Chapter 6 Moine (North)

Introduction

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This chapter describes the area of dominantly Moine rocks that stretches north of a broad line between Inverness and Ullapool to the north coast of mainland Scotland (Figure 6.1). The rocks are bounded to the west by the Moine Thrust and to the east by the Old Red Sandstone outcrop, except for a few inliers of Moine and Lewisianoid rocks adjacent to the Great Glen Fault in the Inner Moray Firth. The area encompasses much of the Northern Highlands and includes Sutherland, Easter Ross, and parts of Wester Ross, Caithness and the Black Isle. The Moine (North) GCR sites cover a wide range of geological features and rock types. Many sites describe elements of the Neoproterozoic Moine Supergroup and older Lewisianoid inliers, others include Neoproterozoic and later Caledonian intrusions, and even the nature of the Old Red Sandstone unconformity with the Moine rocks.

This northern Moine area includes the locality of Mhoine from which the succession was named (see Peach *et al.,* 1907). The peninsula of A' Mhoine west of the Kyle of Tongue is capped by featureless moorland with only a few isolated exposures of Moine psammite, pelite and Lewisianoid gneiss. Indeed, much of this northern Moine area is bleak by comparison with the central and southern parts of the Northwest Highlands. Ben Wyvis and Beinn Dearg dominate the southern part of the area, whereas to the north the mountains are more isolated with Ben Klibreck, Ben Loyal, Ben Hope and Ben Griam Mòr and Beag visible from much of Sutherland. The north Sutherland coast and its hinterland provide good exposure and many of the GCR sites are situated along it.

The Neoproterozoic Moine Supergroup and structurally interleaved Lewisianoid gneisses constitute most of the northern Moine area. The overall succession dips gently to moderately to the east, exposing progressively structurally higher units in that direction (Figure 6.2). Major ductile thrusts, notably the Ben Hope, Naver, Swordly and Skinsdale thrusts, have duplicated and thickened the crustal section as shown in (Figure 6.3). The Lewisianoid gneisses occur as a series of slivers and slices, commonly adjacent to the thrusts and in major fold cores. The gneisses record a complex Archaean history, details of which are still uncertain. U-Pb zircon isotopic studies (Friend *et al.,* 2008) show that their igneous protoliths formed at around 2900–2800 Ma, but provide no evidence of the Palaeoproterozoic reworking (e.g. the Laxfordian event at *c.* 1800 Ma) that is so evident in the Lewisian Gneiss Complex of the Foreland. The relationship between the Lewisian of the Foreland and the Lewisianoid inliers remains unclear.

In the early Neoproterozoic between *c.* 980 Ma and 875 Ma the Lewisianoid rocks formed the basement to fluviatile and shallow-marine basins in which the sand-dominated Moine succession was deposited (Friend *et al.*, 1997, 2003; Krabbendam *et al.,* 2008). The Moine Supergroup consists mainly of psammites, but contains some pelite units in its western part in Sutherland, and more-abundant semipelite and petite units farther east (Figure 6.2). The entire Moine succession was possibly deposited in extensive and long-lived fluviatile and shallow-marine basins (Soper *et al.,* 1998). Moine and Lewisianoid rocks were intruded by Neoproterozoic-age suites of mafic sills and dykes, all now deformed and metamorphosed to amphibolite. Comparable rocks in the southern and central Moine areas were intruded at *c.* 873 Ma (Millar, 1999). There is evidence for Neoproterozoic tectonothermal activity, including deformation and metamorphism that affected the whole succession at *c.* 840–820 Ma and at *c.* 740 Ma. However, the nature and extent of these Knoydartian events remain elusive. Intrusion of granitic bodies, notably the strongly foliated Carn Chuinneag and Inchbae intrusions, occurred in the period 611–588 Ma (Strachan *et al.*, 2002a). The intrusions are interpreted as a product of rifting that culminated in the break-up of the supercontinent Rodinia into Laurentia and Gondwana at *c.* 580 Ma.

The overall succession was subject to Caledonian orogenic activity. This occurred mainly in two events, the early Ordovician Grampian Event that peaked around 470 Ma, and the Mid- to Late Silurian Scandian Event at around 430 Ma. These Grampian and Scandian events interact in the Moine (North) area but their relative intensities are still subject to debate. They both produced penetrative fabrics and lineations and were associated with amphibolite- and greenschist-facies metamorphic events. The Grampian Event reflected arc collision to the south, whereas the Scandian

Event marked the collision of Baltica with Greenland and Scotland. Both resulted in WNW-translation of the Moine rocks onto the foreland.

A widespread suite of Silurian-age Late Caledonian igneous rocks is represented by granite, granodiorite and syenite plutons and related minor intrusions. Several intrusions were emplaced in the waning phases of the Caledonian Orogeny. Those distributed along the Naver Thrust Zone, the Strath Naver, Strath Vagastie and Ben Klibreck sheeted bodies, are foliated, and give emplacement ages of 435420 Ma (Kinny *et al.,* 2003a). Similarly, the Strath Halladale Granite Complex that lies at the northern end of the Skinsdale Thrust was emplaced at 426 Ma (Kocks *et al.,* 2006). The northern Moine area was uplifted and eroded prior to Early Devonian deposition of post-orogenic Old Red Sandstone fluvial and lacustrine conglomerates, sandstones and siltstones.

History of geological work

The early geological maps of the Northern Highlands — made by MacCulloch (1836) and Nicol (1858) — failed to distinguish the difference between the Moine and Lewisian rocks. It was not until Murchison and Geikie compiled their first map in 1861 that the main geological units were recognized as separate entities with different ages and histories. Many of their assignations proved later to be incorrect, for example the Moine was designated as Silurian, and the Torridonian as Cambrian in age, but the overall divisions remain broadly correct to this day. The Geological Survey mapping concentrated initially on the Moine Thrust Belt, but parts of the Moine outcrop were also mapped in the period 1884–1900 (Peach *et al.,* 1907; see Chapter 5, for further details).

Peach and Horne markedly disagreed in their interpretations of the nature and origin of the Moine succession (Peach and Horne, 1930). Peach maintained that the Moine outcrop represented the deformed and metamorphosed equivalent of the Torridonian succession with included lenses of Lewisian gneisses. He attributed the deformation to post-Cambrian movements linked to the Moine Thrust Belt. Horne envisaged the deformation and metamorphism as largely Precambrian with no necessary equivalence of the Moine and Torridonian rocks.

Much of the interior of Sutherland and Ross and Cromarty was mapped later, in the period 1900–1914 (Read *et al.,* 1925, 1926; Read, 1931). In the late 1970s and early 1990s the Geological Survey remapped the solid geology of the Reay Sheet (115E) (British Geological Survey, 2003) in connection with studies around Dounreay for UKAEA and NIREX respectively (McCourt, 1980: United Kingdom Nirex Ltd, 1994a-c). A systematic resurvey of many of the Sutherland 1:50 000 geological sheets that cover the Moine outcrop has been undertaken since 1990, led mainly by R.A. Strachan.

Academic studies have been carried out in various parts of the Moine (North) area, generally focused along the well-exposed north Sutherland coast. During the 1970s the geochemical studies of the Lewisian, Moine and intrusive rocks, allied to mapping, resulted in a greater understanding of Sutherland geology (e.g. Moorhouse, 1977; Moorhouse, 1979). Structural studies started with the work of O'Reilly (1971), but more-significant progress was made in the 1980s and work is still ongoing (e.g. Barr *et al.,* 1986; Holdsworth, 1987, 1988, 1989a, 1990; Strachan and Holdsworth, 1988; Grant, 1989; Alsop *et al.,* 1996; Alsop and Holdsworth, 1999, 2002). These studies have led to the understanding that there are several discrete nappes separated by ductile thrusts that have thickened and duplicated parts of the Moine succession.

More recently, zircon U-Pb and Ar-Ar age dating has been carried out on the northern Moine rocks and Caledonian intrusions (Kinny *et al.,* 1999; Dallmeyer *et al.,* 2001; Strachan *et al.,* 2002a; Kinny *et al.,* 2003a,b; Kocks *et al.,* 2006). This work shows that different parts of Sutherland carry isotopic signatures reflecting two separate Caledonian orogenic phases: the Ordovician Grampian phase and the Silurian Scandian phase. Detrital zircon ages have also shed some light on the provenance of the Moine sediments (Friend *et al.,* 2003).

