay, 1967) where F3/F4 structures refold earlier F1 or F2 minor isoclinal folds.

Between the eastern end of Loch Eilt and Lochailort, two complementary regional large-scale F3 folds, the Loch Eilt Antiform and the Glenshian Synform, infold Morar Group and Glenfinnan Group rocks and fold the bounding Sgurr Beag Thrust (Powell *et al.*, 1981; Tanner and Evans, 2003) (Figure 8.19, and see Figure 8.21, **Lochailort** GCR site report, this chapter). The Morar Group rocks here consist mainly of

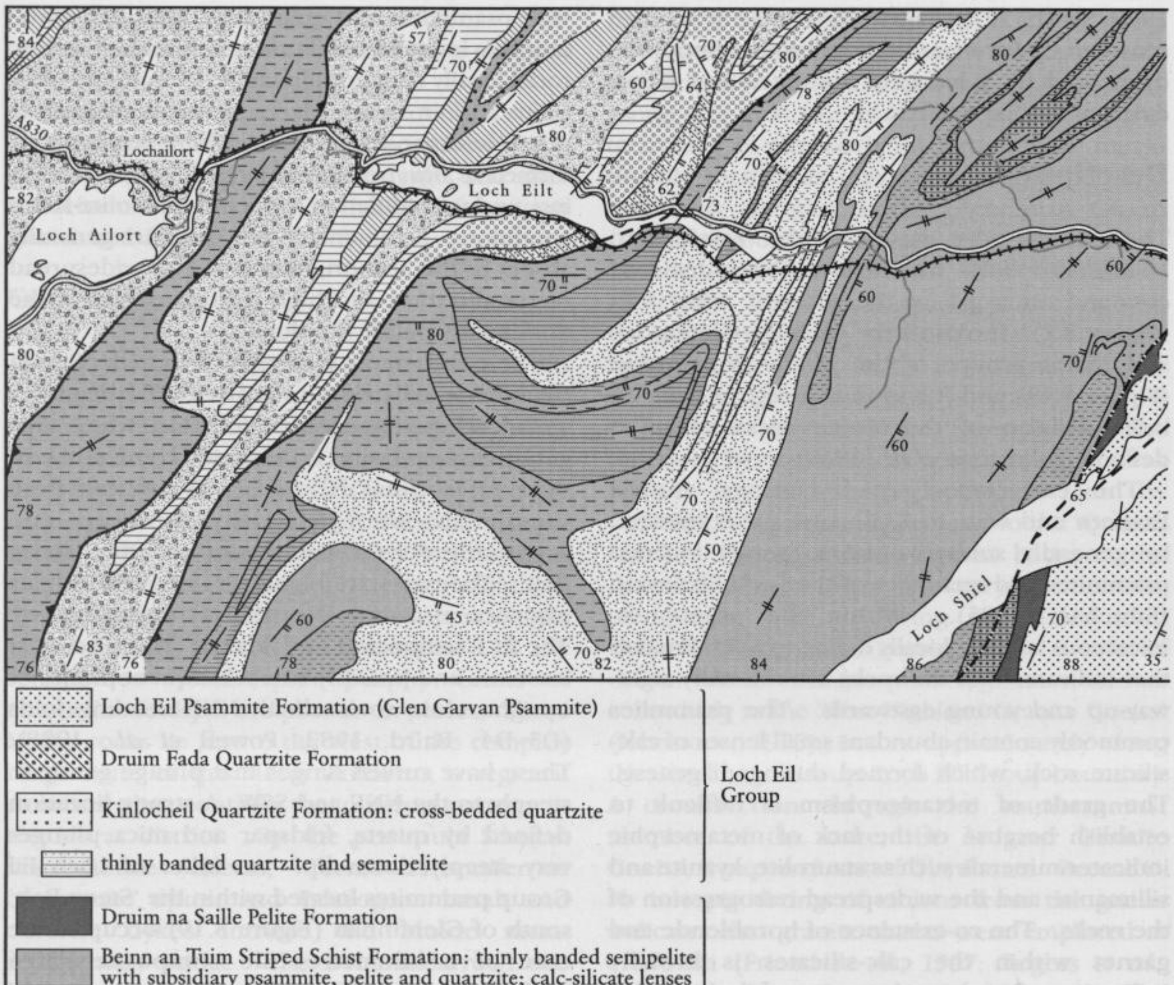
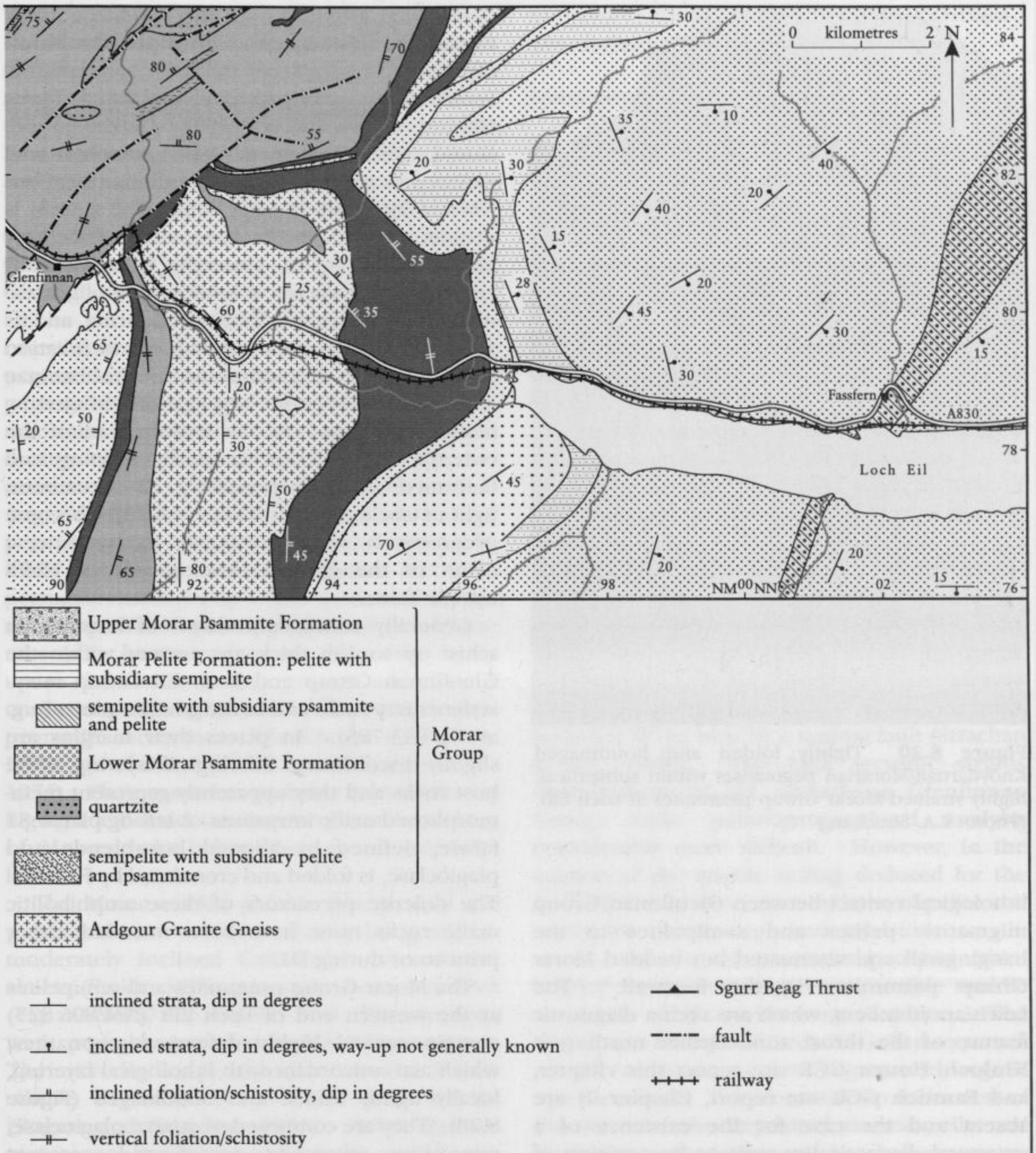


Figure 8.19 Geology of the Fassfern to Lochailort region.

interlayered psammites and micaceous psammites with thin semipelite layers and calc-silicate ribs and lenses. Sedimentary structures are generally absent. These rocks record all the deformation events apparent in the Glenfinnan Group. The presence of garnet and locally staurolite and sillimanite in pelitic rocks and both hornblende and pyroxene with bytownite/anorthite in calc-silicate rocks imply that metamorphic grade lies within the middle-amphibolite facies. However, mineralogical and textural features indicate that the Morar Group rocks have been metamorphosed at a slightly lower metamorphic grade than those of the overlying Glenfinnan Group



(Barr *et al.*, 1986). Comparison of calc-silicate rocks from the two groups shows that those from the Glenfinnan Group have generally higher anorthite contents of plagioclase, and migmatitic textures are generally absent within Morar Group pelites (Powell *et al.*, 1981; Tanner and Evans, 2003).

The contact between the Morar and Glenfinnan groups has been interpreted as a regional-scale tectonic boundary, the Sgurr Beag Thrust (see **Lochailort** GCR site report, this chapter). The thrust is not exposed in the road cuttings, but on the hillsides near Lochailort, and above Loch Eilt it is seen as a sharp, concordant

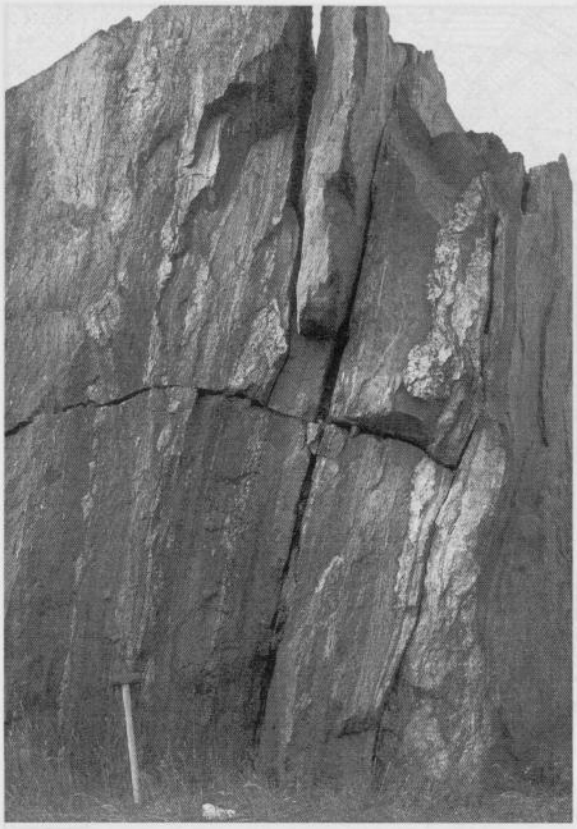


Figure 8.20 Tightly folded and boudinaged Knoydartian/Morarian pegmatites within subvertical, highly strained Morar Group psammites at Loch Eilt. (Photo: R.A. Strachan.)

lithological contact between Glenfinnan Group migmatitic pelites and semipelites in the hangingwall and attenuated but bedded Morar Group psammites in the footwall. The Lewisianoid inliers, which are such a diagnostic feature of the thrust zone farther north (see **Kinloch Hourn** GCR site report this chapter, and **Fannich** GCR site report, Chapter 7) are absent and the case for the existence of a structural discontinuity rests on recognition of the difference in metamorphic grade between the Morar and Glenfinnan groups, and on the identification of high strains typical of major ductile shear-zones. Rathbone and Harris (1979) demonstrated a progressive increase in ductile strain in the Upper Morar Psammite near Lochailort as the thrust is approached from the west, and these features are described in the **Lochailort** GCR site report (this chapter). The present steep orientation of the ductile thrust is a result of subsequent upright, tight Caledonian F3 folding (Powell *et al.*, 1981).

All three Moine groups incorporate a range of mafic to felsic igneous intrusions, the oldest of which were emplaced in the Neoproterozoic. Pre-eminent amongst these is the Ardgour Granite Gneiss (Harry, 1954; Dalziel, 1966; Gould, 1966; Barr *et al.*, 1985), which is well exposed in cuttings east of Glenfinnan between NM 941 797 and NM 914 803. The gneiss is distinguished from its host metasedimentary Moine rocks by its generally homogeneous appearance, its quartz + K-feldspar + oligoclase mineralogy with lesser biotite and garnet, and its granitic geochemistry. A strong coarse foliation is defined by discontinuous biotite laminae and quartzofeldspathic segregations fringed by biotite selvedges. In the eastern part of the outcrop, the foliation is gently dipping and deformed and transposed by F2 recumbent, tight to isoclinal folds. These structures become progressively steeper towards the west as a result of the gradual development of F3/F4 upright folds.

Generally concordant sheets of hornblende schist up to 1 m thick are present within the Glenfinnan Group and Loch Eil Group metasedimentary rocks and in the granitic gneiss (e.g. at NN 043 785). In places their margins are slightly discordant to lithological layering in the host rocks and they apparently represent metamorphosed mafic intrusions. A strong planar S1 fabric, defined by aligned hornblende and plagioclase, is folded and crenulated by F2 folds. The dolerite precursors of these amphibolitic mafic rocks must have been intruded either prior to or during D1.

