Chapter 7 Moine (Central)

Introduction

J. R. Mendum

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

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

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

History of geological work

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

The original surveyors recognized that the Lewisianoid gneisses and Moine metasedimentary rocks were distinct units showing evidence of different geological histories. They discovered rare occurrences of deformed conglomerate in the basal parts of the Moine succession (see Allt Cracaig Coast GCR site report, this chapter), and postulated an unconformable relationship between the two rock units. In the 1950s a series of structural studies of the Scardroy, Fannich and Monar Lewisianoid inliers (Figure 7.1) led some workers to put forward a contrary interpretation (Sutton and Watson, 1953, 1954; Ramsay, 1954). These studies emphasized the 'stratigraphical, structural and metamorphic concordance between the gneissose rocks of the inliers and the surrounding Moine metasedimentary succession. The deformed 'conglomerates' were ascribed to purely tectonic processes of segregation and deformation. The homblendic felsic and mafic gneisses were regarded as possible metavolcanic units within the Moine stratigraphy. Such ideas were an extension of the 'Durcha-type-Moines' advocated by Read *et al.* (1926) farther north (see Allt Doir' a' Chatha GCR site report, Chapter 6).

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

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

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

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

Tanner *et al.* (1970) and Tanner (1971) defined the trace of the Sgurr Beag Thrust in Ross-shire and part of Inverness-shire (see Chapter 8). They recognized that it was a major thrust that controlled the occurrence of Lewisianoid inliers, but was also the site of apparent stratigraphical excision. Rathbone and Harris (1979) documented the strain variations adjacent to the Sgurr Beag Thrust and confirmed that its trace separated Morar Group and Glenfinnan Group rocks. Kelley and Powell (1985) discussed the movement history of the Sgurr Beag Thrust relative to that of the Moine Thrust Belt in the Fannich Mountains (see Fannich and Meall an t-Sithe and Creag Rannich GCR site reports, this chapter).

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

Geological history

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

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

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

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

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

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

Main lithologies

Lewisianoid gneiss inliers

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

(Clifford, 1957; Kelley, 1988; May *et al.*, 1993).

The Glenelg–Attadale Inlier

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

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

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

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

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

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

Metasedimentary rocks generally occur as abundant lenticular units that range from a few metres up to *c.* 450 m thick; some units can be traced for up to 20 km. The most prominent sedimentary lithologies are metalimestones/ metadolomites (formerly termed 'marbles'), gneissose pelites and iron-rich rocks. The meta-limestones and metadolomites contain layers of forsterite or diopside nodules up to 2 m across, as described in the Totaig and Dornie–Inverinate Road Section GCR site reports (this chapter). The pelitic rocks include gneissose garnet-biotite pelites and coarsely gneissose kyanite pelites (Sanders, 1972; Rock *et al.,* 1986), originally aluminous and magnesian mudstones (see Druim Iosal GCR site report, this chapter). More highly iron-rich mudstones or clays are represented by the rare garnet-magnetite eulysites, which contain iron-rich olivine (fayalite) and iron-rich pyroxenes. They are seen around Totaig (Tilley, 1936) and in several other places (Barber, 1968; Sanders, 1972).

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

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

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

Lewisianoid inliers of Ross-shire and other areas

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

Lewisianoid–Moine relationships

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

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

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

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

Moine Supergroup

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

Morar Group

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

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

Glenfinnan Group

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

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

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

It is overlain to the east by a massive gneissose muscovite-biotite-semipelite and pelite unit, here termed the 'Sgurr Beag Pelite Formation' (Tanner, 1971). Quartz and quartzofeldspathic segregation veins and pods are ubiquitous, and muscovite porphyroblasts are common in the formation. Thin psammite units, calc-silicate lenses and garnetiferous amphibolite pods form minor elements of the formation. The pelite unit is widespread but has been given local names in other parts of the Moine (Central) area (Figure 7.3). It is termed the 'Beinn Dronaig Pelite' in Glen Carron, the 'Sgùman Coinntich Pelite' in Kintail, the 'Clach Loundrain Semipelite' in upper Strathconon, the 'Sgurr Marcasaidh Formation' in Strathglass, and the 'Wall an t-Sithe Pelite' in the Fannich Mountains. Farther north this unit is known as the 'Ben Wyvis