Igneous activity has been studied and described by Read (1931), Soper (1963), Robertson and Parsons (1974), Moorhouse and Moorhouse (1979), Smith (1979), Wilson and Shepherd (1979), Rock (1983), Fowler (1988a,b) and Fowler *et al.* (2001). A broad review is given by Johnstone and Mykura (1989). This work has delineated several phases of Neoproterozoic and Caledonian igneous activity, which are described below. Metamorphic studies have been more limited, but the migmatitic rocks of east Sutherland have been the source of considerable discussion. Here, some authors

(Read, 1931; Cheng, 1943; Brown, 1967) have argued for sodic metasomatism as the main agent of migmatization and granite formation. However, McCourt (1980) postulated an igneous origin for the Badanloch and Strath Halladale sodic granites, and Kocks *et al.* (2006) argued that the latter intrusion was emplaced during Scandian deformation and thrusting. Burns (1994) and Friend *et al.* (2000) have suggested that the migmatitic rocks east of Bettyhill are the product of high pressure and temperature conditions related to orogenic crustal stacking during the earlier Grampian Event.

Lewisianoid gneiss inliers

Sheets, lenses and pods of Lewisianoid gneisses, up to several kilometres wide, are common in the Moine succession throughout Sutherland (Figure 6.3), (Figure 6.4). Some inliers retain their original stratigraphical relationship with the unconformably overlying Moine strata; more commonly they are structurally controlled (Strachan and Holdsworth, 1988; Strachan *et al.*, 2002b). These basement inliers consist of striped biotitic or hornblendic granodioritic, tonalitic and granitic orthogneisses, amphibolitic mafic layers and pods, and ultramafic pods. Minor graphitic pelites, gneissose semipelites, and rarely metalimestones and calc-silicate rocks are also recorded. Although they show similar lithological features to the Lewisian Gneiss Complex of the Foreland, the common occurrence of metasedimentary enclaves and the abundance of mafic and ultramafic lenses and pods give the Lewisianoid basement inliers a distinct identity. Descriptions are given in the north coastal GCR sites at Port Vasgo–Strathan Bay and Talmine (Talmine inliers), Strathan Skerray to Skerray Bay (Borgie Inlier), and at Aird Torrisdale and Farr Bay. Inland, Lewisianoid rocks occur in the Allt na Caillich, Allt an Dherue, Ben Klibreck, Airde of Shin, and Allt Doir' a' Chatha GCR sites. Isolated representatives also occur adjacent to the Great Glen Fault in the Cromarty and Rosemarkie Inliers GCR site.

The inliers have been strongly affected by Caledonian deformation, and normally show metamorphic mineralogies similar to the adjacent Moine rocks. However, the larger inliers (e.g. Borgie, Ribigill and Naver) preserve remnants of older Archaean and Palaeoproterozoic structural and metamorphic features. For example, in the Borgie Inlier, garnet-pyroxene-bearing metagabbro pods occur in the felsic and mafic orthogneisses (Holdsworth *et al.,* 2001). The fabrics and assemblages are not well dated, but by analogy with the foreland Lewisian Gneiss Complex many of the structures are probably of Archaean or Palaeoproterozoic age.

Whole-rock geochemical studies have attempted to distinguish Lewisianoid and Moine lithologies, and to characterize different Lewisianoid elements (Moorhouse, 1976; Moorhouse and Moorhouse, 1977). Generally, the Lewisianoid rocks show low K_2O, Ce, Rb and Pb contents, and high CaO, FeO and Sr, typical of granulite-facies Lewisian gneisses of the Foreland, whereas the Moine metasedimentary rocks show high TiO_2, Ce, Y, Rb, and generally higher SiO_2 values. Unfortunately, where discrimination between the two lithologies is difficult in outcrop, for example in the 'Meadie Shear Zone' (see Allt an Dherue GCR site report, this chapter), the geochemistry is not diagnostic (Moorhouse, 1977; Moorhouse *et al.,* 1988). In general terms the inliers have some geochemical similarities to the 'Scourian' terrains of the foreland Lewisian Gneiss Complex. Only some of the more-granitic parts have geochemical similarities with the reworked Laxfordianized Lewisian gneisses that form the foreland west of Loch Eriboll (Moorhouse, 1977) (see Chapter 3).

U-Pb SHRIMP zircon dating by Friend *et al.* (2008) on the Borgie Inlier and the Farr Inlier (Naver Nappe) imply a protolith age of *c.* 2900 Ma. Discordant zircon ages from the Ribigill West Inlier imply a protolith age of *c.* 2760 Ma. Whereas these ages correspond broadly with some of the protolith ages for the foreland Lewisian Gneiss Complex (Kinny and Friend, 1997), the overall isotopic signatures of the Lewisianoid inliers differ from the foreland terrains. There is no evidence of the 2490 Ma granulite-facies event of the Central Region of the Foreland, nor of the *c.* 1670–1740 Ma Laxfordian reworking typical of the Rhiconich and Torridon areas (Friend and Kinny, 1995, 2001). Hence, although the inliers have some features in common with the foreland Lewisian, their lithological and isotopic characters are distinctive, and they cannot be correlated directly with the various foreland Lewisian blocks or terranes.

Moine-Lewisianoid relationships

The relationship between the Lewisianoid inliers and the Moine succession in the Northern Highlands is variable and complex (e.g. see Moorhouse and Moorhouse, 1979; Strachan and Holdsworth, 1988). In most cases the contact has been a locus of high Caledonian shear strain. Fluid movement and recrystallization have focused along such shear zones, resulting in abundant new muscovite, quartz segregations and pegmatites. In such highly deformed areas it is not

easy to distinguish Moine psammites from Lewisianoid felsic gneisses.

Although many Lewisianoid–Moine contacts are ductile thrusts, in places Moine conglomerate lies on or close to the contact with Lewisianoid gneisses (e.g. see Port Vasgo–Strathan Bay and Ben Hutig GCR site reports, this chapter) (Mendum, 1976; Holdsworth, 1989a; Strachan *et al.,* 2002b). In most instances the unconformable contacts have acted as a locus of shearing during subsequent deformation.

The western boundaries of the main inliers are commonly Caledonian ductile shear-zones or thrusts across which WNW-directed translation has occurred (Holdsworth, 1989a). The large Borgie and Naver inliers also lie in the footwall to the Naver Thrust, and small Lewisianoid inliers lie beneath the Swordly Thrust. A structural exception is the folded and lineated Lewisianoid inlier found north of Rosemarkie (Cromarty and Rosemarkie Inliers GCR site), which was probably exhumed during Devonian ductile transpressional movements focused along the Great Glen Fault (Mendum and Noble, 2003).

Moine Supergroup

The Moine rocks were deposited as sands and subsidiary silts and muds, with minor gravels, in a wide, fluviatile and shallow-marine environment during early Neoproterozoic times. Their depositional age is bracketed by the youngest detrital zircons in Morar Group psammites at *c.* 950 Ma (Peters *et al.,* 2001; Kinny *et al.,* 2003a) and by the 870 Ma intrusion age of the West Highland Granite Gneiss Suite (Friend *et al.,* 1997; Rogers *et* al., 2001) (see 'Introduction', Chapter 8).

In the northern Moine outcrop the preserved remnants of this once-thick Moine sequence consist of psammites, locally conglomeratic and arkosic, with subsidiary semipelites and pelites. However, the overall E-dipping succession is essentially a structural rather than stratigraphical sequence (Figure 6.3). Major thrusts delineate several 'nappes'; from west to east these are the A'. Mhoine, Naver, Swordly and Skinsdale nappes ((Figure 6.4); Barr *et al.,* 1986; Holdsworth *et al.,* 1994; Kocks *et al.,* 2006). Additional thrusts are the Ben Hope and Torrisdale thrusts. As a result of this structural duplication and complication, estimates of original stratigraphical thicknesses (Holdsworth *et al.,* 1994) are very imprecise.

Holdsworth *et al.* (1994) provide a summary of the stratigraphy of the northern outcrop of the Moine Supergroup and its correlation with the succession farther south. An updated version is shown in (Figure 6.2). The division into Morar, Glenfinnan and Loch Eil groups can be attempted in Sutherland, but is less convincing than in the southern and central Moine areas. A dominantly psammitic western succession (Morar Group equivalent) is structurally overlain eastwards in the Naver Nappe by more semipelitic and pelitic units (possible Glenfinnan Group equivalent) and the highest structural levels are again dominated by psammites (possible Loch Eil Group equivalent). However, much of the succession seems to lie close to the Lewisianoid basement, at least as far east as Swordly, implying that either lateral facies changes are present or significant onlap has occurred. It is possible that Loch Eil Group rocks are absent, and that the most easterly psammites are either repeated Morar Group rocks or belong to a different group altogether. Also, the nature of the semipelitic and pelitic rocks in the Naver Nappe differs markedly from Glenfinnan Group rocks to the south. A traverse from west to east along the north Sutherland coast and hinterland illustrates the succession.