The Morar Group psammites and semipelites at the western end of Loch Eilt (NM 806 827) contain several highly deformed pegmatites, which are concordant with lithological layering, locally tightly folded and boudinaged (Figure 8.20). They are composed of quartz, plagioclase, microcline, muscovite, garnet, and accessory apatite. Available evidence suggests that the pegmatites did not form *in situ*: they lack biotite selvedges and contain microcline and apatite, which are absent from the migmatitic segregations of the adjacent semipelites. The pegmatites were probably intruded into their Moine host rocks from deeper crustal levels. Muscovite books from one of the pegmatites have yielded a Rb-Sr age of 730 ± 20 Ma (van Breemen *et al.*, 1974), which is within error of a discordant upper intercept U-Pb zircon age of 740 ± 30 Ma that is assumed to date crystallization (van

Breemen *et al.*, 1978). The Neoproterozoic Knoydartian age of the pegmatites is clear but it is difficult to establish the timing of intrusion relative to early deformation phases (D1, D2) as the pegmatites and Moine metasedimentary rocks have undergone high Caledonian tectonic strains and been subject to Caledonian metamorphism.

Most other igneous intrusive bodies were emplaced during the later stages of the Caledonian Orogeny. The Morar and Glenfinnan groups and the Ardgour Granite Gneiss are intruded by a suite of distinctive coarse-grained, discordant and steeply dipping pegmatitic granite veins and lenses. These pegmatites display evidence for variable amounts of foliation development, formed during regional upright D3/D4 folding and associated with the formation of the 'Steep Belt' (e.g. NM 857 815; NM 806 827). Individual pegmatite veins are pink to white, typically 1–4 m thick, but locally they are abundant and form pegmatite-rich zones up to 300–400 m wide. They are composed of quartz, plagioclase, K-feldspar, muscovite, biotite and garnet. Muscovite books up to 4–5 cm across are present and show a crude subvertical alignment. Muscovite from a pegmatite body near Glenfinnan yielded an Rb-Sr age of 450 ± 10 Ma (van Breemen *et al.*, 1974). The pegmatites probably formed during high-grade Caledonian metamorphism by melting of Moine rocks below the present exposure level.

The Moine rocks, granitic gneiss, and the pegmatites are cut discordantly by gently to moderately inclined Caledonian microdiorite sheets (Smith, 1979) generally about 1 m thick (e.g. at NM 857 815, NM 925 794). The intrusions were probably intruded in Mid-Silurian times. The microdiorites pre-date the Strontian Pluton whose emplacement is dated at *c.* 425 Ma (Rogers and Dunning, 1991). Relict igneous textures are locally preserved in the central parts of the microdiorite intrusions, but in most cases they show mineralogies characteristic of the upper-greenschist- or epidote-amphibolite-facies. Although the margins of the intrusions are commonly strongly foliated, they appear to have been intruded after the regional upright D3/D4 folding associated with formation of the 'Steep Belt' (but see Talbot, 1983), but prior to uplift and exhumation of the orogen. At the western end of Loch Eil, numerous discordant sheets of undeformed granite, aplite and pegmatite form part of the late Caledonian Loch Eil Granite Vein-Complex (Table 7.1, Chapter 7; see 'Introduction', this chapter, and Figure 8.5).

Interpretation

The significance of the Fassfern to Lochailort road section lies in the excellent and near-continuous roadside exposure of the three constituent groups of the Moine Supergroup effectively in their type areas. Despite the generally high levels of tectonic strain and the amphibolite-facies metamorphism, it is still possible to make reasoned inferences concerning their environment of deposition and to speculate on the likely geometry of the Moine basins (e.g. see Soper *et al.*, 1998). The relatively competent psammites of the Loch Eil Group preserve numerous sedimentary structures; some of these, such as 'herring-bone' cross-bedding, are certainly consistent with deposition in a shallow-marine, tidal setting (Strachan, 1986). Palaeocurrent directions trend NNE–SSW, probably parallel to their contemporary coastline. The westward thickening of the sequence is consistent with deposition in an extensional basin that was bounded to the west by a normal fault (Strachan *et al.*, 1988). The high tectonic strains characteristic of the underlying Glenfinnan Group make palaeogeographical analysis considerably more difficult. However, in the context of the marine setting deduced for the Loch Eil Group, the extensive belts of pelite and semipelite (metamorphosed mudstone or siltstone) and striped psammite-quartzite (thin-bedded sandstone) suggest a possible middle to outer shelf marine environment. The Glenfinnan Group and Loch Eil Group sequence overall constitute a coarsening-upward, regressive succession. The Morar Group rocks west of the site were also deposited as sands, silts and muds in a fluviatile and/or shallow-marine extensional basin (Glendinning, 1988; Bonsor and Prave, 2008). However, the relationship of this Morar Group basin to the Glenfinnan–Loch Eil basin is uncertain given the subsequent displacements on the Sgurr Beag Thrust. Farther north both Morar Group and Glenfinnan Group rocks were apparently deposited upon Lewisianoid basement, and hence it is possible that the Glenfinnan Group is a distal equivalent of the Morar Group.

The granitic gneiss was formerly thought to have formed *in situ* as a result of melting of

Moine metasediments (Harry, 1954; Dalziel, 1966), but the current consensus is that it represents a syn-tectonic granite which was intruded during D1 accompanied by high-grade metamorphism (Barr *et al.*, 1985; see also **Quoich Spillway** GCR site report, this chapter). An Rb-Sr whole-rock isochron of 1028 ± 43 Ma obtained from the granitic gneiss by Brook *et al.* (1976) was interpreted to date formation of the gneiss during high-grade metamorphism. However, more-recent U-Pb SHRIMP and TIMS dating of zircons from the granitic gneiss and its migmatitic segregations indicates a younger age of 873 ± 7 Ma (Friend *et al.*, 1997); this is considered a more-reliable estimate of the granite emplacement and metamorphism. The *c.* 740 Ma pegmatite within the Morar Group at Loch Eilt is one of a suite of 'Morarian' pegmatites that has yielded U-Pb isotopic ages of *c.* 780–740 Ma in the region (van Breemen *et al.*, 1974, 1978). Detailed studies of several of these pegmatites suggest that they formed as a result of segregation during deformation and amphibolite-facies metamorphism (Hyslop, 1992), although for the Loch Eilt pegmatite it is difficult to see back through the superimposed pervasive high Caledonian strain. The significance of these Neoproterozoic events is still the subject of discussion (see Strachan *et al.*, 2002a; Tanner and Evans, 2003). Isotopic ages of between *c.* 1000 Ma and 750 Ma that have been obtained from the Moine Supergroup have traditionally been attributed to orogenesis (e.g. Bowes, 1968; Lambert, 1969; Powell, 1974; Brook *et al.*, 1976, 1977; Piasecki and van Breemen, 1979a; Powell *et al.*, 1981, 1983; Barr *et al.*, 1986; Harris and Johnson, 1991). An alternative model has been proposed by Soper (1994) and Ryan and Soper (2001) who speculated that high heat flow during continental rifting – perhaps enhanced by emplacement of the igneous protoliths of the widespread amphibolitic metabasic sheets and dykes – may account for melting and formation of granitic gneisses and pegmatites at mid-crustal levels, contemporaneous with sedimentation at the surface. Distinction between these two models on structural criteria alone is not possible. Ductile extension at depth could produce flat-lying foliations and folds (perhaps equivalent to the D1 structures in the Glenfinnan and Loch Eil groups), which could not be distinguished from similarly orientated compressional structures. Critical to this discussion is the pressure (i.e. crustal depth) at which the high-temperature metamorphism occurred. Metamorphic and isotope studies of Zeh and Millar (2001) and Tanner and Evans (2003) suggest that the Knoydartian tectonothermal event occurred under relatively high pressures, implying contractional orogenesis, rather than at low pressures, which would favour an extensional origin.

The Sgurr Beag Thrust was identified initially as a syn-metamorphic discontinuity (ductile shear-zone) within the Moine rocks and Lewisianoid gneiss basement inliers of the Kinloch Hourn area (Tanner, 1971; see also **Kinloch Hourn** GCR site report, this chapter). It was termed the 'Sgurr Beag Slide' because at that time its geometric significance was uncertain and it appeared to place younger rocks over older rocks. However, later work demonstrated that it is best interpreted as a ductile thrust that emplaced high-grade Glenfinnan Group rocks (with locally underlying Lewisianoid basement) westwards onto lower-grade Morar Group rocks (Rathbone and Harris, 1979; Powell *et al.*, 1981; Rathbone *et al.*, 1983).

The age of the Sgurr Beag Thrust and its full history remain unclear. In northern Ross-shire, the Carn Chuinneag Granite Complex, whose intrusion is dated at *c.* 610–560 Ma (Strachan *et al.*, 2002a), contains a fabric assigned to D2 that appears also to be associated with displacement along the Sgurr Beag Thrust, suggesting the thrust is Caledonian in age (Wilson and Shepherd, 1979). The Sgurr Beag Thrust has thus been interpreted as a W-directed ductile thrust, which formed at an early stage (Early Ordovician?) of the Caledonian Orogeny (Powell *et al.*, 1981; Barr *et al.*, 1986). However, U-Pb TIMS titanite ages of 737 ± 5 Ma from 'syn-D2' amphibolite-facies assemblages near Lochailort imply that the Sgurr Beag Thrust is mainly a Knoydartian structure (Tanner and Evans, 2003).

The Glendessarry Syenite, which outcrops *c.* 10 km north of Glenfinnan, is dated by the U-Pb bulk zircon method at 456 ± 5 Ma (van Breemen *et al.*, 1979b). The syenite is deformed by F3 upright 'Steep Belt' folds (Roberts *et al.*, 1984), and thus the regional upright F3 and F4 folding of the Sgurr Beag Thrust must have occurred between *c.* 456 Ma and *c.* 440 Ma (the youngest ages obtained from the late pegmatite suite). Some models portray the deformation as generally propagating westwards, ultimately resulting in the formation of the Moine Thrust during the Early Silurian (Barr *et al.*, 1986). Crustal thickening was accompanied by amphibolite-facies metamorphism and melting of Moine metasediments at a slightly deeper structural level, resulting in formation of pegmatites. This was followed by the emplacement of the regional Microdiorite Sub-suite which partly overlapped intrusion of the Silurian-age Caledonian 'Newer Granite' suite (Smith, 1979).

Conclusions

The Fassfern to Lochailort road cuttings are of national importance because they provide the most easily accessible and informative section across the Loch Eil, Glenfinnan and Morar groups of the Moine Supergroup. They include critical localities that have yielded invaluable isotopic data constraining the tectono-metamorphic evolution of the Moine Supergroup, notably specimens of the Ardgour Granite Gneiss and members of the 'Morarian/Knoydartian' pegmatite suite. These intrusive elements confirm that significant Neoproterozoic tectonothermal events occurred in the Moine succession between *c.* 870 Ma and *c.* 740 Ma. At Glenfinnan it seems that the *c.* 870 Ma age was associated with granite emplacement, deformation (D1 fabrics), metamorphism and migmatization. The tectonic setting of the events, in particular whether they represent orogenic activity or are the result of extension during sedimentary basin development, remains the subject of discussion. The D2 Sgurr Beag Thrust emplaced the Glenfinnan Group and the Loch Eil Group westwards onto the Morar Group. The age of the main movements on the thrust remains unclear; some evidence suggests it was mainly active during the Knoydartian at *c.* 740 Ma, whereas other evidence suggests it is a mainly Caledonian structure. Thrusting was followed by widespread upright, tight D3–D4 folding and formation of the 'Steep Belt' between *c.* 456 Ma and *c.* 440 Ma. Amphibolite-facies metamorphism and the generation of pegmatites accompanied this deformation. The rocks were subsequently intruded at a late stage in the Caledonian Orogeny (Mid-Silurian) by the regional Microdiorite Sub-suite and granite vein-complexes.

LOCHAILORT (NM 770 820)

E.K. Hyslop

Introduction

One of the most accessible and informative sections across the Sgurr Beag Thrust is exposed at Lochailort, about 35 km west of Fort William. The Sgurr Beag Thrust forms the boundary between the Morar Group and the Glenfinnan Group and is the most significant tectonic dislocation within the Moine succession. The thrust is a southerly continuation of the structure first recognized at Kinloch Hourn, approximately 30 km to the NNE (see **Kinloch Hourn** GCR site report, this chapter); near Lochailort, it is folded by a major synform–antiform pair (Figure 8.21). Good exposure allows examination of the contrasting nature of the two sequences on either side of the thrust, and the development of characteristic platy fabrics along the junction and in its footwall, which illustrate its tectonic nature. This boundary is of fundamental importance in understanding the orogenic history of the Moine and the early geological history of the Scottish Highlands. The geology of the Lochailort area has been described in detail in the regional studies of Powell (1964, 1966, 1974), Powell *et al.* (1981) and Baird (1982). The Lochailort GCR site is complementary to the **Fassfern to Lochailort Road Cuttings** GCR site that describes the structural and stratigraphical succession immediately to the east.