Pelite Formation' (see Carn Gorm GCR site report, Chapter 6). In the Kinlochhourn–Loch Quoich area, Roberts *et al.* (1987) failed to distinguish a significant pelite unit and assigned the rocks to the Quoich Banded Formation, a mixed unit that encompasses much of the Glenfinnan Group rocks farther south (Holdsworth *et al.,* 1994). However, a thin pelite unit can be traced southwards where it links with the Lochailort Pelite Formation (see (Figure 7.3), and (Figure 8.2), Chapter 8).

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

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

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

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

Loch Eil Group

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

Igneous rocks

Neoproterozoic metadolerite

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

Caledonian igneous rocks

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

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

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

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

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

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

Structure, metamorphism and Neoproterozoic and Caledonian orogenic evolution

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

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

Structural sequence in the Moine succession

In much of the Moine succession in this central area, three main penetrative deformational and metamorphic events can be readily distinguished (see (Table 7.2)). In that respect there is a similarity to the Moine (North) area, but it is unclear whether the deformation phases are direct correlatives. In north Sutherland, west of the Naver Thrust Zone, Sm-Nd ages on metamorphic garnet and hornblende suggest that the earliest fabric-forming event (D1) occurred around 800–830 Ma (Strachan *et al.,* 2002b), but Ar-Ar and Rb-Sr mica and hornblende dating implies that the main fabrics (? 'D2') formed during the Scandian Event (Dallmeyer *et al.,* 2001). East of the Naver Thrust Zone U-Pb zircon age dating suggests that the main 'D2' fabrics and mineralogy result from the Grampian Event (see Chapter 6). In contrast, in the Moine (South) area, available geochronological evidence suggests the main 'D2' deformation may well be Knoydartian (Neoproterozoic). The recognition and dating of at least four separate phases of metamorphism based on detailed garnet studies in the Moine (South) area (Zeh and Millar, 2001 — see below) suggests that the metamorphic evolution of the Moine spanned some 450 million years. However, little direct dating evidence from the tectonic fabrics or metamorphic assemblages is available for the Moine (Central) area. Emery *et al.* (2004) obtained a U-Pb SHRIMP zircon age of 727 ± 6 Ma from kyanite-bearing migmatitic semipelite from the Achnaconeran Striped Formation in Glen Urquhart. They interpreted this age as dating anatexis and hence Neoproterozoic high-grade metamorphism.

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

D1 deformation

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

D2 deformation

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

D2 slides and the Sgurr Beag Thrust

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

The Sgurr Beag Thrust can be traced from Kinlochhourn, north to Glen Shiel, and via the central Ross-shire Lewisianoid inliers to Garve.

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

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

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

D3 deformation

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

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

D4 and later phases

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

Metamorphism

The overall pattern of metamorphism in the Moine (Central) area is one of increasing metamorphic grade from west to east. Plagioclase compositions in calc-silicate rocks have been used to show the rise from greenschist facies (< $An_{a)}$) on Sleat in the west, to lower- and middle-amphibolite-facies assemblages (> An6o) in the Glenfinnan Group rocks in the east (Winchester, 1972; Tanner, 1976; Fettes *et al.,* 1985). Diopside occurs in only a few of the highest-grade calc-silicate pods. Loch Ell Group calc-silicate rocks show evidence of hornblende replacement of pyroxene and development of two-stage garnets. Later retrograde actinolite, biotite and clinozoisite are also commonly developed in many of these calcareous rocks (May and Highton, 1997). Index minerals relating to pelitic rocks are not abundant, and although kyanite does occur in some of the pelitic units, for example in Glen Cannich (Tobisch, 1963; Peacock *et al.,* 1992) and around Loch a' Chrithaich (May and Highton, 1997), normally it is partly or wholly pseudomorphed by muscovite. Muscovite also occurs abundantly as shimmer aggregate in the higher-grade areas, probably after fibrolite and sillimanite. Garnet, muscovite and biotite porphyroblasts are also common. Garnets show flat compositional profiles in the higher-grade areas, but zoning profiles are present farther east where retrogression has reduced the grade to lower-amphibolite facies. Relict staurolites have been reported in some muscovite porphyroblasts in the south-west part of the Invermoriston district (May and Highton, 1997).