The A' Mhoine Psammite Formation is the most westerly and structurally lowest Moine unit. It directly overlies mylonitic Moine rocks and Lewisianoid gneisses, close to the Moine Thrust. Near its base, the formation locally contains prominent conglomerate lenses and thin garnetiferous pelite units. In Strath Melness a deformed but apparently unconformable relationship between the A' Mhoine Psammite and the underlying gneisses is exposed. In this area an actinolitic amphibolite unit, possibly representing a mafic metavolcanic or volcani-clastic unit, occurs a few metres above the base of the formation. The A' Mhoine Psammite Formation is bounded to the east by the Ben Hope Thrust (see Allt na Caillich GCR site report, this chapter). The overlying dominantly psammitic unit is termed the Altnaharra Psammite Formation' and also contains pelitic units, notably the staurolite-garnet-bearing Meadie Pelite (Figure 6.2) (Holdsworth *et al.,* 2001). A basal conglomerate is also reported from farther south in Strath Evelix (Strachan and Holdsworth, 1988). Both basal psammite formations lie with apparent local unconformity on Lewisianoid gneiss and are probably laterally equivalent, being merely repeated by thrusting along the Ben Hope Thrust. In low-strain areas the psammites commonly exhibit

excellent examples of cross-bedding and more rarely convolute lamination, graded bedding, channel features and slump-fold structures.

Farther east, between the Naver and Torrisdale thrusts, lies the strongly deformed, and partly migmatitic, Druim Chuibhe Psammite Formation (Holdsworth *et al.,* 2001). It consists of feldspathic and micaceous psammites with prominent semipelitic and pelitic units and minor calc-silicate lenses. The rocks have been metamorphosed under middle amphibolite-grade conditions and are commonly schistose and even gneissose with abundant quartz-feldspar segregations. Amphibolite sheets and pegmatitic granite veins and pods are common.

Above the Torrisdale Thrust, the Bettyhill Banded Formation constitutes the main unit of the Naver Nappe (Holdsworth *et al.,* 2001). The formation consists of gneissose psammite inter-layered with semipelite and pelite with very abundant amphibolite sheets. Sedimentary structures are absent and the rock types are commonly migmatitic. The amphibolites represent original intrusive basalt or dolerite sheets and dykes and locally still retain some low-angle, discordant contacts (Friend *et al.,* 2000). Intercalated Lewisianoid slices occur at Farr Bay (see Farr Bay GCR site report, this chapter) and farther east at Swordly. The Moine rocks show middle amphibolite-facies assemblages with the pelitic units containing sillimanite. Farther south, the equivalent unit is termed the 'Klibreck Psammite Formation' (Figure 6.2). These units have been interpreted as equivalent to the highest formations of the Morar Group (Moorhouse, 1977; Holdworth *et al.,* 1994), but they may be laterally equivalent to Glenfinnan Group rocks, or belong to a separate Sutherland Moine succession.

To the east the Swordly Thrust forms the upper boundary of the Bettyhill Banded Formation. If Glenfinnan Group rocks are restricted to the Swordly Nappe, this structure would be equivalent to the Sgurr Beag Thrust to the south. Note that Kinny *et al.* (1999) suggested that the main structural break occurs a little farther east at Kirtomy, and named this structure the 'Kirtomy Thrust'. However, this interpretation has now been retracted (Strachan *et al.,* 2002b). The Swordly Nappe contains the Kirtomy Semipelite and Portskerra Psammite formations, which Holdsworth *et al.* (1994) equated with the Glenfinnan Group and Loch Eil Group respectively. The Kirtomy Semipelite Formation (formerly termed 'Kirtomy Pelite Formation') consists of variable and locally strongly migmatitic and gneissose semipelite and pelite with subsidiary psammites and minor pyroxene-bearing calc-silicate lenses. Note that within this unit lies the enigmatic Strathy Complex (see below). At the base of the formation is the Swordly Pelite Member, a schistose to gneissose, garnet-muscovite-biotite pelite with prominent quartz and granitic segregations and veins. The overlying Portskerra Psammite Formation ranges from quartzose to micaceous psammite with thin lenses of semipelite, pelite and calc-silicate, again gneissose and migmatitic with middle amphibolite-facies mineralogies. Farther south the Loch Coire Formation is equivalent to the Kirtomy Semipelite Formation and on Ben Klibreck individual gneissose and migmatitic psammite and pelite units have been delineated (Read, 1931; Holdsworth *et al.,* 1994) (see Ben Klibreck GCR site report, this chapter). In eastern Sutherland and Caithness, an additional ductile thrust, the Skinsdale Thrust, has been recognized (Kocks *et al.,* 2006). This structure juxtaposes migmatitic Moine rocks in the foot-wall against non-migmatitic psammites, quartzites and semipelites of the Skinsdale Nappe in the hangingvvall. These structurally highest Moine units include the Kildonan Psammite – containing cross-bedding and graded bedding, – the Suisgill Semipelite, and the Scaraben Quartzite formations. The nature of the psammites has prompted correlation with the Loch Eil Group farther south (Strachan, 1988; Holdsworth *et al.,* 1994). The Scaraben Quartzite Formation is preserved only in E-plunging synclinal hinge zones north-west of the Helmsdale Granite. It is an orthoquartzite with subsidiary feldspathic quartzite and rare psammite and semipelite interbeds.

In Easter Ross and Cromarty the succession is more comparable to that found in the Loch Eil–Glenfinnan–Morar type area (Shepherd, 1973; Holdsworth *et al.,* 1994). The formation names given in (Figure 6.2) result from rationalization of the stratigraphy by the British Geological Survey during desk revision of sheets 93W (Ben Wyvis) and 93E (Evanton) (British Geological Survey, 2004a,b). The Morar Group rocks consist of the Glascarnoch Psammite Formation, which extends west to the Moine Thrust, the garnetiferous Vaich Pelite Formation ('Sgurr Mor Pelite' of Winchester, 1976), and the Crom Psammite

Formation. Sedimentary features in the psammite units include cross-bedding, convolute bedding, grading, and minor pebbly units. A notably low-strain area in the Crom Psammite Formation west of the Carn Chuinneag Granite but outwith its thermal aureole, shows almost undeformed sedimentary structures and bedding features. Above the Crom Psammite is the Diebidale Pelite Formation, which lies mostly within the andalusite-bearing thermal aureole of the Carn Chuinneag

Granite. It is semipelitic near its base and contains calc-silicate pods. The structurally overlying Glenfinnan Group rocks lie east of the Sgurr Beag Thrust (Grant and Harris, 2000). They consist of the Garve Psammite Formation (formerly 'Ben Wyvis Psammite' of Wilson, 1975; Holdsworth *et al.,* 1994), which is absent in parts, overlain by the thick gneissose Ben Wyvis Pelite Formation. The quartzose, feldspathic and micaceous psammites of the Tarvie Psammite Formation above are assigned to the Loch Eil Group.

Strathy Complex

In the vicinity of Strathy Point is a broadly triangular, partially fault-bounded, 6 km-wide outcrop of mostly grey, gneissose, quartz-rich 'psammites' and subsidiary 'semipelites' (Figure 6.1), (Figure 6.4). The rocks contain unusual mineral assemblages and are of uncertain age and provenance. The 'psammites' are commonly garnet-bearing and magnetite-rich, and in places contain orthoamphibole (gedrite, anthophyllite). Locally, as at Port Mor [NC 7736 6558], meta-limestone, calc-silicate rock and para-amphibolite are present. Abundant amphibolitic mafic sheets and pods, ultramafic pods (formerly pyroxenites), leucotonalite veins and pegmatitic granite veins and pods intrude the 'psammitic' rocks. Beneath the lighthouse at Strathy Point a *c.* 4 m-thick pod of gneissose 'semipelite' contains the mineral assemblage quartz-garnet-orthoamphibole-staurolite-hercynite (Moorhouse and Moorhouse, 1983). Towards its margins biotite + sillimanite-bearing assemblages dominate, and a little farther north on the point itself cordierite- and staurolite-bearing semipelites also occur. The rocks are highly depleted in potash and their geochemical signature is similar to that of granulite-facies rocks. They have been deformed and metamorphosed at lower crustal levels, possibly with some partial melting. The age and nature of the protolith is unknown; it may represent unusual Lewisianoid or Moine lithologies. However, Burns *et al.* (2004) used geochemical and oxygen isotope data to interpret the siliceous and mafic rocks as meta-somatically altered, bimodal volcanic rocks (dacite/basalt). On the basis of the unusual geochemistry and T_{DM} model ages they suggested that the complex represents a fragment of juvenile Grenvillian crust that predates and thus underlies the adjacent Moine succession. The complex is interpreted as having been incorporated into the Moine succession of the Swordly Nappe during Caledonian thrusting and deformation.