Description

The Sgurr Beag Thrust (here locally termed the 'Lochailort Thrust') is exposed in a prominent NNE–SSW-trending elongate glaciated hillock, approximately 300 m in length, called 'Tom na Faing', on the floor of the small valley of Glenshian at the head of Loch Ailort (Figure 8.22a). Tom na Faing is a roche moutonnée, with ice-smoothed striated surfaces on its gentle northern side and a steep, ice-plucked SSW side, indicating a down-valley south-westerly direction of ice movement.

The hillock is composed dominantly of gneissose pelite, part of the Lochailort Pelite Formation, which is the lowermost unit of the

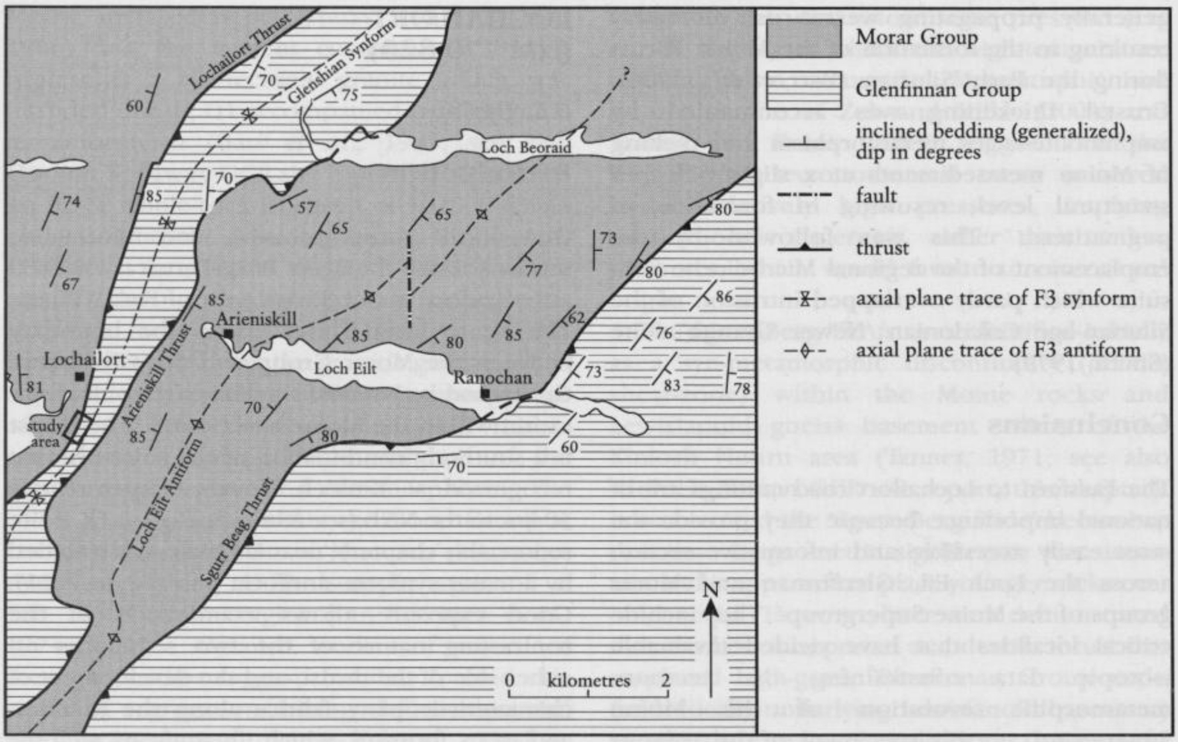


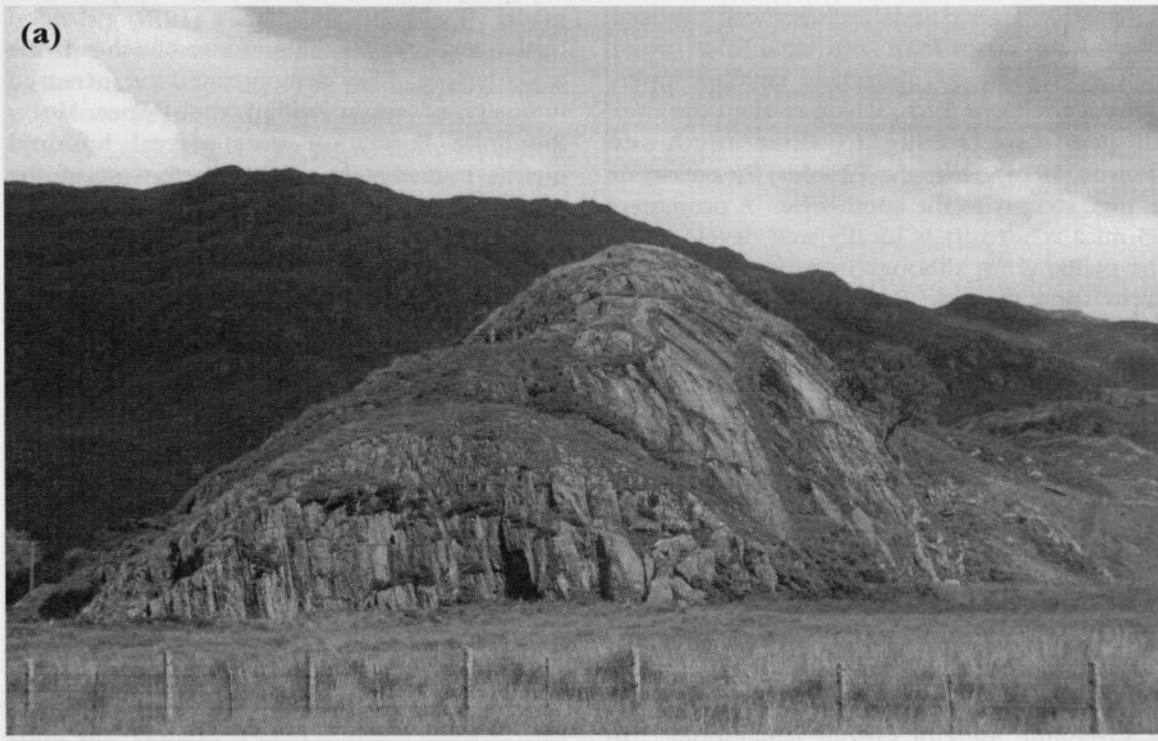
Figure 8.21 Map of Lochailort–Loch Eilt area showing the regional structure. Note that the Lochailort, Arieniskill and Sgurr Beag thrusts are one and the same dislocation. After Baird (1982).

Glenfinnan Group succession (Figure 8.3; Johnstone *et al.*, 1969; Holdsworth *et al.*, 1994). Here it is a very coarsely foliated and migmatitic pelite and semipelite, with abundant garnet. Subordinate psammitic interbeds are present, and both the foliation and lithological layering trend NNE. The gneissose pelite and semipelite contain abundant concordant lenticular quartz and quartz-feldspar veins, typically a few centimetres thick and up to 40 cm long. Larger concordant pegmatitic veins, composed of quartz-plagioclase-muscovite with garnet-rich margins and biotite selvedges, and rare large east–west cross-cutting quartz veins are also present.

Rocks of the Morar Group are exposed on the south-west flank of Tom na Faing. Strongly attenuated, planar psammite units of the Upper Morar Psammite, several tens of centimetres thick are folded into F3 folds with steep SW-plunging axes. The contact between the Glenfinnan Group gneissose pelitic rocks to the east and the Morar Group psammites to the west is exposed along the south-western side of Tom na Faing, and is particularly clear at the southern end of the hillock (Figure 8.22b). Here, the pelitic rocks change their character over several metres, with the coarse-grained leucosomes becoming attenuated and reduced to the texture of a medium-grained streaky gneissose pelite. On the west side of the boundary, the layered psammites are highly strained, with attenuated siliceous units producing a distinctive 'tram-lined' appearance over several metres. At the boundary, individual psammite units have a thickness of only a few centimetres. Despite the clear macroscopic evidence for high strain, there is little obvious grain-size reduction or mylonitization, and the pelitic lithologies retain their gneissose texture.

Close to the contact, both lithologies contain tight to isoclinal minor F2 folds whose axes plunge steeply to the south-west and whose axial planes trend sub-parallel to bedding, and to the Sgurr Beag Thrust. The F2 structures fold the gneissose foliation, psammitic ribs, and the quartz-feldspar segregations. In the pelitic units the F2 folds have an intense axial-planar fabric that is a result of recrystallization to a finer grain-size and boudinage and flattening of the quartz and quartz-feldspar pegmatite veins and pods.

On Tom na Faing F3 folds of the S1/S2 foliation, the bedding, and the quartzo-



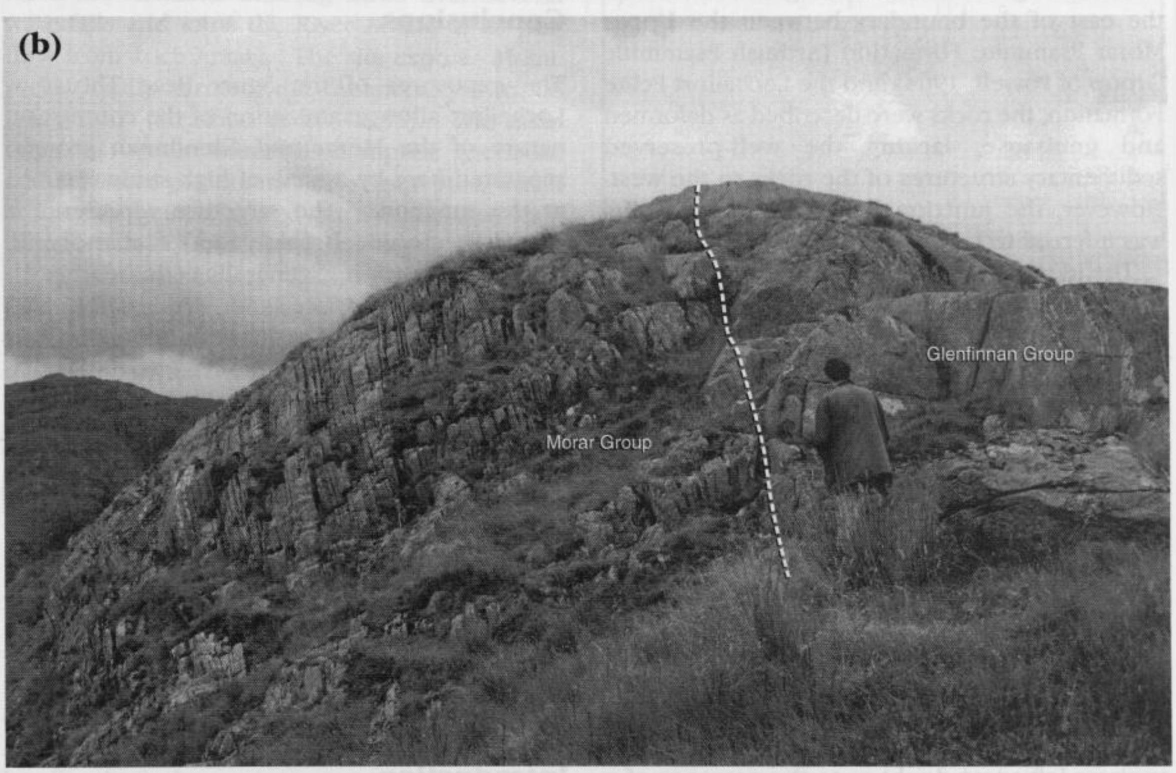


Figure 8.22 (a) General view of the Sgurr Beag Slide at Tom na Faing looking towards the north-east. The low flaggy rocks on the left are the layered psammites of the Morar Group to the west, whilst the higher more-massive ground on the right are the pelitic gneisses of the Glenfinnan Group to the east. (b) Closer view of the Sgurr Beag Slide, again with flaggy banded psammites of the Morar Group to the west, and pelitic gneisses of the Glenfinnan Group to the east. The figure is standing immediately to the right of the contact. (Photos: E.K. Hyslop.)

feldspathic segregations are also well exposed. The folding varies from large tight folds several metres across, to abundant smaller, open, neutrally vergent folds, which re-align the overall gneissose layering to strike north-west (Powell, 1974). Like the F2 folds, F3 axes again plunge steeply to the south-west. A prominent S3 mica schistosity is locally well developed in the pelitic units, although in parts only a strong crenulation cleavage is seen. Persistent, thin, NE-trending quartz-feldspar veins are commonly developed, axial planar to the F3 folds, a feature characteristic of F3 folding elsewhere. The larger-scale Glenshian Synform and Loch Eilt Antiform that refold the Sgurr Beag Thrust on a regional scale are F3 structures.

Interpretation

The stratigraphy and structure of the Lochailort area was originally described by Powell (1964, 1966) as a continuous stratigraphical sequence from west to east, repeated by a series of roughly N–S-trending folds of various generations. To the east of the boundary between the Upper Morar Psammite Formation (Ardnish Psammitic Group of Powell, 1964) and the Lochailort Pelite Formation, the rocks were described as deformed and gneissose, lacking the well-preserved sedimentary structures of the rocks to the west. However, the junction between the two units was inferred to be a sedimentary transition.