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

Devonian and later faulting

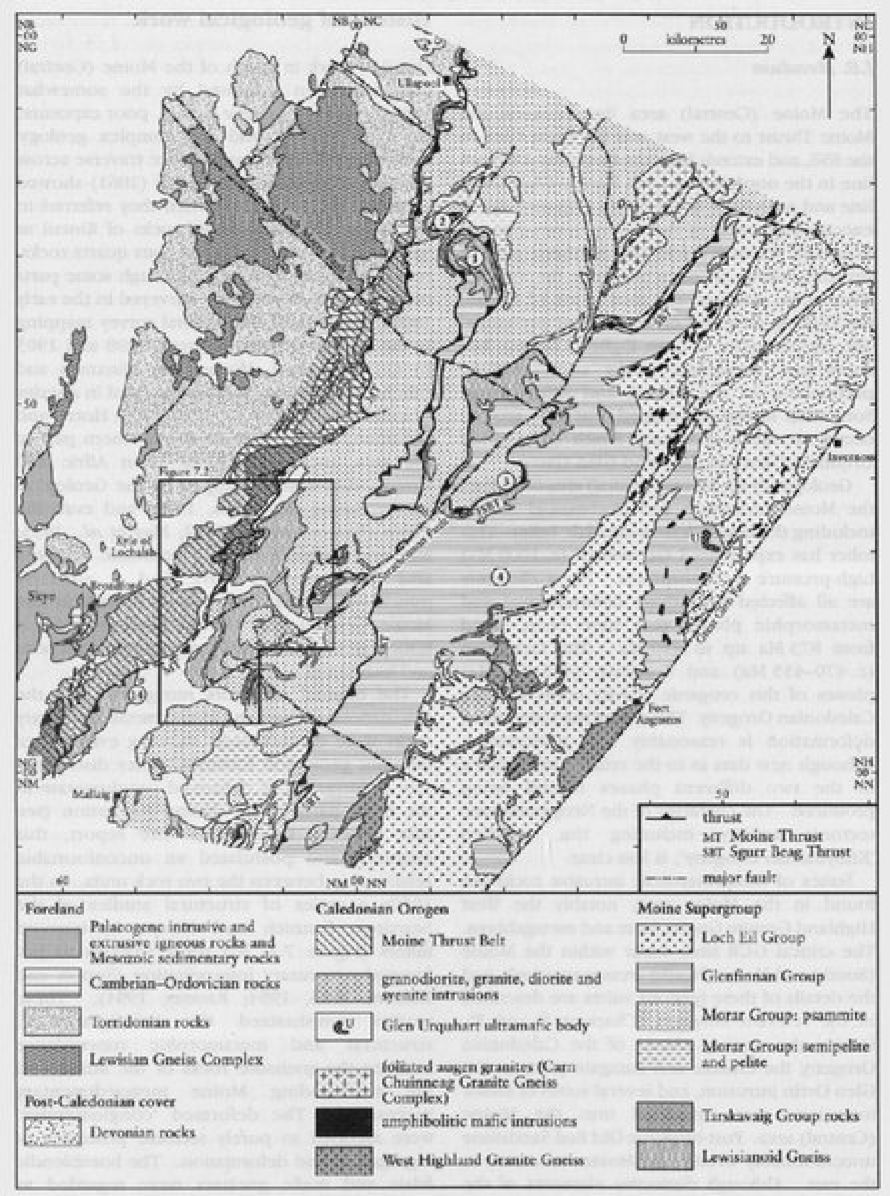
The dominant fault trend in the Moine (Central) area is north-east–south-west, with the Great Glen, Strathconon and Strathglass faults being the major structures. These faults were generated or strongly reactivated at the close of the Caledonian Orogeny, when they were the sites of significant sinistral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