Neoproterozoic intrusive rocks

Basic meta-igneous rocks

Several generations of basic meta-igneous rocks are recognized in the northern Moine rocks. Most of these mafic bodies pre-date the earliest metamorphism and deformation and are now foliated or schistose amphibolites, containing hornblende, plagioclase, quartz and garnet. Garnet porphyroblasts up to 1 cm across are common. The amphibolites form sheets and lenticular bodies up to 100 m thick, but only rarely are dykes seen. The sheets occur in laterally persistent belts or swarms and represent originally intrusive basalt or dolerite sills.

A recent garnet, hornblende and whole-rock Sm-Nd age of 799 ± 26 Ma was obtained from the Ben Hope amphibolite (Strachan *et al.,* 2002a). This dates the metamorphic assemblage, but also defines a lower limit to the age of the mafic rocks. The rocks may be equivalent to the metabasic igneous intrusions near Glen Doe, dated at *c.* 873 Ma (Millar, 1999 — see 'Introduction' and Glen Doe GCR site report, Chapter 8.

Moorhouse and Moorhouse (1979) used field relations and major- and trace-element geochemistry to characterize different suites. In north Sutherland they recognized two pre-tectonic suites, the Ben Hope Suite and the Bettyhill Suite. The Ben Hope Suite forms composite sills that crop out both east and west of the Kyle of Tongue, generally coincident with the main thrust zones. They were sourced from sub-alkaline tholeiitic basaltic magma, which showed geochemical affinities to continental within-plate basalts, transitional to plate-margin types (Winchester and Floyd, 1984).

The main concentration of the Bettyhill Suite lies between Strath Naver and Strath Halladale. Swarm intensity appears broadly related to the presence of Lewisianoid inliers, with the Moine-Lewisianoid boundary forming a locus for intrusion of the mafic sheets. The Bettyhill Suite (see Ard Mor GCR site report, this chapter) was also sourced from sub-alkaline tholeiitic basaltic magma, but has geochemical affinities with plate-margin to ocean-floor basalt types (Winchester and Floyd, 1984). Other concentrations of amphibolitic mafic intrusions occur in Easter Ross, in Freevater Forest and Strath Carron, and in Strath Conon (see Comrie GCR site report, this chapter). Their geochemistry suggests they were

originally alkaline basalts or dolerites (Winchester, 1976).

In addition to the older mafic intrusive rocks described above, there is a younger suite — the Loch a' Mhoid Metadolerite Suite (Moorhouse and M000rhouse, 1979) — that does not share all the fabrics seen in the country rocks. These intrusions are concentrated in central north Sutherland between Altnaharra and the Kyle of Tongue. They range from metadolerite to metagabbro, and rarely metanorite, and include several ultramafic, originally dunite-peridotite bodies. Examples are described in the Allt an Dherue GCR site report (this chapter). Their geochemistry implies that they represent sub-alkaline to alkaline basalts with a continental within-plate signature. They cross-cut the bedding and layering in the adjacent Moine and Lewisianoid rocks respectively, and also reportedly cross-cut tight F2 folds and D2 fabrics (e.g. at [NC 5414 5097]) (Holdsworth *et al.,* 2001). In their central parts igneous textures and mineralogies are normally present, but their margins are foliated and commonly altered to biotitic amphibolite. Moorhouse and Moorhouse (1979) and Holdsworth *et al.* (2001) suggested that they are syn- to post-D2 in age (i.e. Ordovician or Silurian). The majority show lower-amphibolite-or greenschist-facies metamorphic assemblages and contain shear zones and strong marginal, penetrative planar fabrics attributable to D3.

Acid meta-igneous rocks

The oldest granitic rocks in the northern Moine area are thick, foliated pegmatitic granite pods that occur sparsely in the Ben Wyvis Pelite (Glenfinnan Group), as described in the Carn Gorm GCR site report (this chapter). Muscovite 'books' from this pegmatitic granite were dated by Rb-Sr methods, giving ages ranging from 625 Ma to 776 Ma (Long and Lambert, 1963; van Breemen *et al.,* 1974). Similar foliated granitic pegmatites from the Moine (South) area have given more-reliable Knoydartian U-Pb monazite ages of 824 Ma and 784 Ma (Rogers *et al.,* 1998). Several bodies of foliated granitic rocks also occur in the northern Moine area. The intrusions cross-cut an early fabric, but are affected by the main regional foliation (S2) and have an amphibolite-facies mineralogy. The most notable are the Carn Chuinneag and Inchbae intrusions in Easter Ross (Figure 6.1), which are mainly composed of foliated, coarse-grained muscovite-biotite augen granite. Within the main Can Chuinneag intrusion are smaller masses of amphibolitic gabbro and pyroxene diorite, fine-grained porphyritic granite (Lochan a' Chairn rock), non-porphyritic granite, and riebeckite granite. The mafic rocks pre-date the main porphyritic (augen) granite, but the other granites post-date it. The range of rock types and mineralogy suggest derivation by sub-lithospheric mantle melting with differentiation and crustal contamination of the resulting magma. Near the intrusion margins the S2 foliation is locally very strongly developed. Peach *et al.* (1912), Harker (1962), Wilson and Shepherd (1979) and Johnstone and Mykura (1989) describe the nature, distribution and relationships of the various elements. Andalusite and cordierite pseudomorphs are present in the Diebidale Petite Formation in its thermal aureole, where fine sedimentary structures such as ripple marks, mud cracks and fine lamination are preserved. The aureole overprints an early greenschist-facies fabric and mineralogy, yet is itself overprinted by kyanite-grade, amphibolite-facies metamorphism.

The intrusion of the Carn Chuinneag–Inchbae granites has been dated at 611 ± 11 Ma (U-Pb TIMS zircon; Strachan *et al.,* 2002a). Foliated augen granites also occur in the valley of the Berriedale Water in southern Caithness. Their chemistry suggests they were crustal melts and they have been dated at 588 ± 8 Ma (Braeval) and 599 ± 9 Ma (Berriedale) (SHRIMP U-Pb zircon; Kinny *et al.,* 2003b). The age range of granitic magmatism at 590–610 Ma is coeval with extrusion of the Tayvallich volcanic rocks in the south-west Highlands. The emplacement of the granitic intrusions and mafic volcanic activity were precursors to the rifting and break-up of the Rodinia supercontinent.

Caledonian igneous rocks

The main Caledonian igneous intrusions in this northern area form part of the Argyll and Northern Highlands Suite of Late Silurian to Early Devonian age, marking the end of orogenic deformation (Highton, 1999). They appear to form a coherent high Ba-Sr suite in terms of their major-, trace-element and isotopic geochemistry (Fowler *et al.,* 2001). The main granitic intrusions are the Rogan, Fearn, Migdale and Helmsdale plutons, and the partly foliated granite-sheeted complexes of Strath Halladale and Strath Naver. Extensive granite veining also occurs in Strath Kildonan, Strath Brora, Strath Naver, and the Kirtomy area. In addition there is the foliated Clerkhill Intrusion, the Reay Diorite, and the scattered Ach'uaine Appinitic Intrusion-swarm. The Loch Loyal Syenite Complex is slightly older (Silurian; 426 ± 9 Ma U-Pb bulk zircon; Halliday *et al.,* 1987) and forms part of the North-west Highlands Alkaline Suite (Robertson and Parsons, 1974;

Parsons, 1999). A full description of the various elements is given in Stephenson *et al.* (1999). In addition, examples of the Late Caledonian minette suite, the microdiorite suite, and later Permo–Carboniferous monchiquite suite are present (Rock, 1983; Johnstone and Mykura, 1989).

The Rogart Quartz-monzodiorite–granite Pluton consists of a central granodiorite surrounded by a marginal quartz-monzodiorite. Biotite granite occurs in the southern part of the pluton in Strath Fleet, and earlier appinitic Ach'uaine Hybrid mafic intrusions are also found here (see Loch Airighe Bheg GCR site report in the *Caledonian Igneous Rocks of Great Britain* GCR Volume – Stephenson *et al.,* 1999). The Rogan Pluton is notable for its internal foliations and lineations, its general concentric and funnel-shaped nature, and its migmatitic envelope (Soper, 1963). The main granodiorite body appears to have invaded an earlier-formed migmatitic envelope. The various migmatitic features and textures are illustrated at the Aberscross Burn–Kinnauld, Creag na Croiche and Brora Gorge GCR sites. The granodiorite intrusion was dated at 420 Ma (K-Ar biotite; Brown *et al.,* 1968), but this probably reflects uplift and cooling of the pluton. More-recent U-Pb TIMS dating of the main granodiorite has given an emplacement age of 425 ± 1 Ma Oohnson and Strachan, 2006).