The identification of the Sgurr Beag Thrust to the north (see **Kinloch Hourn** GCR site report, this chapter, and Tanner, 1971) as a major tectonic discontinuity separating lower-grade Morar Group rocks to the west from higher-grade Glenfinnan Group rocks the to the east, was followed by its extrapolation southwards to Loch Eilt and Lochailort. Powell (1974) then recognized that the western outcrop of the Lochailort Pelite occurred as an F3 infold (the Glenshian Synform) of Glenfinnan Group rocks bounded on either side by the Sgurr Beag Thrust. The underlying Upper Morar Psammite Formation and succession to the west were assigned to the Morar Group.

The absence of tectonic slices of Lewisianoid gneisses left some doubt as to the presence of a major discontinuity at this junction. However, Powell *et al.* (1981) documented the metamorphic assemblages across this boundary, notably those in calc-silicate rocks, and showed that it juxtaposes rocks of differing metamorphic grade. Rathbone and Harris (1979) provided further evidence for the presence of a shear zone at Lochailort. They demonstrated the increased intensity of strain within the Upper Morar Psammite Formation over several hundred metres immediately to the north-west of the thrust. The strain is extremely high close to the boundary. The lack of grain-size reduction or mylonitization in the shear zone suggests that the Sgurr Beag Thrust was active at sufficiently high temperatures and pressures to enable ductile deformation and recrystallization and recovery processes to occur, probably contemporaneous with regional amphibolite-facies metamorphism. The lack of high-strain microfabrics in the Sgurr Beag Thrust has also been noted at Kinloch Hourn (Tanner, 1971).

The age of the Sgurr Beag Thrust and associated D2 structures is still controversial, but it appears that the thrust was active during the Knoydartian and reactivated later in the Caledonian Orogeny (Tanner and Evans, 2003; see also 'Introduction', this chapter).

Conclusions

The exposures of the Sgurr Beag Thrust at Lochailort allow examination of the contrasting nature of the Morar and Glenfinnan groups, separated here by a zone of high strain focused at the junction. The structure represents a major tectonic break and metamorphic discontinuity, yet it is generally concordant with the regional structure and stratigraphy, and shows no evidence of major grain reduction and mylonitization. These features are indicative of ductile deformation occurring during a metamorphic event at relatively high temperature and deep crustal levels. The site is of national importance and remains suitable for teaching and research purposes.

EAS CHIA-AIG WATERFALLS (NN 176 889)

R.A. Strachan

Introduction

The Eas Chia-Aig Waterfalls GCR site, near Loch Arkaig, is located within an antiformal inlier of gneissose and schistose Moine semipelites and psammites adjacent to the Great Glen Fault. The inlier lies within the 'Flat Belt' (Clifford, 1957), which elsewhere is dominated by the psammites of the Loch Eil Group. The partially migmatitic gneissose Moine rocks have been correlated on lithological grounds with the Glenfinnan Group succession, which outcrops mainly to the west of the Quoich Line within the 'Steep Belt' (Institute of Geological Sciences, 1975b; Johnstone, 1975; Strachan, 1986; Strachan *et al.*, 1988, 2002a). The site provides an opportunity to examine typical Glenfinnan Group lithologies unaffected by the intense upright F3 folding and associated high tectonic strains characteristic of the 'Steep Belt'. J.E. Wright first mapped the area for the Geological Survey in 1953 and it has been subject to further work by R.A. Strachan (1986).

Description

The 'striped' gneissose semipelites and psammites are exposed in a rocky, forested gorge at the southern end of Gleann Cia-aig (Figure 8.23). Here the Abhainn Chia-Aig flows over several waterfalls and joins the River Arkaig at its outflow from Loch Arkaig. The site exposes Moine rocks locally termed the 'Achnacarry Striped Formation' (Strachan *et al.*, 1988). The main outcrops by the waterfalls comprise gneissose and schistose psammites and semipelites, which are regularly interlayered on a centimetre-scale (Figure 8.24). Lithological layering is extremely variable in orientation. Thin, white to grey calc-silicate layers are common within the psammites. Subordinate layers of coarsely schistose pelite up to 1–2 m thick also occur, with biotite and muscovite defining a prominent fabric, aligned parallel to compositional layering. Concordant and discordant quartz-feldspar segregations are abundant. Amphibolitic mafic sheets and pods, up to 2 m thick, occur within the metasedimentary rocks. A foliation defined by aligned hornblendes is commonly developed adjacent to the margins of the mafic bodies, and lies parallel to schistosity in the adjacent Moine rocks, but their cores are generally massive and locally contain garnet. The mafic bodies are mainly concordant with the gneissose layering but locally they show cross-cutting relationships, suggesting that they represent deformed and metamorphosed dolerite intrusions.

The metasedimentary rocks and amphibolitic bodies are both deformed by close to tight and locally isoclinal folds. At least two separate fold phases can be identified. An early set of tight to isoclinal folds of the bedding and migmatitic segregations probably correspond to structures assigned to the D2 deformation event in this part of the Moine outcrop (Holdsworth and Roberts, 1984; Strachan, 1985). These are refolded by later close to tight folds, which could correspond to either or both of the D3 and D4 deformation events identified a few kilometres to the south-west (Strachan, 1985). The later folds generally trend north–south and show gently to steeply plunging axes, but they vary in style from recumbent to upright and are markedly disharmonic with varied axial surface orientations. The Moine rocks are intruded by numerous discordant granitic veinlets and pegmatite veins, some of which lie parallel to the axial surfaces of the D3/D4 folds. Some of the granitic veinlets have marginal biotite selvedges and have probably

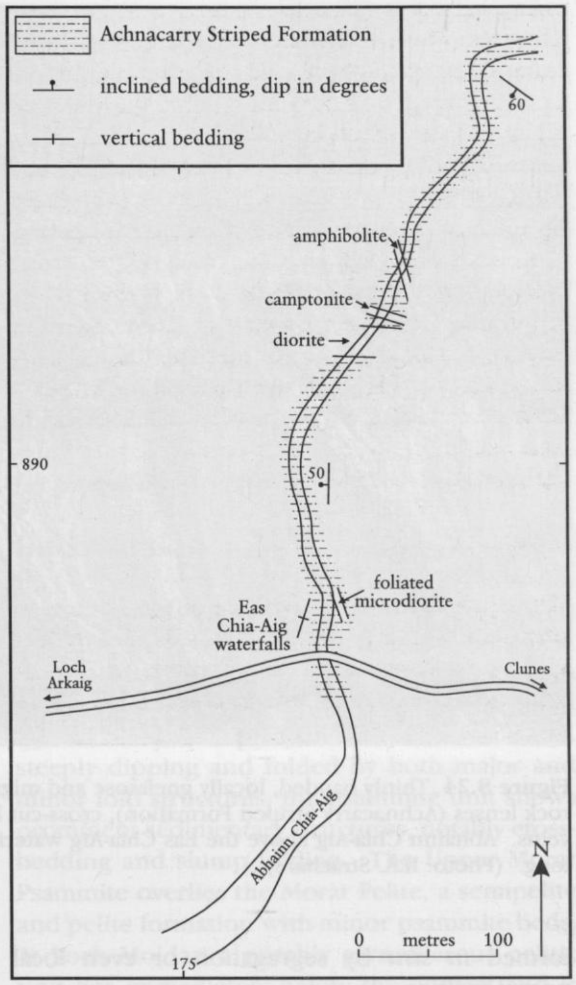


Figure 8.23 Map of Eas Chia-Aig Waterfalls GCR site.

Figure 8.24 Thinly banded, locally gneissose and migmatitic psammite, semipelite and pelite with calc-silicate rock lenses (Achnacarry Striped Formation), cross-cut by concordant and discordant quartz-feldspar pegmatite veins. Abhainn Chia-Aig above the Eas Chia-Aig waterfalls (NN 176 890). The compass (upper right) is 10 cm long. (Photo: R.A. Strachan.)

formed *in situ* by segregation or even local partial melting.

The grade of metamorphism is difficult to evaluate because of the lack of aluminosilicate minerals. The presence of hornblende and garnet in the amphibolites and calc-silicates indicates amphibolite-facies conditions. The ubiquitous migmatitic segregations suggest that at least middle-amphibolite conditions prevailed both prior to D2 and during D3/D4. This is consistent with the presence of sillimanite elsewhere in the Achnacarry Striped Formation (Institute of Geological Sciences, 1975c). The markedly disharmonic D3/D4 fold styles are characteristic of high metamorphic grade rocks, which contain segregation veins and possibly indicate localized partial-melting at the time of deformation (e.g. Hopgood, 1980; McLellan, 1984).

Downstream of the waterfall, the Moine rocks are cut by a discordant 1 m-thick, NW-trending microdiorite sheet. Although largely undeformed, the original igneous mineralogy has been modified by lower amphibolite-facies metamorphism. The intrusion is probably a member of the late Caledonian Microdiorite Sub-suite (Smith 1979), which was emplaced in mid-Silurian times during the final stages of the orogeny. Upstream of the waterfall, the gneisses are cut by a 1 m-thick, E–W-trending, fine-grained basaltic dyke. It shows no signs of deformation or metamorphism and is probably a camptonite of the Permo–Carboniferous alkali-basalt dyke-swarm.

Interpretation

The significance of the Eas Chia-Aig Waterfalls GCR site lies in the occurrence of Moine migmatitic gneisses within largely non-migmatitic psammites of the Loch Eil Group that underlie the majority of ground between the Quoich Line and the Great Glen Fault. Johnstone (1975) suggested on lithological grounds that these gneisses correlate with the Glenfinnan Group rocks, which underlie the Loch Eil Group *c.* 12 km to the west. Subsequent work near the site has shown that the Achnacarry Striped Formation passes transitionally into the structurally overlying and younger rocks of the Loch Eil Group, supporting the suggested correlation (Strachan, 1986). The rocks lie in the core of a broadly antiformal zone of folds and are therefore plausibly interpreted as a fold inlier of the Glenfinnan Group (Strachan *et al.*, 1988). Similar relationships are seen to the north-east where the Achnaconeran Striped Formation also passes laterally and vertically up into Loch Eil Group psammites (May and Highton, 1997). Both the Glenfinnan Group and Loch Eil Group rocks share a common tectonothermal evolution and the absence of significant migmatization within the Loch Eil Group is attributed to its relatively quartz-rich psammitic nature (see also **Fassfern to Lochailort Road Cuttings** GCR site report, this chapter).

By analogy with Glenfinnan Group rocks in their type area, the early gneissic layering and migmatitic segregations within the Achnacarry Striped Formation probably formed during the Neoproterozoic tectonothermal event known to have affected the Glenfinnan Group at *c.* 870 Ma (Friend *et al.*, 1997). The age of the D2 folding is uncertain. The D3/D4 folds are thought to be of the same age as the Caledonian upright folds, which dominate the structure of the 'Steep Belt', i.e Ordovician or Silurian in age (see Roberts and Harris, 1983; Roberts *et al.*, 1984; Strachan *et al.*, 2002a). The disharmonic D3/D4 fold styles, variable foliation attitude and discordant contacts within the gneisses at the site contrast with the highly flattened, more-harmonic fold styles, uniformly steep foliation attitude, and concordant contacts characteristic of the Glenfinnan Group within the 'Steep Belt'. These differences are attributed to variations in the intensity of Caledonian tectonic strain across the North-west Highlands during this D3 phase of folding.

Conclusions

The Eas Chia-Aig Waterfalls site is located within the 'Flat Belt' and exposes gneissose Moine psammites and semipelites of the Achnacarry Striped Formation. The gneissose rocks display evidence for polyphase folding and migmatization; fold styles are markedly disharmonic and the foliation attitude highly variable. The gneisses form part of an antiformal inlier of the Glenfinnan Group, which is surrounded by the structurally overlying and younger psammites of the Loch Eil Group. The main outcrop of the Glenfinnan Group is located farther west within the 'Steep Belt', and the site is important as it provides a unique opportunity to examine Glenfinnan Group lithologies where they are unaffected by the high tectonic strains and tight folding characteristic of the Caledonian D3 steep belt.

LOCH MOIDART ROAD CUTTINGS (A861) (NM 681 737–NM 697 728)

J.R. Mendum

Introduction

The Loch Moidart Road Cuttings GCR site provides a cross-strike section through the Upper Morar Psammite, the younger of the two major psammite units of the Morar Group of the Moine succession (Figure 8.25a). Although steeply dipping and folded by both major and minor fold structures, the psammite unit shows prominent sedimentary structures, notably cross-bedding and slump folding. The Upper Morar Psammite overlies the Morar Pelite, a semipelite and pelite formation with minor psammite beds. At Loch Moidart a notably garnetiferous pelitic unit lies immediately below the contact and is exposed near Kylesbeg at NM 678 739. Glendinning (1988) followed Powell (1974) in showing a 'slide' or shear zone at this lower psammite–pelite contact, and correlated this structure with the Knoydart Thrust ('Slide') farther north (see **North Morar** GCR site report, this chapter). This correlation is no longer favoured. Increasing strain marks the upper eastern boundary of the Upper Morar Psammite Formation, which is overlain by migmatitic pelite and semipelite of the Lochailort Pelite Formation (Glenfinnan Group). The contact is the Sgurr Beag Thrust whose trace runs through Kinlochmoidart. Late Caledonian microdiorite sheets, Permo–Carboniferous camptonite dykes and quartz-dolerite bodies, and Palaeogene dolerite dykes cross-cut the Moine rocks in the section (Figure 8.25b).