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

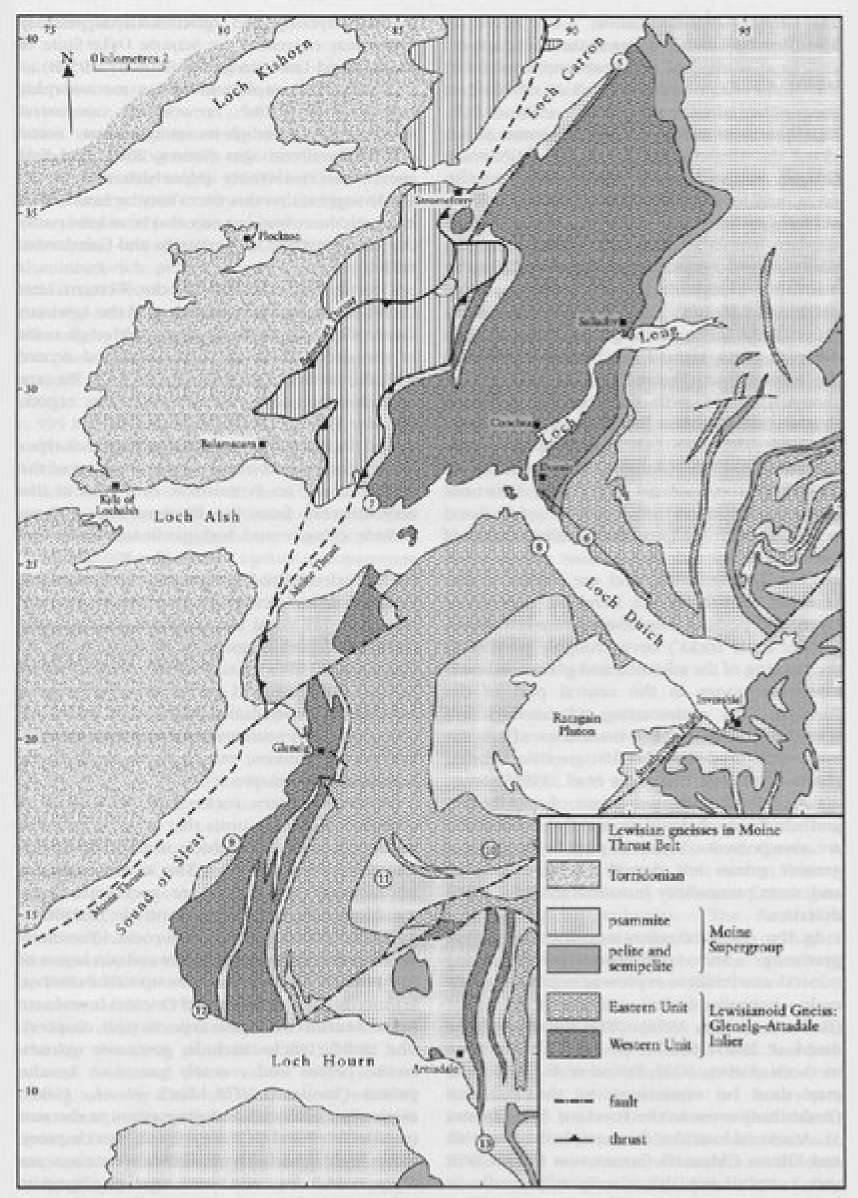
The Strathconon Fault is a complex fault-zone marked by cataclasite, breccia and soft gouge. The overall fractured zone is up to 1.5 km wide. The net sinistral displacement of *c.* 6 km is shown by displacement of the microdiorite, andesitic and microgranite (felsite) dykes related to the Ratagain Pluton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