The Strath Halladale Granite Complex consists of a series of thick biotite granodiorite sheets that dip moderately eastwards. Its intrusion was dated at 426 ± 2 Ma (U-Pb TIMS zircon age; Kocks *et al.,* 2006). The granodiorite sheets lie in a wider zone of migmatites and sodic granite veins, which are now thought to be older than the granite complex. Lintern and Storey (1980) record that veins and sheets of the main granodiorite cross-cut D2 folds and fabrics, but are locally internally foliated. The granite complex is interpreted as having been intruded coeval with the latest D3 penetrative deformation (Kocks *et al.,* 2006). This Late Silurian-age Scandian deformation is widespread and related to WNW-directed thrusting of the country rocks. The granite is correlated with the foliated Strath Naver (429 ± 11 Ma), Klibreck (420 ± 6 Ma) and Strath Vagastie (423 ± 8 Ma) granite intrusions (Kinny *et al.,* 2003a) and the foliated dioritic and granodioritic Clerkhill Intrusion. The partly foliated Reay Diorite, which also includes quartz-diorite and granodiorite, appears to relate spatially and geochemically to the Strath Halladale Granite Complex (McCourt, 1980; Kocks *et al.,* 2006).

Immediately east of the Naver Thrust lies the Torrisdale Vein-Complex, a series of granite sheets up to *c.* 100 m wide (Holdsworth *et al.,* 2001). The intrusions locally cross-cut bedding and D2 structures, but are folded by F3 fold structures. The sheets and veins carry planar and linear fabrics that can be matched in the adjacent rocks, showing structural relationships similar to the Strath Naver and Klibreck granites farther south.

The Helmsdale, Migdale and Fearn plutons are more-uniform monzogranites showing sharp contacts with the adjacent Moine rocks. The Migdale and Fearn plutons have some migmatitic rocks in their aureoles. A biotite K-Ar age of 400 ± 15 Ma was obtained from the Helmsdale Granite (Miller and Brown, 1965), and Pidgeon and Aftalion (1978) obtained a lower intercept of around 420 Ma from bulk zircon U-Pb TIMS analyses. The small Grudie Granite south of Loch Shin has considerable associated sulphide mineralization with molybdenite reported (Gallagher *et al.,* 1974).

The Ach'uaine Hybrid intrusions are scattered widely across the Moine outcrop throughout Sutherland. They occur as small pods and sheets up to 1.5 km long and 200 m wide and range from ultramafic to syenitic and even granitic. They are mostly meladiorites, characterized by coarse hornblende. There is a concentration of these small bodies around and within the Rogart Pluton (e.g. see Loch Airighe Bheg GCR site in Highton, 1999). Although Read (1931) originally interpreted these intrusions to be a product of hybrid ultramafic–granitic magmas, they are now considered to form a cluster within the Appinite Suite. They are more fully described and discussed by Highton (1999).

Old Red Sandstone

The deformed and metamorphosed Moine and Lewisianoid rocks that formed the bulk of the Caledonian Orogen are unconformably overlain to the east by the Old Red Sandstone. Hence, by Early Devonian times local conglomerate- and sandstone-dominated successions were being widely developed on the already deeply eroded remnants of the Caledonian Orogen. The Old Red Sandstone strata can be divided into two successions; an Early Devonian (Emsian) conglomerate, sandstone and subsidiary mud-stone sequence, and a Mid-Devonian (Eifelian–Givetian) conglomerate, sandstone and siltstone sequence (D.A. Rogers *et al.,* 1989). The older rocks are the remnants of a post-orogenic fluvial

and lacustrine sequence, laid down in a desert environment. They commonly show evidence of local derivation in fault-bounded half-graben basins. For example, the dominant syenite clasts in the conglomerates at the Coldbackie Bay GCR site can be matched with outcrops on Ben Stumanadh some 10 km to the SSE. The Early Devonian succession was once widely developed across much of the northern Moine but now occurs only at the margin of the main Old Red Sandstone outcrop or in scattered outliers (e.g. Strath Vaich, Ben Griam More, Meall Odhar) (Figure 6.1). The younger Mid-Devonian rocks, mainly Caithness 'flagstones', relate to the thicker, more-coherent, Orcadian lake succession. The characteristic cyclic sandstone–siltstone–calcareous mudstone ('fish bed') succession can be traced from Caithness to Orkney and even to the Moray and Nairn areas. However, marginal fluvial and lacustrine facies occur in Caithness and east Sutherland. They commonly reflect the highest lake levels and are marked by the local development of stroma-tolitic dolomitic limestones, as at the Dirlot Castle GCR site. The outliers at Kirktomy and on Eilean nan Ron are not readily attributed to either the Early or Mid-Devonian successions, but the Strathy outlier is clearly a down-faulted part of the Mid-Devonian lacustrine succession.

Structure and metamorphism and Neoproterozoic and Caledonian orogenic evolution

Caledonian orogenic effects dominate the overall structure of the northern Moine area. The Moine Thrust Belt forms a natural western boundary to this internal part of the orogen (see Chapter 5). East from the thrust belt the Moine and Lewisianoid rocks are disposed in a series of major nappes within the Moine Thrust Sheet separated by E-dipping ductile shear-zones (Figure 6.1), (Figure 6.2), (Figure 6.3). From west to east the main nappes are the A' Mhoine, Naver, Swordly and Skinsdale nappes (Moorhouse and Moorhouse, 1983; Barr *et al.,* 1986; Kocks *et al.,* 2006). Each 'nappe' has its own stratigraphical, structural, and metamorphic character. The lower three nappes have been equated roughly to the Moine, Knoydart and Sgurr Beag 'nappes' farther south (Barr *et al.,* 1986; Holdsworth *et al.,* 1994), although such correlations are problematic.

The term 'Moine Nappe' has been used to describe different tectonic features in the Northwest Highlands. It is commonly applied to the whole Moine succession that lies structurally above the Moine Thrust (Barr *et al.,* 1986), here termed the 'Moine Thrust Sheet'. Holdsworth *et al.* (2001) term the lowest major thrust sheet in Sutherland the 'Moine Nappe' but here it is termed the ‘A’ Mhoine Nappe' and the term 'Moine Nappe' is retained for the lowest thrust sheet in the Moine South area.

Detrital zircon ages show that the Moine rocks are younger than *c.* 950 Ma (Peters *et al.,* 2001; Kinny *et* W., 2003a), and it is clear that both Moine and Lewisianoid rocks have shared a common tectonic and metamorphic history since that time. The Caledonian elements of this history comprise a Grampian (Ordovician) and a Scandian (Silurian) phase. One of the current issues of research is to determine which structures can be attributed to each orogenic phase. There is also evidence of pre-Caledonian tectonic activity. It is possible that some extension affected the sequence around 870 Ma, related to the intrusion of the West Highland Granite Gneiss Suite and basic meta-igneous rocks dated farther south (see Chapter 8). Nd-Sm ages from garnet (and staurolite) from pelite units and the Ben Hope Sill imply that the Sutherland Moine rocks experienced significant deformation and metamorphism during a Neoproterozoic Knoydartian orogenic event (see below), but its role, extent and structural expression remain somewhat unclear (see Strachan *et al.,* 2002b).

Deformation phases

The main deformation phases in the Moine rocks are labelled D1, D2, D3, D4 and so on. Each phase has its corresponding set of structures with planar fabrics termed S1, S2 and so on, linear fabrics L1, L2, and related folds, F1, F2. In the northern Moine rocks one of the main problems is to correctly correlate structures between different areas and to understand their relative ages and intensities. In this volume the terminology corresponds mainly to that used in the literature and refers to the local structural sequence. In many instances, structures are difficult to assign solely to a specific deformation phase. For instance, quartz lineations may reflect the cumulative (finite) strain of all the deformation phases, but this is by no means always the case. Also, folds in Sutherland tend to be coaxial, such that successive deformation phases apparently enhance or modify the preexisting geometry of an earlier deformation phase. This strongly influences the way in which the later structures develop. F2 and F3 folds in the Melness, Port Vasgo-Strathan Bay, Ben Hutig, and Coldbackie Bay GCR sites all show examples of this phenomenon.

D1 deformation results in a generally bedding-parallel fabric defined by biotite, muscovite, quartz and feldspar in the psammitic lithologies. In the pelitic units a pervasive biotite-muscovite S1 schistosity is present, and garnet, staurolite and kyanite porphyroblasts are all recorded (Holdsworth *et al.,* 2001). In the metabasic rocks a foliation defined by hornblende and overgrown by garnet typically results. In places, a N-trending L1 lineation is folded by F2 folds or preserved in low-strain areas (Holdsworth *et al.,* 2001). The interleaving of Moine and Lewisianoid rocks has been attributed to D1 (Johnstone, 1975; Moorhouse and Moorhouse, 1979), but the lack of both large-scale F1 folding and downward-facing D2 structures suggest that the main basement-cover interleaving was basically a D2 phenomenon (Holdsworth, 1989a). D1 deformation is probably Neoproterozoic in age (see below).