A.G. Macgregor initially mapped the area for the Geological Survey in 1930 and 1933. Subsequently Brown *et al.* (1970) postulated that tight F2 major folds control the structure

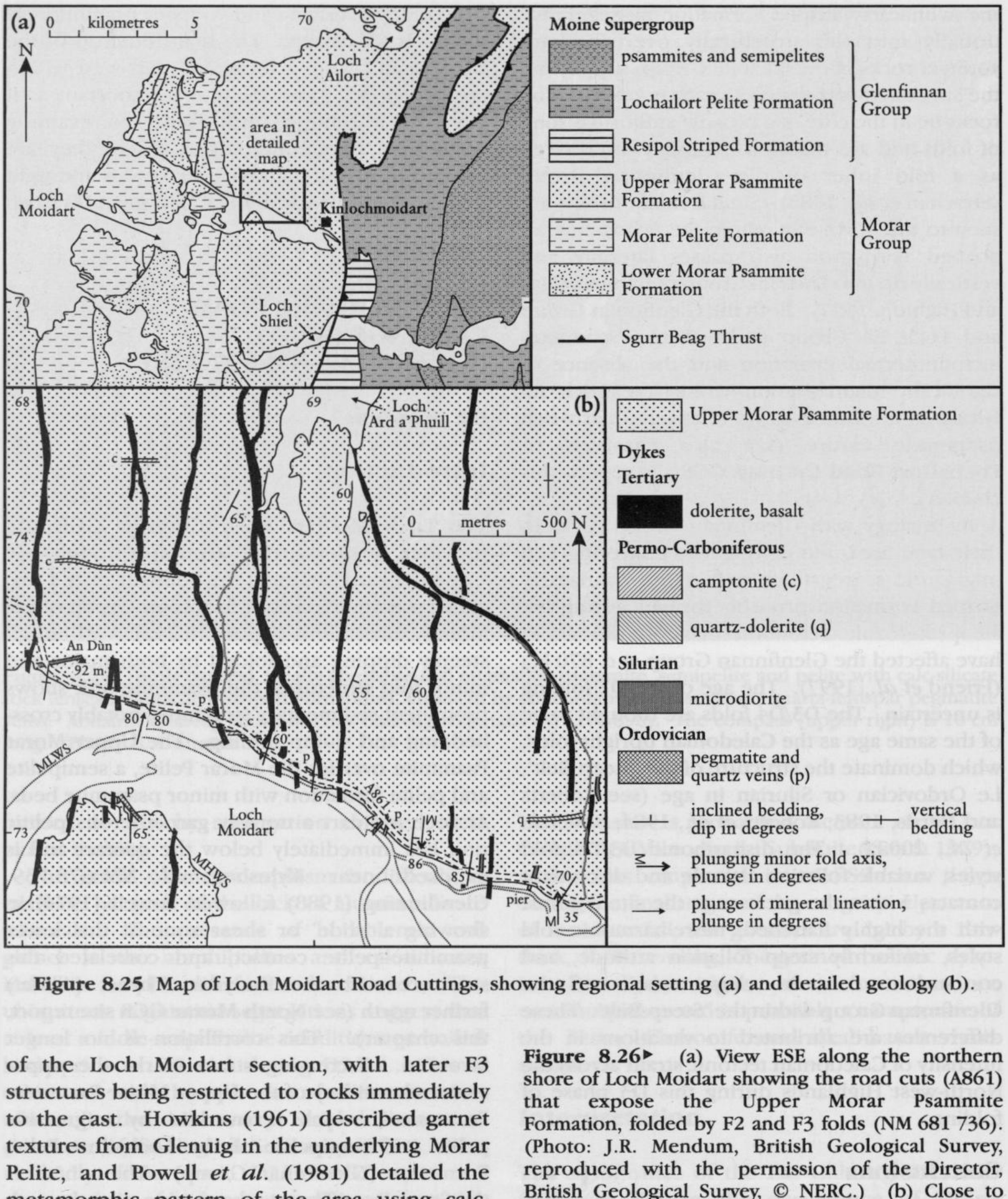


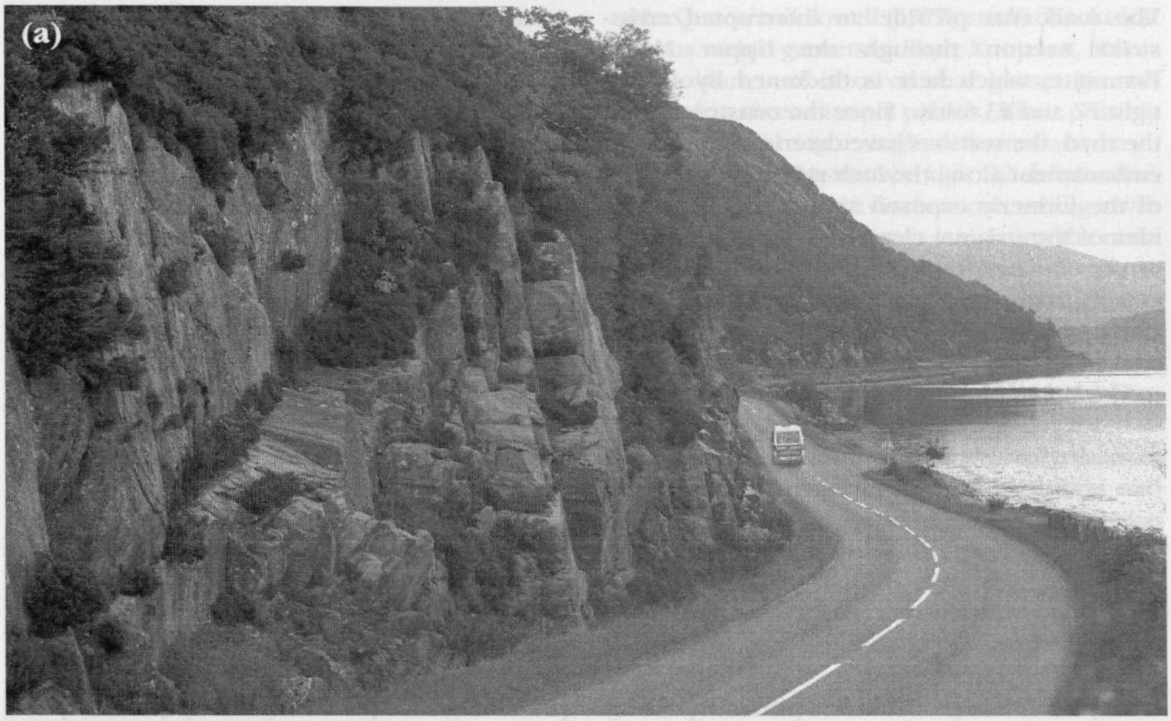
Figure 8.25 Map of Loch Moidart Road Cuttings, showing regional setting (a) and detailed geology (b).

of the Loch Moidart section, with later F3 structures being restricted to rocks immediately to the east. Howkins (1961) described garnet textures from Glenuig in the underlying Morar Pelite, and Powell *et al*. (1981) detailed the metamorphic pattern of the area using calc-silicate mineral assemblages.

Description

The Loch Moidart Road Cuttings GCR site lies along the A861 and also includes the narrow raised marine benches and cliffs that reach up to 30 m above sea level in this area (Figure 8.26a).

Figure 8.26▸ (a) View ESE along the northern shore of Loch Moidart showing the road cuts (A861) that expose the Upper Morar Psammite Formation, folded by F2 and F3 folds (NM 681 736). (Photo: J.R. Mendum, British Geological Survey, reproduced with the permission of the Director, British Geological Survey, © NERC.) (b) Close to tight, moderately plunging F2 + F3 folds in striped psammites and semipelites of the Upper Morar Psammite Formation. The quartz and quartz-feldspar veins lie close to the penetrative S3 axial-planar cleavage. Rock face adjacent to the A861 at An Dùn on the northern side of Loch Moidart (NM 6815 7354). The hammer head is 14 cm long. (Photo: J.R. Mendum, British Geological Survey, reproduced with the permission of the Director, British Geological Survey, © NERC.)


(a)


(b)

The road cuts provide an interrupted cross-strike section through the Upper Morar Psammite, which here is thickened by several tight F2 and F3 folds. Since the construction of the road, the sections have deteriorated and the embankment along the loch side obscures parts of the formerly exposed shore section. Some idea of the original clean nature of the section can be obtained from more recently blasted road cuts through the same formation farther north along the A830 (Fort William–Mallaig), west of Lochailort.

The Upper Morar Psammite at Loch Moidart is mostly a pale-grey, thick, well-bedded, feldspathic to micaceous psammite sequence with abundant thin semipelite beds. Thicker units of white to pale-grey, indurated, siliceous psammite occur in parts. Finely interbedded psammite and semipelite beds are common, in which grading from psammitic base to semipelitic top is seen locally. The semipelitic units are biotite-rich and locally contain garnet. Cross-bedding is locally well seen in the psammites and generally enables the determination of way-up. Trough-parallel sets are most common but trough-festoon sets occur near An Dùn at NM 6815 7353. Glendinning (1988) measured the cross-bed foreset orientations from the Upper Morar Psammite between Ardnamurchan and Morar, and concluded that the palaeocurrents were bimodal with a primary current direction towards the NNE or north and a secondary direction towards the south or south-east.

Calc-silicate pods and lenses are abundant in both psammitic and semipelitic lithologies and represent diagenetically formed calcareous concretions in the original sandy or silty sequence. In the western part of the section, they contain zoisite + biotite + garnet assemblages, indicating epidote-amphibolite-facies metamorphism. In the eastern part of the section, higher-grade hornblende + garnet + clinozoisite assemblages are found (Powell *et al.*, 1981). A zone with abundant clinozoisite extends some 1.7 km west of the Sgurr Beag Thrust. Powell *et al.* (1981) showed that clinozoisite occurrence corresponds to the local decrease in the anorthite content of plagioclase, caused by the breakdown of plagioclase feldspar and zoisite. In the high-grade rocks east of the Sgurr Beag Thrust, the semipelitic and pelitic units are migmatitic, and both kyanite- and staurolite + sillimanite-bearing assemblages are recorded. Plagioclase compositions in the calc-silicate rocks again become more anorthite-rich.

Quartz pods and veins up to 60 cm thick are locally common throughout the section and are generally fairly randomly orientated. Around NM 6898 7320 aplitic and pegmatitic granite veins also occur, forming variably orientated, pink and white irregular veins up to 30 cm thick. The aplitic granite veins commonly cross-cut quartz veins and they post-date the F2 and F3 folding. Garnet-muscovite-bearing pegmatitic granite veins up to 1 m wide are also present in the section (e.g. on An Dùn).

The section shows several major, tight, upright folds with a wavelength of between 700 m and 2 km. F2 folds are the dominant structures. A broad F2 anticlinal hinge zone is exposed in the cliffs west of Kinlochmoidart pier at NM 6965 7287. The related syncline to the west is tighter and marked by a 2 m-wide microdiorite sheet with sheared margins. Associated with this F2 fold pair are tight minor folds with a prominent axial-planar schistosity. Farther WNW at NM 6934 7296 tight minor F2 folds are well exposed on the middle limb of a large-scale Z-profile F3 fold pair, whose axes plunge gently south. A steeply pitching, almost down-dip L2 intersection lineation is also present. A further example of the complex effects of F2 folding is seen at An Dùn (NM 6815 7354), where the cross-bedding is prominent in, and adjacent to, the hinge zones of F2 folds, but has been strongly attenuated on F2 fold limbs. Here, F2 axes plunge gently to moderately northwards, whereas F3 axes plunge gently to the north or south (Figure 8.26b).

Microdiorites are abundant along the Loch Moidart section and range from subvertical dykes to gently dipping sheets up to 2 m thick that cross-cut the folds and pegmatitic veins. Smith (1979) showed that the transition from greenschist- to amphibolite-facies metamorphic assemblages in the microdiorite sheets occurs within the section. Permo–Carboniferous quartz-dolerite dykes are also common in the area (e.g. at NM 6992 7312). A 2.5 m-thick E-trending camptonite dyke at NM 6872 7333 has the appearance of a fine-grained basalt but is a barkevikite + plagioclase-bearing lamprophyre. There are also numerous, thick Palaeogene dykes of olivine- and feldspar-phyric tholeiitic basalt and dolerite of the Skye swarm that trend approximately north. These probably belong to the Preshal Mhor type (Thompson, 1982).