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

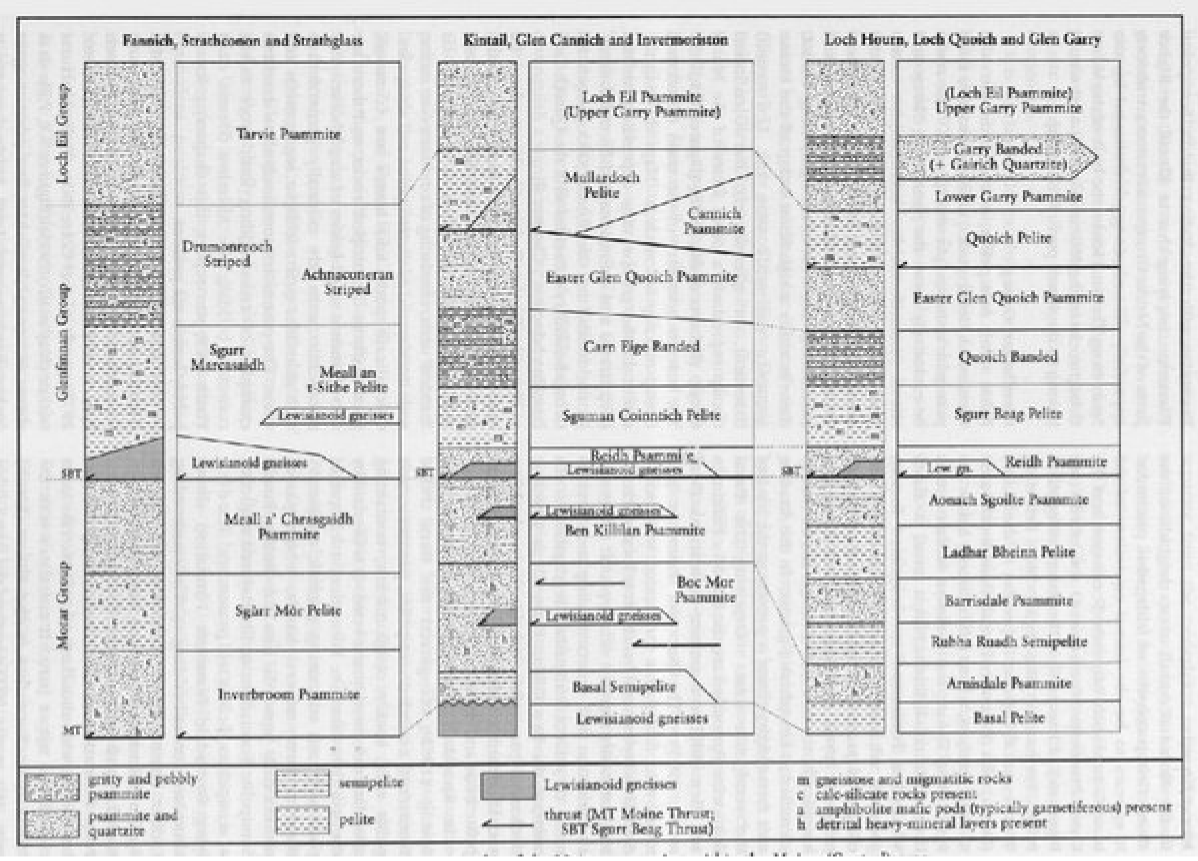
References



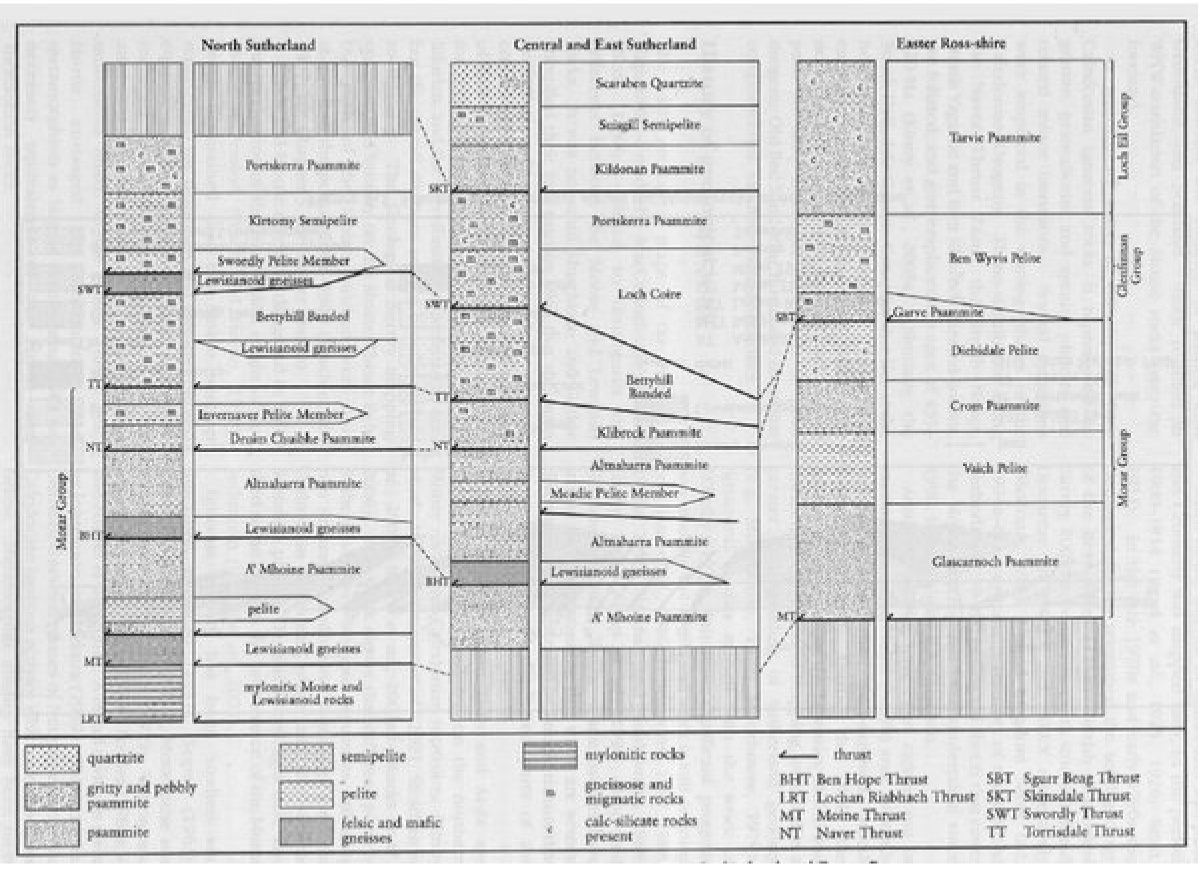
(Figure 7.1) Geological map of the Moine (Central) area, with the location of the GCR sites: 1 — Fannich; 2 — Meall an t-Sithe and Creag Rainich; 3 — Loch Monar; 4 — Abhainn Gleann nam Fiadh; 14 — Ard Ghunel. GCR sites 5–13 are located within or marginal to the Glenelg–Attadale Inlier and are shown on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