D2 refers to the main compressional, WNW-directed, shear-dominated, penetrative deformation that affects the Moine and Lewisianoid rocks. It resulted in penetrative S2 fabric in all rock types, large- and small-scale F2 folds and pervasive L2 lineations. Most of the ductile thrusts are also of D2 origin. Lewisianoid inliers commonly occur as F2 fold inliers (Strachan and Holdsworth, 1988) and even the large Borgie and Naver inliers appear to lie in large antiformal F2 hinge zones. In the structurally higher Naver and Swordly nappes the rocks are typically migmatitic and the main migmatitic foliation/ layering corresponds to S2. Fold axes generally lie parallel to the L2 lineation. In parts F2 axes are markedly curvilinear on both small- and medium-scales (Strachan and Holdsworth, 1988; Alsop *et al.,* 1996; Alsop and Holdsworth, 1999, 2002).

The ductile thrusts and shear-zones are marked by an intensification of the S2 schistosity resulting in strongly platy to mylonitic Moine and Lewisianoid rocks. F2 folds tighten and their axes rotate towards WNW parallel to the main movements in the Moine Thrust Belt (Peacock, 1975; Mendum, 1979; Strachan and Holdsworth, 1988) (see The Airde of Shin GCR site report, this chapter). Moine psammites become finely platy, with enhanced occurrence of muscovite, and show development of local quartz and quartz-feldspar veins. Lewisianoid rocks become laminated with the larger felspars and hornblendite pods forming more-resistant inclusions. These fine-grained blastomylonitic rocks formed mainly under greenschist- and lower-amphibolite-facies conditions, but show evidence of enhanced fluid movement during their formation. At higher metamorphic grades, such as in the Naver and Kirtomy nappes, the rocks in slide zones are more strongly recrystallized and coarser grained. Many of the GCR sites in northern Sutherland include examples of these ductile shear-zones.

In the A' Mhoine Nappe D3 deformation has resulted in widespread open to tight, small- to large-scale folding, and limited thrusting. An associated S3 crenulation cleavage defined by chlorite and biotite is variably developed. The deformation phase effectively either reinforces or refolds the earlier D2 structural pattern. Alsop and Holdsworth (1993) noted that the Moine Thrust and the Ben Blandy Shear Zone, 2–4km ESE of the Kyle of Tongue, were active during D3 deformation. The large-scale Borgie Forest Antiform and Ben Stumanadh Synform, that fold the Borgie D2 fold Inlier, both show an abundance of SE-plunging F3 minor folds that refold the regional S2 fabrics (Holdsworth *et* al., 2001). To the east, in the higher-grade Naver and Kirtomy nappes, F3 folds are more upright and commonly have an associated, locally penetrative, amphibolite-facies S3 schistosity. They refold the pervasive S2 foliation, and in parts excellent F2–F3 fold interference patterns are developed (e.g. Farr Bay GCR site). In parts F3 folds are difficult to separate from F2 structures as both are tight with related penetrative fabrics. Farther south in Sutherland and Easter Ross F3 folds are locally important, but for significant stretches they are absent. Grant and Harris (2000) showed that different phases of movement had occurred along the Sgurr Beag Thrust near Garve and that the later ductile phase may well be D3 in age.

Later structures loosely termed 'D4' by several authors are typically local monoformal folds, steep zones, or minor kink- and box-folds. Holdsworth (1989b) documented such structures from the Coldbackie Bay–Scullomie area of north Sutherland. He ascribed them to late-stage extensional movements related to the collapse of the Caledonide orogen. Farther east on the north coast lies the Torrisdale Steep Belt, marked by a flaggy, steeply ENE-dipping foliation, re-orientation of D2 and D3 structures, and an abundance of tight F3 folds (see Aird Torrisdale GCR site report, this chapter). Holdsworth *et al.* (2001) and Burns (1994) noted that structural indicators (e.g. feldspar porphyroclasts, aymmetrical boudinage, shear bands) indicate that dextral transpression has occurred. They attributed this movement to a post-D3 deformation episode.

Caledonian and Knoydartian metamorphism

Within the Moine sequence of Sutherland there is a progressive increase in metamorphic grade from greenschist facies adjacent to the Moine Thrust through lower-amphibolite grade in the Mhoine Nappe to middle- and upper-amphibolite facies in the Naver and Kirtomy nappes (Soper and Brown, 1971; Burns, 1994). A similar west to east increase in grade prevails farther south. However, the metamorphic pattern in the northern Moine is undoubtedly an amalgam of at least three main events, and it remains unclear as to their relative timing, extent and the nature of the formative crustal mechanisms.

Pelitic rocks in the R. Mhoine Nappe contain the metamorphic minerals garnet, staurolite and kyanite. Staurolite and kyanite porphyroblasts are only found at a few localities, for example in the Meadie Pelite (see Ant an Dherue GCR site report, this chapter). Kyanite has apparently contradictory age relationships with the main S2 fabric; in parts it is deformed by the fabric, elsewhere it overgrows S2 (Holdsworth *et ed.,* 2001). Two or more phases of kyanite-grade metamorphism have apparently affected these rocks, a not unlikely scenario given the complex tectonic history of the area. The recent age dating implies that the main metamorphic minerals and fabrics are Knoydartian, with Grampian and Scandian overprints of variable intensity.

Garnet from pelitic units at Talmine and garnet + staurolite from the Meadie Pelite have been dated by Sm-Nd leaching methods at 827 ± 16 Ma and 829 ± 4 Ma respectively (Strachan *et al.,* 2002a). These pelitic units lie close to the base of the A'. Mhoine Psammite and Altnaharra Psammite formations respectively. A Sm-Nd garnet–whole-rock–hornblende age of 799 ± 26 Ma was also obtained from the Ben Hope Suite amphibolite. Farther south the Carn Gorm pegmatitic granite, a product of segregation from the enclosing pelite and semipelite, also gives Rb-Sr ages of *c.* 800 Ma (van Breemen *et al.,* 1974). These ages provide evidence of a widespread M1 Knoydartian (formerly termed 'Morarian) metamorphic event in the Moine succession, which is probably related to the D1 structures. Note that this metamorphic M1 fabric pre-dates the main penetrative deformation in the western Sutherland Moine rocks (Holdsworth, 1989a) and hence probably relates to the D1 event.

In the southern Moine U-Pb TIMS ages of 737 ± 5 Ma on metamorphic sphene from near Lochailort (Tanner and Evans, 2003), and monazite ages of 827 ± 2 Ma and 784 ± 1 Ma from the pegmatite bodies at Ardnish and Sgurr Breac respectively (Rogers *et al.,* 1998), imply that Knoydartian orogenic events also affected at least the western part of the Moine outcrop in Moran. Similar ages for the main phase of garnet growth in Glen Doe (Zeh and Millar, 2001; Millar, pers. comm., 2001) also suggest that Knoydartian events have affected the Glenfinnan Group and Loch Eil Group rocks of the Sgurr Beag Nappe.

In the western part of the A' Mhoine Nappe, greenschist-facies retrogression affects the lower amphibolite-facies assemblages. This has traditionally been linked to WNW-directed movements on the Moine Thrust Belt that generated the extensive mylonites (Read, 1931, 1934; Holdsworth *et al.,* 2001) and is probably Scandian (Silurian) in age (see Dallmeyer *et al.,* 2001).

Early Ordovician (Grampian) ages have been obtained from the migmatitic metasedimentary rocks of the higher nappes. Kinny *et al.* (1999) obtained zircon overgrowth ages (U-Pb SHRIMP) of 467 ± 10 Ma and 461 ± 13 Ma from migmatitic semipelites and psammites of the Naver and Kirtomy nappes respectively. Rare relict granulite-facies assemblages of garnet + diopside + plagioclase have been recorded from basic meta-igneous sheets from the Naver Nappe by Friend *et al.* (2000). These higher-pressure metamorphic assemblages are interpreted to link to crustal stacking during the Grampian Event. However, monazites from the Kirtomy migmatitic rocks gave a younger age (U-Pb SHRIMP) of 431 ± 10 Ma reflecting the later Silurian (Scandian) event. There is a marked change to migmatitic semipelitic and pelitic rocks across the Naver Slide, probably representing a significant structural and metamorphic break in the succession.

Dallmeyer *et al.* (2001) studied the cooling history across the Moine outcrop of north Sutherland based on the pattern of hornblende ^{40}A-^{39}Ar ages and muscovite Rb-Sr and ^{40}Ar-^{39}Ar ages. These ages become younger eastwards, reflecting the thicker nappe stack and somewhat later post-orogenic uplift and cooling. Ages ranged from 460–470 Ma in the A'. Mhoine Nappe to 400–410 Ma in the upper parts of the Kirtomy Nappe. Ages from the Moine mylonites and several of the pelitic units in the A' Mhoine Nappe showed considerable discrepancies between ^{40}Ar-^{39}Ar and Rb-Sr values. These were ascribed as 'excess' argon and it was inferred that the main deformation and uplift in the northern Moine rocks related to the Scandian orogenic event, although the higher nappes do show evidence of an earlier Grampian history.