Interpretation

The Loch Moidart section provides a traverse through the Upper Morar Psammite Formation and through the transition zone between lower-grade, structurally less-deformed rocks in the west, and higher-grade, more structurally complex rocks to the east. The psammitic nature of the Moine rocks is not ideally suited to show the effects of these changes. To the east, pelitic rocks contain kyanite, staurolite and then sillimanite, with the rocks becoming migmatitic (middle-amphibolite facies) above the Sgurr Beag Thrust. In the west the pelitic rocks below the psammite unit contain essential garnet + biotite; the calc-silicate and pelite lithologies contain assemblages typical of the epidote-amphibolite facies. This metamorphic pattern reflects the peak metamorphic conditions associated with the D3 deformation at *c.* 455 Ma (Late Ordovician). The variation in metamorphic grade shown by the later microdiorite sheets (Smith, 1979) reflects the pattern prevailing at a late stage of the orogenic cycle, in the Silurian (*c.* 425–420 Ma), after significant uplift had occurred.

Brown *et al.* (1970) and Powell (1974) both argued that D3 structures were abundant in Glenfinnan Group rocks east of Lochailort and Kinlochmoidart but appeared to terminate farther west. However, Powell *et al.* (1981, 1983) and Powell and MacQueen (1976) later recognized D3 deformation structures farther west in Skye, which they linked to those seen in the Loch Eilt and Glenfinnan areas (see **Fassfern to Lochailort Road Cuttings** GCR site report, this chapter). Powell (1974) initially recognized the Morar Antiform as a D2 structure, but it is now generally accepted that it is basically a D3 structure. A N-plunging antiform near Loch na Bairness (NM 656 758) *c.* 2 km north-west of the site area, is a southerly en echelon extension of the Morar Antiform and thus also probably a D3 structure. Although the Sgurr Beag Thrust has been interpreted as basically a D2 structure, significant reactivation and further thrusting occurred during the D3 Grampian Event (Powell *et al.*, 1981; Tanner and Evans, 2003). Similar structural relationships are seen in the Loch Moidart section where there is a combination of D2 and D3 structures. In Moidart, Brown *et al.* (1970) assigned the NNW-trending folds that refold D2 structures east of Kinlochmoidart to D3, but Powell (1974) more correctly assigned them to D4.

MacQueen and Powell (1977) studied inclusion patterns within garnets in Skye, Knoydart, Morar and Moidart, and showed that garnet growth occurred in three distinct phases, albeit possibly all occurring during a single deformation phase. Their major conclusion was that D2 deformation and garnet growth were diachronous, with growth in the interior of the orogen pre-dating the main deformation in more-peripheral parts. Subsequent work and isotopic dating has shown that D2 probably occurred within the period 737–820 Ma (e.g. Tanner and Evans, 2003) and that the D3 event followed at *c.* 455 Ma (van Breemen *et al.*, 1974). The D3 event resulted in amphibolite-grade metamorphism in the east and greenschist-grade assemblages in Skye and western Morar. Howkins (1961) interpreted garnet profiles from Glen Uig, immediately east of Loch Moidart, as indicating two periods of metamorphism with the outer garnet zone related to later deformation and metamorphism. Vance *et al.* (1998) interpreted the garnet profiles from a sample from Polnish (3 km WNW of Lochailort) similarly. They obtained core–whole rock Sm-Nd isochron ages of *c.* 820 Ma and a rim–whole-rock isochron age of 788 ± 4 Ma. Tanner and Evans (2003) obtained a U-Pb TIMS age of 737 ± 5 Ma from titanite in Morar Pelite from the western end of Loch Eilt. They argued that this dated the peak metamorphism as Knoydartian with temperature conditions reaching *c.* 650° C and pressures of around 10 kbar. This would argue that the Neoproterozoic tectonothermal events are orogenic in character, rather than extensional (cf. Soper *et al.*, 1998; Dalziel and Soper, 2001). However, despite the evidence for both Knoydartian and Grampian orogenic events in the Morar–Moidart region, their relative intensity, accompanying metamorphic grade, and spatial extent still remain unclear.

Conclusions

The Loch Moidart road section provides a cross-section through the Upper Morar Psammite Formation. This is the uppermost thick psammite unit in the Morar Group of the Moine succession and is noted for its good preservation of sedimentary structures, including cross-bedding and local grading. The formation regionally dips steeply east, but it is tectonically thickened by several large-scale folds, whose axes plunge gently to moderately north. Both minor and major F2 and F3 fold closures are seen. Mineral assemblages in pelitic units and calc-silicate pods show that metamorphic grade was higher in the eastern part of the section. Farther north, recent road cuts to the west of Lochailort provide larger and presently cleaner sections through the same unit. These show various types of cross-bedding (tabular, festoon), convolute bedding, and slump structures. The GCR site is important in that it provides a link between the metamorphic and structural features of the western seaboard and those associated with the Sgurr Beag Thrust. The site is important in that it is representative of the Upper Morar Psammite and provides a good cross-section for further study to enable the regional patterns of folding and metamorphism to be more fully understood.

EILEAN MÒR AND CAMAS CHOIRE MHUILINN (NM 571 614–NM 599 608, NM 521 630)

J.R. Mendum

Introduction

The coastal sections along the southern shore of the Ardnamurchan peninsula provide clean sections through the thick Upper Morar Psammite Formation, which here preserves a range of sedimentary structures in a largely undeformed state. This is the uppermost unit of the Morar Group in the Moine Supergroup and is also described in the **Loch Moidart Road Cuttings** GCR site farther north, albeit in a more-deformed state.

The Moine rocks around the Eilean Mòr site are overlain to the west by near-horizontal Palaeogene basalt lavas, which preserve beneath them a thin unit of sandstone, mudstone and lignite beds (Figure 8.27). These units occur on Beinn Bhuithe (NM 570 630) and are down-faulted to form the peninsula of Ardslignish, immediately west of Rubha Dubh. Around Eilean Mòr the Moine psammites generally dip steeply to the south-west on the western limb of a large complex N-trending antiform, which itself lies en echelon to the Morar Antiform farther north.

At the Camas Choire Mhuilinn site, 6 km west of Eilean Mòr, the Upper Morar Psammite dips gently south-east. It is overlain to the west by a thick Palaeogene dolerite sill, the Ben Hiant Dolerite, and is truncated by a thick quartz-dolerite plug to the east. In the hinterland a down-faulted block contains Palaeogene lavas that overlie Jurassic (Lower Lias) sandstone, shale and limestone, and Triassic red sandstones and conglomerates.

Numerous Palaeogene dolerite and basalt dykes intrude all the above lithologies. The dykes belong to the Skye–Mull swarm, except in Camas Choire Mhuilinn, where they relate to the Ardnamurchan igneous centre.

The southern part of the Ardnamurchan peninsula was mapped by the Geological Survey between 1921 and 1923. O'Brien (1985) subsequently studied the Moine rocks and summarized the structural sequence in the central part of the peninsula. Glendinning's (1988) detailed study of the sedimentary structures and sequence within the Upper Morar Psammite included the Eilean Mòr and Camas Choire Mhuilinn localities.

Description

The Eilean Mòr site stretches from the wooded, rocky eastern side of Glenmore Bay, westwards for some 1.5 km to include Eilean Mòr, Camas Fearna and Rubha Dubh (NM 574 613). The small bay of Camas Choire Mhuilinn lies some 5 km farther to the WNW (see Figure 8.27). At the Eilean Mòr GCR site, the shoreline consists of clean glaciated rocky promontories separated by low-lying sandy bays. A prominent raised rock platform is present. Eilean Mòr is separated from the mainland only at high tide.

East of Eilean Mòr, the Upper Morar Psammite Formation is underlain by a semipelite–pelite sequence that forms the upper part of the Morar Pelite Formation (Figure 8.3). The folded contact is exposed on the east side of Glenmore Bay around NM 5955 6132. The dark-grey, blocky to massive, biotite-rich semipelite is coarsely schistose with abundant purplish-red euhedral garnets and quartz-feldspar segregation veins. The transition to psammite is rapid, and in cliffs east of the road, mid- to pale-grey, laminated feldspathic and micaceous psammites are locally cross-bedded. Individual psammite beds range in thickness from 10 cm to 1 m, and thin semipelitic and pelitic interbeds are common. Calc-silicate lenses up to 10 cm thick are locally abundant in these transitional lithologies. A late-stage weak crenulation cleavage is present. The Upper Morar Psammite and the Morar

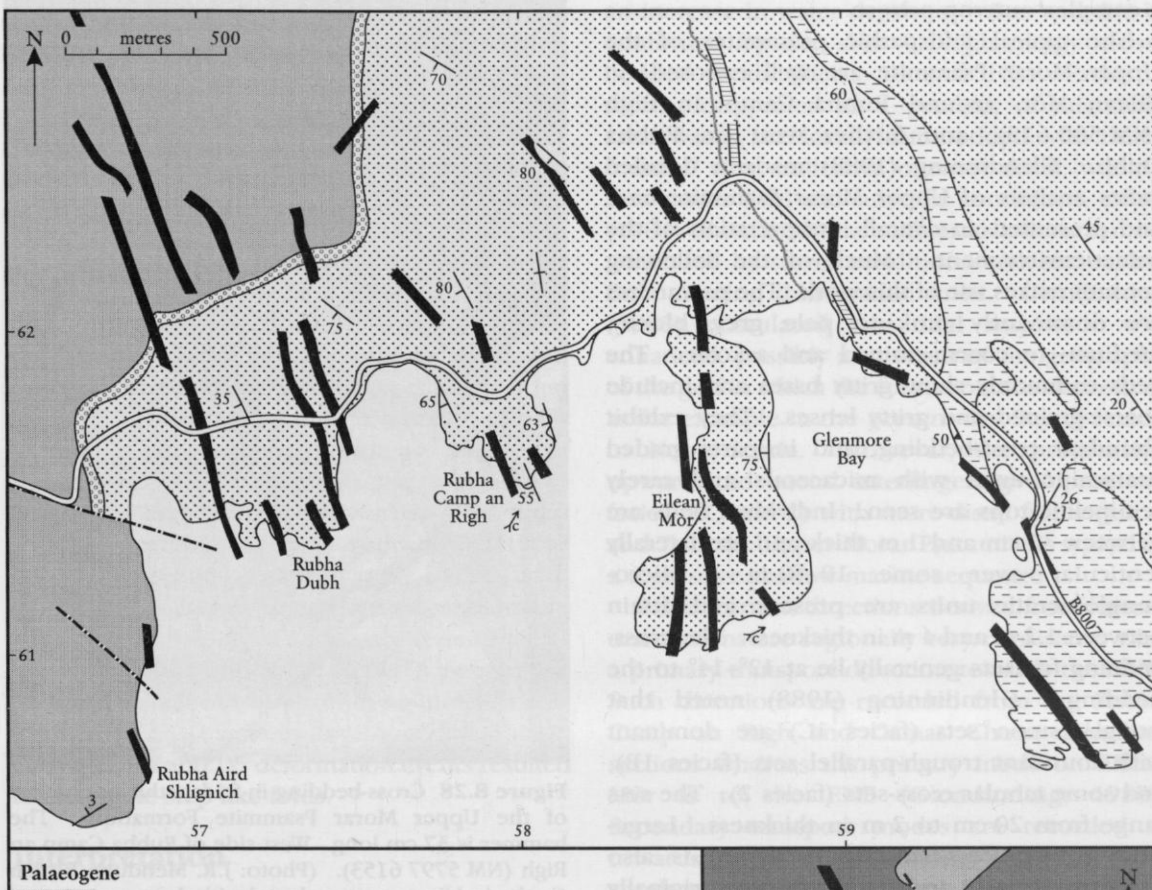


Figure 8.27 Map of Eilean Mòr GCR site (based on British Geological Survey maps).

Pelite formations are infolded and thrust to form a complex outcrop pattern.

The typical feldspathic psammites of the Upper Morar Psammite are well exposed on Eilean Mòr, around Rubha Camp an Righ (NM 580 615), and farther west on Rubha Dubh. Glendinning (1988) made a detailed facies analysis of Upper Morar Psammite here and presented an overall interpretation of the palaeoenvironment. Much of the following account makes use of this work. The psammites are dominantly pink to pale grey, blocky, medium- to coarse-grained and arkosic. The beds commonly show gritty bases and include coarse-grained and gritty lenses. They exhibit abundant cross-bedding, and in parts graded psammitic units with micaceous and rarely semipelitic tops are seen. Individual beds are between 30 cm and 1 m thick and are laterally lenticular over some 10–50 m. Micro-conglomeratic units are present and attain between 1.2 m and 4 m in thickness. The cross-bedding foresets generally lie at 12°–14° to the bedding. Glendinning (1988) noted that trough-festoon sets (facies 1C) are dominant with abundant trough-parallel sets (facies 1B), and some tabular cross-sets (facies 2). The sets range from 20 cm to 2 m in thickness. Large-scale trough-cross-bedding (facies 3) is also present. Facies 2 and 3 units involve originally gravelly sands with clasts averaging 4 mm across and ranging up to 8 mm. Good examples are seen on Rubha Camp an Righ (Figure 8.28). Plane-laminated (facies 4) and cross-laminated fine-grained psammites (facies 5) are less common, as are interbedded psammites and semipelites (facies 6) and massive semipelite (facies 7). In the transitional zone into the underlying Morar Pelite sedimentary structures and lithologies include flaser bedding (Glendinning, 1988, fig. 2.20), cross-bedded psammite sheets (facies 1B and 4), interbedded psammite and semipelite (facies 6), and massive semipelite units (facies 7).