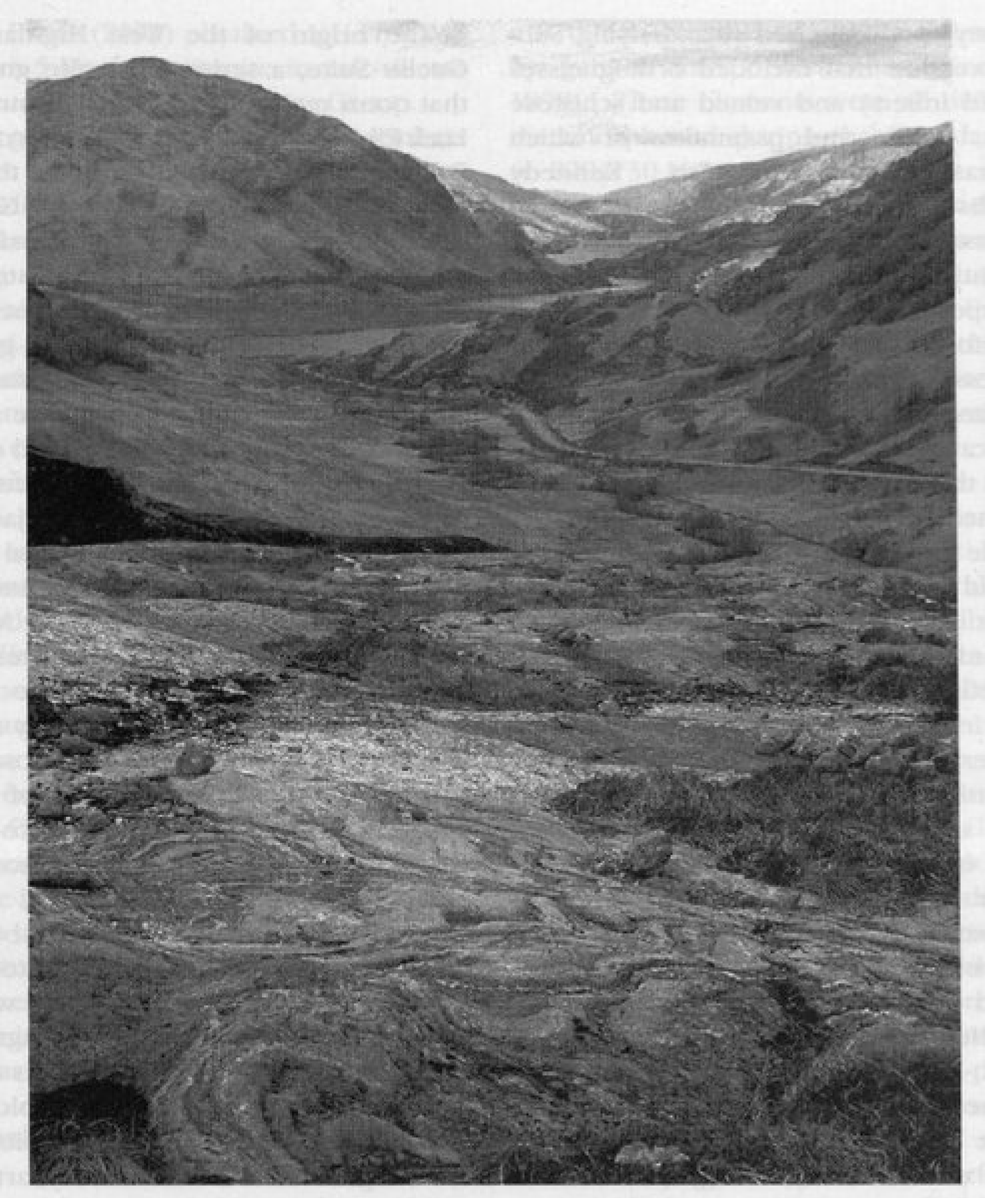
(Figure 7.2) Geological sketch map of the Glenelg–Attadale Inlier and surrounding area (after Barber and May, 1976), showing the location of the GCR sites within or marginal to the Glenelg–Attadale Inlier. 5 — Attadale; 6 — Dornie—Inverinate Road Section; 7 — Avernish; 8 — Totaig; 9 — Allt Cracaig Coast; 10 — Druim Iosal; 11 — Beinn a' Chapuill; 12 — Eilean Chlamail—Camas nan Ceann; 13 — Rubha Camas na Cailinn.