The Ben Loyal Syenite, dated at 426 ± 9 Ma (Halliday *et al.,* 1987) was intruded after ductile deformation and hence dates the end of penetrative deformation associated with the Caledonian Orogeny in this area (Holdsworth *et al.,* 1999). Farther east the Strath Naver, Klibreck and Strath Vagastie granites and the Strath Halladale Granite Complex give intrusion ages ranging from 420 Ma to 429 Ma, but all show late Scandian deformation fabrics (Kinny *et al.,* 2003a; Kocks *et al.,* 2006).

Relationship with the Moine Thrust structures

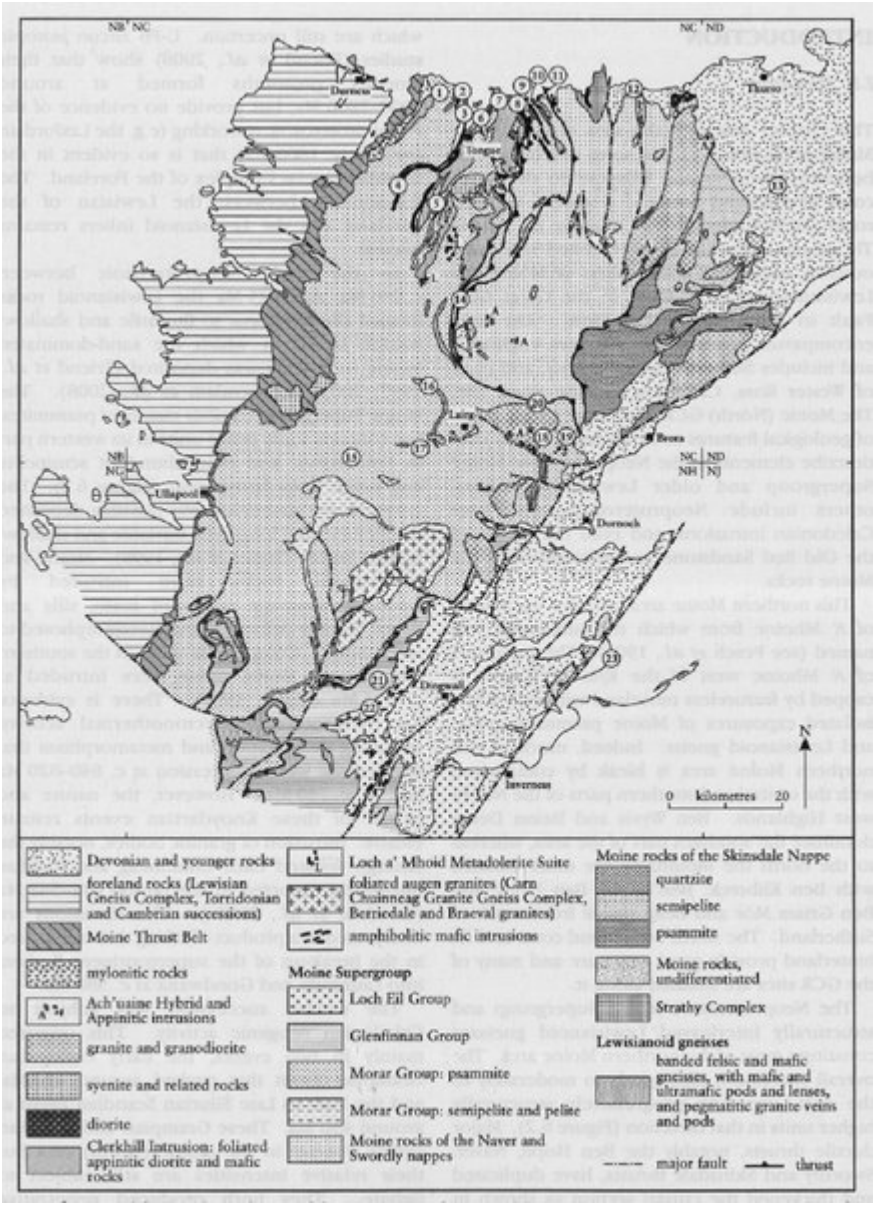
The mylonites of the Moine Thrust Belt are best developed in the Moine (North) area, notably east of Loch Eriboll, but their outcrop extends as far south as the Assynt Window. Note that in the Loch Eriboll area the mylonites lie beneath the Moine Thrust plane in its footwall (Holdsworth *et al.,* 2001). They are mainly derived from Moine and Lewisianoid rocks, but include some Cambrian quartzite protoliths. The mylonites are distinct from mylonitic Lewisian and Cambrian foreland rocks that occur in the lower part of the Moine Thrust Belt. Two generations of minor folds occur within the mylonites; tight to isoclinal folds with an axial-planar mylonitic fabric, and later open to tight folds that refold the mylonitic fabric. However, such structures can only be correlated locally. Greenschist-facies mylonitic fabrics and lineations in the mylonites can be readily correlated with the S2 schistosity and the SE-plunging L2 in the overlying Moine rocks, and many authors have related the mylonitic fabrics to the main phase D2 deformation of the Moine (Soper and Wilkinson, 1975; Mendum, 1979; Evans and White, 1984). However, farther south in the Fannich Mountains (see Meall an t-Sithe and Creag Rainich GCR site report, Chapter 7) Kelley and Powell (1985) show that pegmatitic granite veins cut the D2 fabrics and the Sgurr Beag Slide, yet are progressively mylonitized westwards as the Moine Thrust is approached. Similar pegmatites relate to the D3 deformation phase in the central Moine area and have been dated at *c.* 450 Ma at Loch Monar and near Glenfinnan (van Breemen *et al.,* 1974). This would imply that the Moine mylonites are post-450 Ma, in accord with the 437–408 Ma Rb-Sr white mica ages from Moine Thrust Belt mylonites obtained by Freeman *et al.* (1998). In contrast, the main D2 deformation in the Moine rocks appears to have occurred prior to 450 Ma, although Strachan *et al.* (2002a) postulate that the main D2 deformation in Sutherland west of the Naver Thrust Zone may well be Scandian (Dallmeyer *et al.,* 2001).

Devonian and later faulting

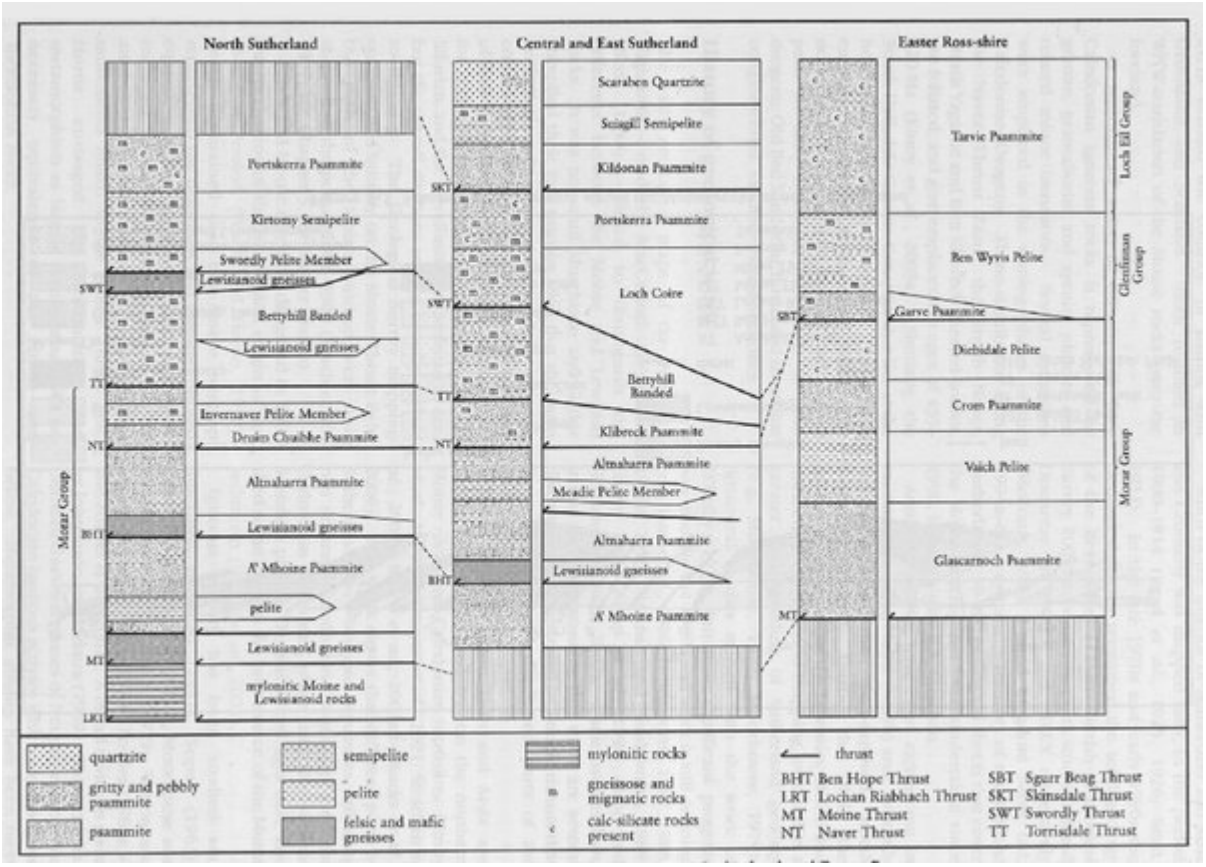
Post-Caledonian fault patterns are unclear for many parts of the Moine outcrop. In north Sutherland the effects of Devonian and Permo–Triassic basin formation offshore has resulted in the formation of generally N- or NNE-trending normal faulting. Large normal faults with easterly downthrows occur along Strath Halladale and the valley of the Strathy Water. The NE-trending Bridge of Forss Fault in Caithness had a significant Early Devonian history prior to its Mid- and Late Devonian expression. Farther south, NW-trending faulting along Strath Fleet, Loch Shin and Loch Stack post-dates the Rogart Pluton, and similarly trending faults occur in Glen Cassley to the south-west.