Magnetite-rich heavy-mineral bands up to 1 cm thick, and ovoid iron-rich nodules up to 10 cm across occur in the Upper Morar Psammite, notably in the thick, lenticular, arkosic, coarse-grained psammite units. In many units the cross-beds are strongly oversteepened and commonly may be disrupted and tightly folded. Glendinning (1988) documents extensive sheets of highly contorted psammite with large-scale convolute bedding structures, typically truncated by the overlying bed, signifying local erosion. On Rubha Camp an Righ cross-bedded psammites can be traced laterally over a short distance into asymmetrical slump-folded units, implying either rapid gravitational instability or strong current drag during deposition of the overlying unit.

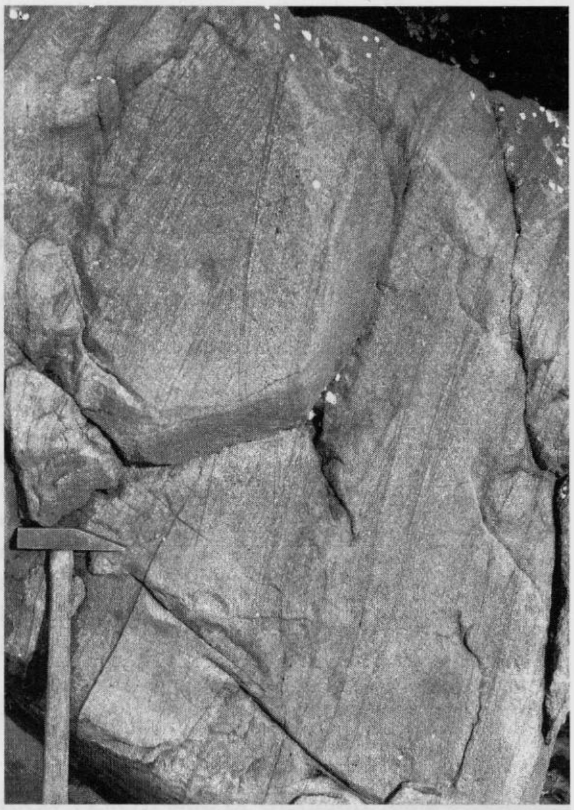


Figure 8.28 Cross-bedding in feldspathic psammites of the Upper Morar Psammite Formation. The hammer is 37 cm long. West side of Rubha Camp an Righ (NM 5797 6153). (Photo: J.R. Mendum, British Geological Survey, reproduced with the permission of the Director, British Geological Survey, © NERC.)

At Camas Choire Mhuilinn higher stratigraphical levels of the Upper Morar Psammite are exposed. The limited shoreline exposures show flaggy, medium- to coarse-grained psammites locally with feldspar clasts. The upper parts of the formation are coarse grained and the sequence overall is upward-coarsening (Glendinning, 1988). Soft-sediment deformation structures are also notably abundant.

The Upper Morar Psammite Formation was estimated by Glendinning to exceed 4800 m in thickness in the western part of Ardnamurchan, its maximum development in the North-west Highlands. The rocks are metamorphosed to epidote-amphibolite facies, although the diagnostic mineralogies are best seen in the subsidiary pelitic units and in the underlying Morar Pelite Formation east of Glenmore Bay. The main foliation and associated recumbent folding at the site are attributed to D2. The later upright, open to tight folds that refold the earlier structures, are termed 'D3'. Note that O'Brien (1985), who recognized four phases of folding in central Ardnamurchan, terms the earlier structures 'D1' and the later structures 'D2', but the terminology used here is compatible with that used in the other GCR sites in Morar and Moidart. The notes below are based on O'Brien (1985). F2 folds are typically asymmetrical with sheared common limbs, which act as sites of dislocation. No consistent sense of vergence was noted and there are few areas of inverted rocks. Nevertheless it is probable that the complex interfolding pattern at the eastern edge of the site is largely a product of medium- to large-scale F2 folding. F3 folds are generally box-like or step-like and trend NNW. A penetrative S3 foliation is locally present in pelitic units, but elsewhere S3 is a variably developed crenulation cleavage. D4 and D5 deformation events resulted in conjugate step-like folds.

Interpretation

The Eilean Mòr and Camas Choire Mhuilinn GCR sites show examples of the typical sedimentary structures that occur in the Upper Morar Psammite Formation (Morar Group). This formation reaches its acme in this area, attaining some 5 km in thickness. Glendinning (1988) documented the sedimentary structures present and constructed a palaeoenvironmental model for the deposition of the unit. He interpreted the original sand sheets, interbedded sands and silts, and massive silts of the upper parts of the underlying Morar Pelite to be mostly of tidal origin with parts of the sequence as intertidal or shallow sub-tidal. The movement of sand sheets may relate to local storms but the general lack of channelling and other features suggest relatively low energy conditions. The Upper Morar Psammite represents a transgression which overall coarsens upwards (regressive). Conditions remained tidal and shallow marine, as shown by the occurrence of thick units of planar laminated sands (facies 4), indicative of the upper flow regime and hence relatively high velocity currents. The upward appearance of thick tabular cross-bedded sands (facies 2) indicates an increase in water depth to > 5 m and this is confirmed by the shift to high-energy cross-bedded sands (facies 1B and 1C). Facies 1 sands, interpreted as a product of migrating sand waves, are locally interbedded with facies 6 and 7 silts, indicative of more-distal, waning flow under tidal and sub-tidal conditions. Allen (1984) illustrated that such associations can be generated by storm conditions with the return flow creating thin graded units. Glendinning (1988) postulated that tidal amplitude was enhanced, possibly as a result of the geography of the gulf in which the formation was deposited, as for example in the present-day Bay of Fundy in Nova Scotia. However, the progressive upward and lateral interfingering of proximal facies (1C and 2) with more-distal facies (1B, 6 and 7) in the Upper Morar Psammite is typical of a regressive shallow-marine sequence.

Palaeocurrent directions derived from foreset orientations are regionally very consistent, with a primary transport direction towards the NNE. Such directions are recorded from the Rubha Camp an Righ and Camas Choire Mhuilinn sections whereas the primary mode on Eilean Mòr is to the ENE (Glendinning, 1988). Secondary transport modes are recorded as towards the SSE at Rubha Camp an Righ and the south-west at Eilean Mòr. The direction of vergence of the slump or current drag folds also implies current flow to the NNE. Bimodal, bipolar palaeocurrents that are near-exclusive to trough-parallel sets (facies 1B) appear to have been dominant in the lower parts of the formation. The convolute bedding is interpreted mainly as a dewatering structure, with possible periodic seismic events occurring along a possible western graben-bounding fault. It is also indicative of the high rate of sand accumulation and a high water content.

Glendinning (1988) interpreted the Upper Morar Psammite Formation as having been deposited in a N-trending marine tidal gulf, formed by a half-graben structure during a regional extension event around 900 to 1000 Ma. The coarsest, pebbly psammites, the most proximal parts of the formation, occur in Ardnamurchan and the overall model implies that a bounding fault occurred a short distance to the west of the present outcrop. Fine-grained psammites and semipelites are more abundant both eastwards and northwards where the formation becomes markedly thinner, representing more-distal parts of the sedimentary basin. Soper *et al*. (1998) adapted the Glendinning (1988) model and extended it to interpret the palaeogeography of the whole Moine succession of the North-west Highlands.

In contrast, Bonsor and Prave (2008), working around Rubha Ruadh on the northern coast of the Ardnamurchan peninsula, documented five sandstone lithofacies types ranging from coarse to medium-fine, based on grain size, cross-bedding styles, bar forms, soft-sediment deformation features, and the incidence of gravel lags. They concluded that the formation represents a retrogradational braidplain fluvial environment. They interpreted the rocks as part of a foreland molasse formed by erosion of the Grenville Orogen to the north-west.

Conclusions

The Eilean Mòr and Camas Choire Mhuilinn GCR site on the south side of the Ardnamurchan peninsula provides very good exposures of the Upper Morar Psammite Formation, comprising psammites and subsidiary semipelites. This originally immature, sand-dominated formation lies at the top of the Morar Group of the Neoproterozoic Moine Supergroup, and on Ardnamurchan it reaches its maximum exposed thickness of some 5 km. The rocks have been metamorphosed under epidote-amphibolite-facies conditions. They also show evidence of several phases of folding, related to the Grampian and possibly older orogenic events. The intensity of folding and degree of metamorphism diminish westwards on the Ardnamurchan peninsula, and around Eilean Mòr the psammites exhibit abundant sedimentary features, notably cross-bedding and convolute and disturbed bedding structures.

The GCR site is of national importance as it provides reference sections that enable the sedimentation conditions that prevailed during deposition of the Upper Morar Psammite Formation to be deduced. This formation is unique in that it is sufficiently undeformed in Mull, Ardnamurchan and Morar to enable its depositional conditions and palaeogeography to be reconstructed with some confidence. It can be identified as either a shallow-marine, tidally dominated, thick, sand infill of a restricted basin formed during regional extension, or as part of an extensive alluvial–fluvial foreland basin system draining the eroding Grenville Orogen.

ARDALANISH BAY (MULL) (NM 376 188–NM 363 168)

A.J. Highton

Introduction

The Ardalanish Bay GCR site provides a traverse through the thermal aureole of the Ross of Mull Granite Pluton. In the aureole, medium-pressure, kyanite-bearing, regional metamorphic assemblages in the surrounding Moine metasedimentary rocks have been replaced by high-temperature contact metamorphic minerals. The Ross of Mull Pluton is notable for showing one of the finest examples of a 'ghost' country rock stratigraphy within an intrusion. This demonstrates that the pluton was intruded through a process of sheeting, wedging and stoping, but with little disruption of the country rocks. Details of the pluton and its emplacement mechanism are described in the Cnoc Mor to Rubh' Ardalanish GCR site (Highton, 1999) and by Zaniewski *et al*. (2006); this description focuses on the thermal aureole. Halliday *et al*. (1979) obtained a mineral–whole-rock Rb-Sr age of 414 ± 3 Ma from the outer granite, but this probably dates the cooling of the pluton rather than its emplacement.

The raised shoreline of Ardalanish Bay on the Ross of Mull exposes the most westerly known outcrops of the Neoproterozoic Moine succession (Cunningham Craig *et al*., 1911; Bailey and Anderson, 1925; Riley, 1966). The Moine rocks are bounded to the west by the Ross of Mull Pluton. The Moine succession on Mull comprises an older Shiaba Group and a younger Assapol Group, which have been correlated with the Morar and Glenfinnan groups respectively of the mainland Moine succession (Holdsworth *et al*., 1987; Figure 8.3). The nature of the contact between the two groups has been subject to various interpretations. Rathbone (1980) and Barr (1983) described it as high-strain contact, equivalent to the Sgurr Beag Thrust, which on the mainland separates the Morar and Glenfinnan groups. However, more-recent work favours a transitional stratigraphical boundary along which there is some localized ductile high strain (Holdsworth *et al*., 1987). If the later interpretation is correct, and correlation with the mainland succession valid, then the Ross of Mull uniquely preserves the original stratigraphical relationships between the Morar and Glenfinnan groups or their equivalents. Unusually, the Moine succession contains metamorphic index minerals with kyanite and staurolite present in some pelitic and semipelitic lithologies as a result of the regional amphibolite-facies metamorphism. The regional metamorphic assemblages are overprinted by contact metamorphic effects close to the Ross of Mull Pluton, with development of andalusite, sillimanite and cordierite (Bosworth, 1910; Bailey and Anderson, 1925; MacKenzie, 1949; Brearley, 1984; Mangan, 1996, Wheeler *et al.*, 2004). Hence, all three aluminosilicate polymorphs occur at the site, although not within a single sample as previously reported by Bosworth (1910). Clough (in Bailey and Anderson, 1925) noted the occurrence of a small suite of hornfelsed microdioritic intrusions ('lamprophyres') close to the eastern margin of the pluton, which pre-date granite emplacement.

Description

The Ardalanish Bay GCR site encompasses the raised rocky coastal outcrops along the western side of Ardalanish Bay and on the Rubh' Ardalanish peninsula on the southern coast of the Ross of Mull (Figure 8.29). Of special interest are the contact metamorphic effects on the originally kyanite-grade Moine country rocks that resulted from the emplacement of the Ross of Mull Pluton. East of Port Mòr, the eastern margin of the granitic pluton is in contact with the Assapol Striped and Banded Formation (Assapol Group). The formation comprises thinly to thickly interbedded feldspathic and micaceous psammite, semipelite and minor pelite (Figure 8.30). Small pods and lenticles of grey-cream to green calc-silicate rock within the micaceous psammites locally exhibit compositional zoning, shown by the distribution of garnet, hornblende and/or biotite. Numerous mafic

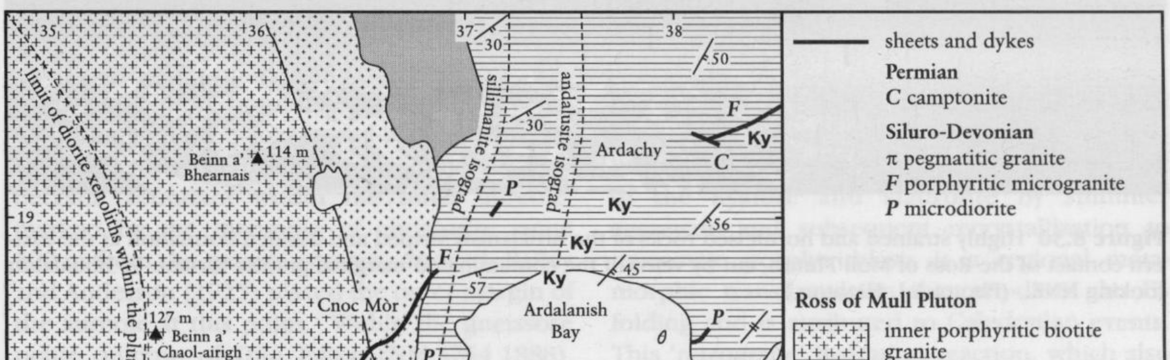


Figure 8.29 Map of the Ardalanish Bay GCR site on the eastern margin of the Ross of Mull Pluton. Adapted from 1:50 000 Sheet 43S, Ross of Mull (British Geological Survey, 1997a) and unpublished work, University of Liverpool.