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



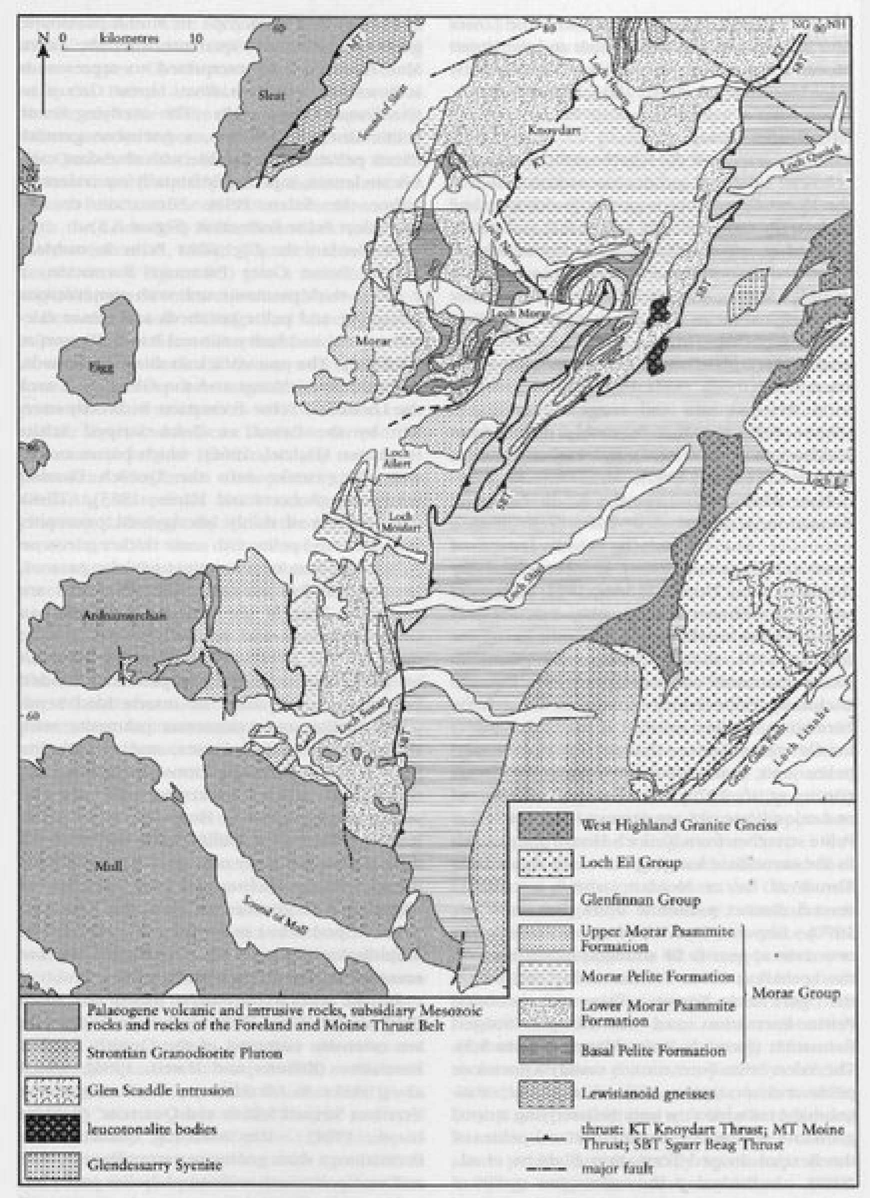
(Figure 6.2) Stratigraphy of the Moine Supergroup in Sutherland and Easter Ross.



(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.)

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

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



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

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

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