The NE-trending Great Glen Fault mostly lies concealed beneath the Moray Firth but is a major feature of the Cromarty and Rosemarkie Inliers GCR site. It is undoubtedly a complex structure with a long and varied history of movement. However, it is clear that the fault moved sinistrally in Late Silurian and Mid-Devonian times and was subject to dextral reactivation in the Mesozoic. The onshore features of the Great Glen Fault are discussed further in the 'Introduction' to Chapter 7. The related Strathconon and Helmsdale faults crosscut Mid-Devonian units with the latter structure acting as a basin-bounding fault to the offshore Mesozoic succession of the Moray Firth.

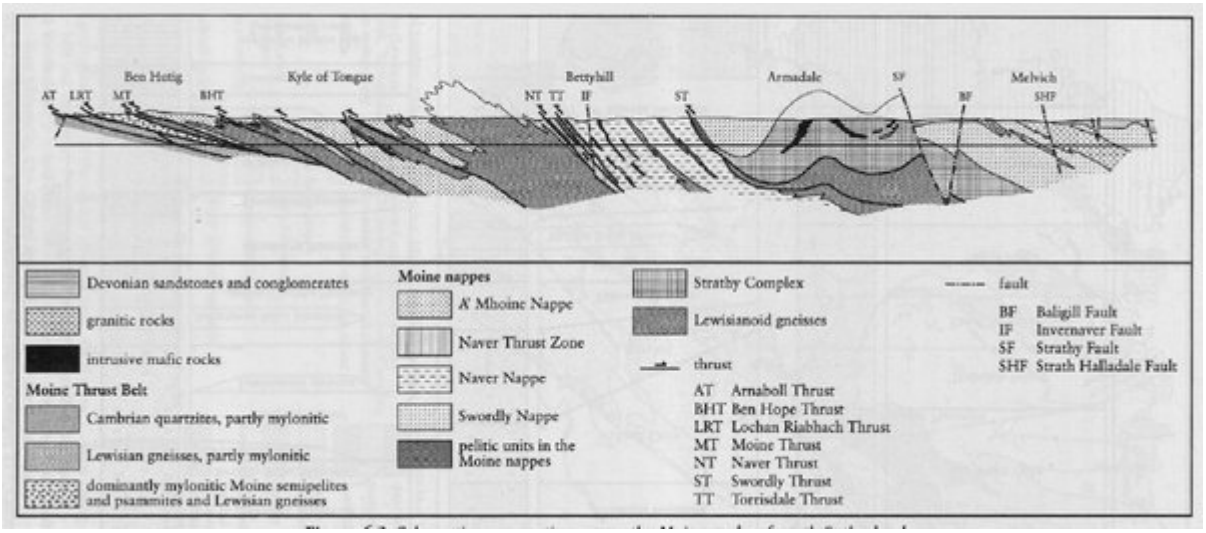
References



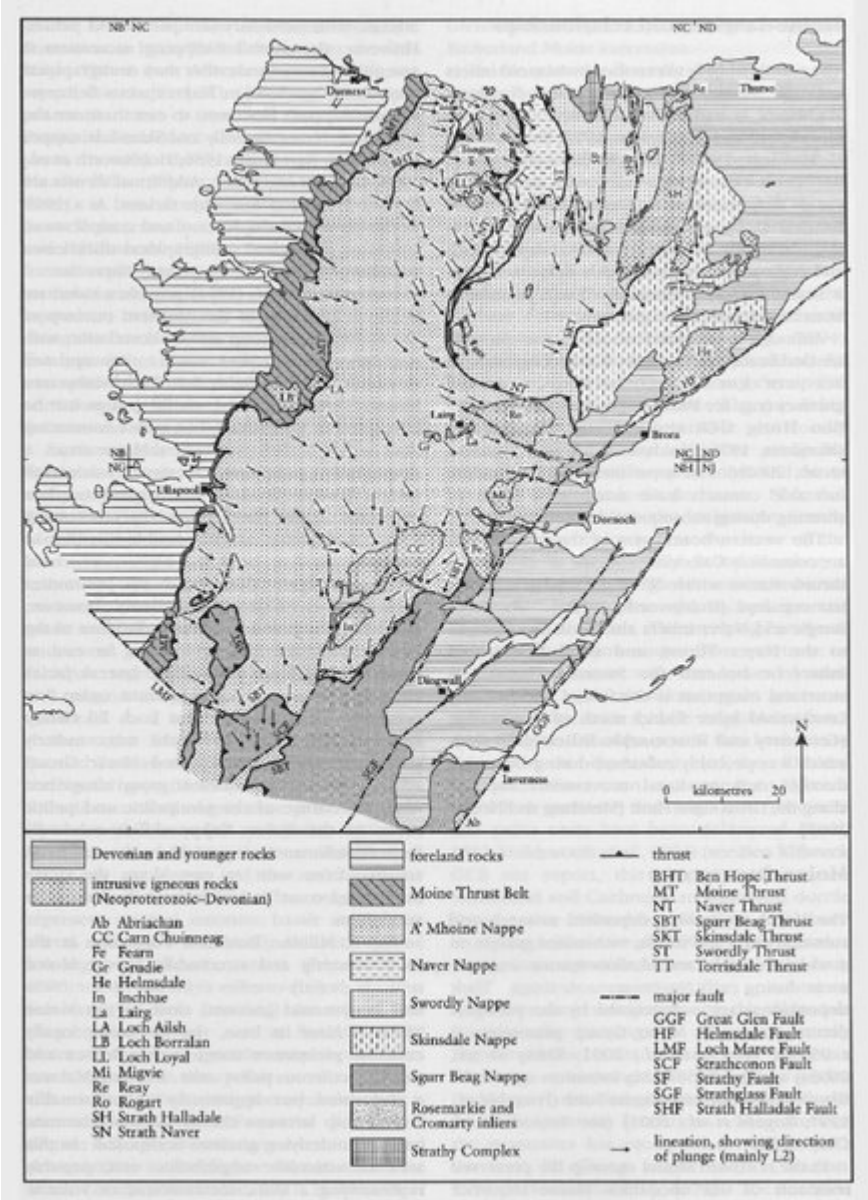
(Figure 6.1) Simplified geological map of the Moine (North) area. GCR sites: 1— Ben Hutig; Port Vasgo—Strathan Bay; 3 — Melness; 4 — Allt na Caillich; 5 — Allt an Dherue; 6 — Coldbackie Bay; 7 — Strathan Skerray to Skerray Bay; 8 — Aird Torrisdale; 9 — Ard Mor; 10 — Farr Bay; 11 — Glaisgeo—Farr Point; 12 — Sgeir Ruadh; 13 — Dirlot Castle; 14 — Ben Klibreck; 15 — Oykel Bridge; 16 — The Airde of Shin; 17 — Allt Doir' a' Chatha; 18 — Creag na Croiche; 19 — Aberscross Burn—Kinnauld; 20 — Brora Gorge; 21 — Carn Gorm; 22 — Comrie; 23 — Cromarty and Rosemarkie Inners.



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



(Figure 6.3) Schematic cross-section across the Moine rocks of north Sutherland.



(Figure 6.4) Tectonostratigraphy of the Moine (North) area.