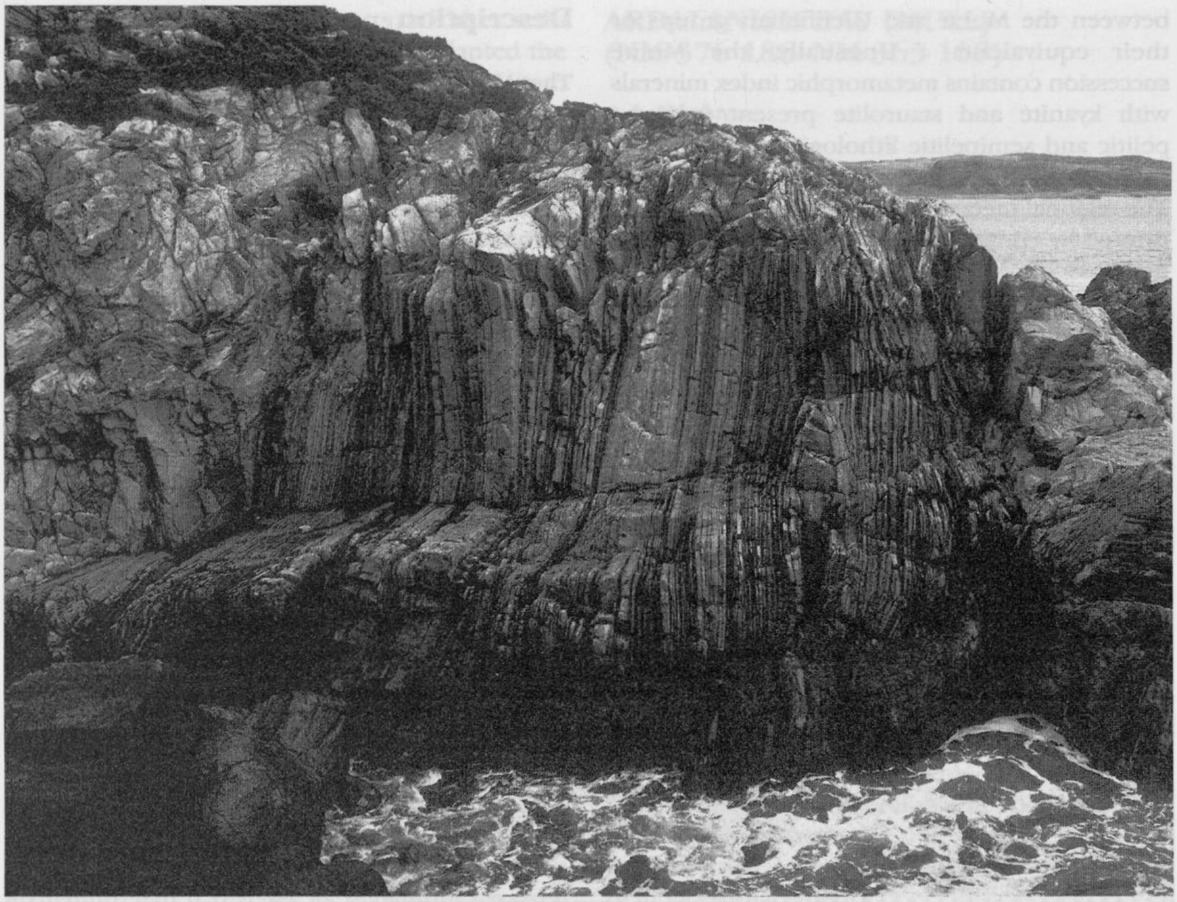


Figure 8.30 Highly strained and hornfelsed rocks of the Ardalanish Striped and Banded Formation at the eastern contact of the Ross of Mull Pluton, cut by veins of the contaminated marginal granite variant. A' Bhualaidh looking NNE. (Photo: A.J. Highton.)

lenses of garnetiferous amphibolite up to several metres thick are also present. These amphibolitic bodies are typically concordant with bedding in the surrounding Moine rocks, but examples of cross-cutting bodies do occur farther east (see Holdsworth *et al.*, 1987). They are generally interpreted to represent pre-tectonic mafic intrusions, but Rock and Macdonald (1986) describe amphibolite layers within the Assapol Striped and Banded Formation which they interpreted to be of sedimentary origin (see also Highton, in prep).

The semipelitic and pelitic layers are variably gneissose, with abundant thin quartzofeldspathic segregations that lie generally parallel to the predominant schistosity. The overall resultant foliation is generally a transposed penetrative fabric (S2) within which relict early tight to isoclinal folds of the primary gneissose foliation (S1) are locally preserved (NM 3767 1870). A finer bedding-parallel mica fabric in the psammitic lithologies is inferred to be S1. F2 folds are typically small-scale, reclined, tight to near-isoclinal structures, accompanied by intense L2 rodding (NM 3817 1868). The GCR site lies on the western limb of the tight, near-upright SSW-trending F3 Assapol Synform. Locally, minor F3 folds are abundant, and an accompanying upright crenulation cleavage is typically developed where the rocks are pelitic or semipelitic.

Scattered beach outcrops south of Ardalanish Bay (Figure 8.29) expose pelitic units that contain kyanite, garnet, tourmaline and subsidiary staurolite. Blades or granular aggregates of blue-grey to blue-green kyanite up to 5 cm long stand out in relief on the weathered surfaces. The larger blades are skeletal and contain inclusions of quartz, biotite, monazite, sphene and zircon. Most kyanite and staurolite porphyroblasts lie within the plane of the regional schistosity, and clearly pre-date the S3 crenulation cleavage. Replacement by fine-grained white mica (shimmer aggregate) is common, with kyanite (and less commonly staurolite) preserved only as corroded relict grains. Locally these white mica aggregates have recrystallized to larger muscovite porphyroblasts. The larger garnet porphyroblasts show composite zoning and prominent curved inclusion trails at a high angle to the regional fabric. The outer margins of these porphyroblasts and the smaller inclusion-free porphyroblasts both commonly overgrow the penetrative S2 cleavage foliation. A short distance east of Ardalanish Bay at Port Bheathain (NM 4036 1891), examples of ragged relict intergrown kyanite and staurolite porphyroblasts, armoured by muscovite, are found. These aggregates and porphyroblasts of muscovite are wrapped by the penetrative S2 fabric and folded by the D3 crenulation.

Evidence for contact metamorphism is found throughout the exposed Moine metasedimentary rocks. The outer limit of the aureole, some 2 km from the pluton boundary, is marked by the incoming of a 'foxy' red-brown biotite. However, thermal metamorphic minerals only become abundant within the inner aureole, marked by the incoming of andalusite some 500 m from the granite contact. Indeed, Bailey and Anderson (1925) placed the outer margin of the aureole at this point. Within the gneissose pelite outcrop of Dùn Fuinn (NM 3754 1888), the blue colour of the kyanite porphyroblasts becomes less intense as the rocks take on the pink colouration of andalusite. Knots of sillimanite (up to several centimetres across) and small porphyroblasts of andalusite are prominent in the semipelitic and pelitic lithologies, and small dark-grey well-formed circular to ovoid crystals of cordierite are ubiquitous. Cordierite grows at the expense of biotite in the more-micaceous psammitic lithologies. Regional metamorphic muscovite disappears from the Moine metasedimentary rocks in reactions associated with the growth of andalusite (Figure 8.29). Large ragged porphyroblasts of white mica commonly replace andalusite with the incoming of sillimanite and further breakdown of biotite. Within 300 m of the pluton the rocks are strongly hornfelsed. In outcrops close to Port Mòr (NM 368 182) and west of Ardachy (NM 371 193) the regional tectonic fabrics and mineral assemblages are locally barely recognizable owing to recrystallization. The higher-grade assemblages containing fibrolite and sillimanite only appear within the inner aureole close to the granite contact (Brearley, 1984; Mangan, 1996). Here, there is evidence of small-scale partial-melting and migmatization. The weakly foliated microdiorite sheets outcropping at NM 3682 1822 and NM 3615 1907 are extensively recrystallized, with hornblende overgrown and replaced by red-brown biotite.

Interpretation

The presence of kyanite and staurolite in the pelitic and semipelitic rocks of the Moine succession points to a regional lower amphibolite-facies metamorphism (Rock and Macdonald, 1986; Holdsworth *et al*., 1987), with the mineralogies implying pressures of *c*. 7 kbar and temperatures in the range 650 ± 50° C (Mangan, 1996). This metamorphism was probably contemporaneous with generation of the gneissose fabric and quartz-feldspar segregations and coeval with the D2 deformation; hence probably of Neoproterozoic age (Fettes *et al*., 1985; Tanner and Evans, 2003; see also 'Introduction', this chapter). The replacement of the kyanite and staurolite by shimmer aggregate and subsequent recrystallization to muscovite porphyroblasts is a regional metamorphic transformation that pre-dates the F3 folding and is attributed to Caledonian events. This 'retrograde' hydration reaction, which also consumed enclosing biotite and plagioclase, is found in assemblages outside the aureole and thus not directly related to the contact metamorphism associated with the emplacement of the Ross of Mull Pluton.

Within the metamorphic aureole of the Ross of Mull Pluton, the regional metamorphic assemblages are preserved locally as metastable relics. The thermal effects of the pluton are defined by a series of discontinuous reactions that took place under isobaric conditions, with the partial pressure of water (aH_2O) varying from 0.4 to 0.55 at the upper stability of muscovite (Brearley, 1984). Mineral assemblages show apparent disequilibrium textures, suggesting that reactions were incomplete on the attainment of kinetic equilibrium (Mangan, 1996; Wheeler *et al*., 2004). The inner aureole is defined by the development of a discrete andalusite-bearing zone with both fibrolite and/or sillimanite absent. Andalusite appears to be stable at the first development of fibrolite, but becomes metastable and replaced by white mica at the incoming of coarse sillimanite, approximately 200 m from the contact. Closer to the contact, sillimanite is the only Al_2SiO_5 polymorph present. Here, localized partial-melting is seen in the pelitic rocks, and is reflected in the lowering of aH_2O from 0.55 to 0.4 (Brearley, 1984). Metastable kyanite is locally present within the andalusite-bearing zone, but it is mostly pseudomorphed by andalusite. The reported co-existence of all three aluminosilicate phases within a single specimen as reported by Bosworth (1910) is erroneous (Rock and Macdonald, 1986). However, the conditions at the time of granite emplacement (Brearley, 1984) should have allowed the regional metamorphic kyanite to remain stable within the outer aureole. Within the aureole, temperatures range from 700° C at the contact to 525° C in the outer aureole, with the rocks lying at a crustal depth of approximately 12 km (pressures of *c.* 4 kbar) (Brearley, 1984).

Conclusions

The Ardalanish Bay GCR site preserves the most westerly known outcrop of the Neoproterozoic Moine succession in Scotland. The succession on Mull comprises an older Shiaba Group and a younger Assapol Group, correlated with the Morar and Glenfinnan groups respectively. At Ardalanish Bay regional lower amphibolite-facies metamorphic assemblages that include kyanite and staurolite are locally well developed, notably in the semipelite and pelite lithologies. The regional structures, fabrics and metamorphism relate to the D2 deformation, but are overprinted by a thermal aureole associated with the emplacement of the Silurian-age Ross of Mull Pluton. Within the aureole, contact metamorphic minerals developed, including andalusite, sillimanite and cordierite. Throughout much of the broad metamorphic aureole, kyanite is metastable. However, kyanite disappears within the high-temperature inner aureole, where andalusite and sillimanite are the successively stable polymorphs. Although all three aluminosilicate polymorphs occur within the thermal aureole, they do not co-exist at a single locality. The site is nationally important as it provides a well-documented example of the effect of the late orogenic granitic plutons on the earlier regional metamorphic assemblages in the Moine succession. It shows that the three distinct aluminosilicate (Al_2SiO_5) polymorphs can occur within a restricted area where thermal metamorphic effects overprint regional assemblages. It also provides an apparent stratigraphical transition from Morar Group to Glenfinnan Group rocks, a boundary obscured by the Sgurr Beag Thrust elsewhere in the North-west Highlands.