# *Lewisian, Torridonian and Moine Rocks of Scotland*

**J.R. Mendum,**

**A.J. Barber,**

**R.W.H. Butler,**

**D. Flinn,**

**K.M. Goodenough,**

**M. Krabbendam,**

**R.G. Park**

**and**

**A.D. Stewart**

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

JOINT NATURE CONSERVATION COMMITTEE

British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

# Chapter 6

# Moine (North)

## INTRODUCTION

### *J.R. Mendum*

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 A' 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 North-west 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 pelite 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

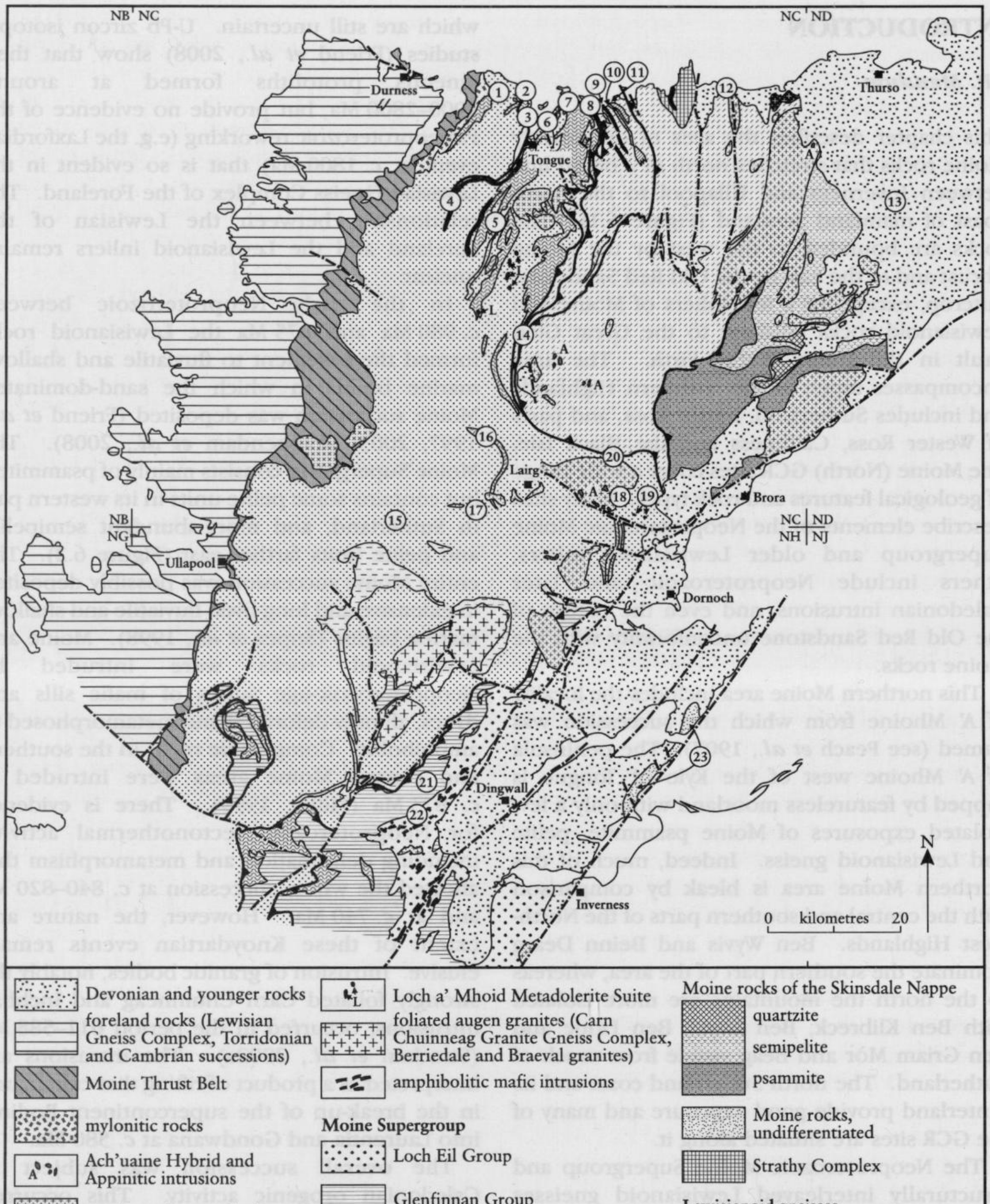


**Figure 6.1** Simplified geological map of the Moine (North) area. GCR sites: 1 – **Ben Hutig; Port Vasgo–Strathan Bay**; 3 – **Melness**; 4 – **Allt na Caillich**; 5 – **Allt an Dherue**; 6 – **Coldbackie Bay**; 7 – **Strathan Skerray to Skerray Bay**; 8 – **Aird Torrisdale**; 9 – **Ard Mor**; 10 – **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 Inliers**.

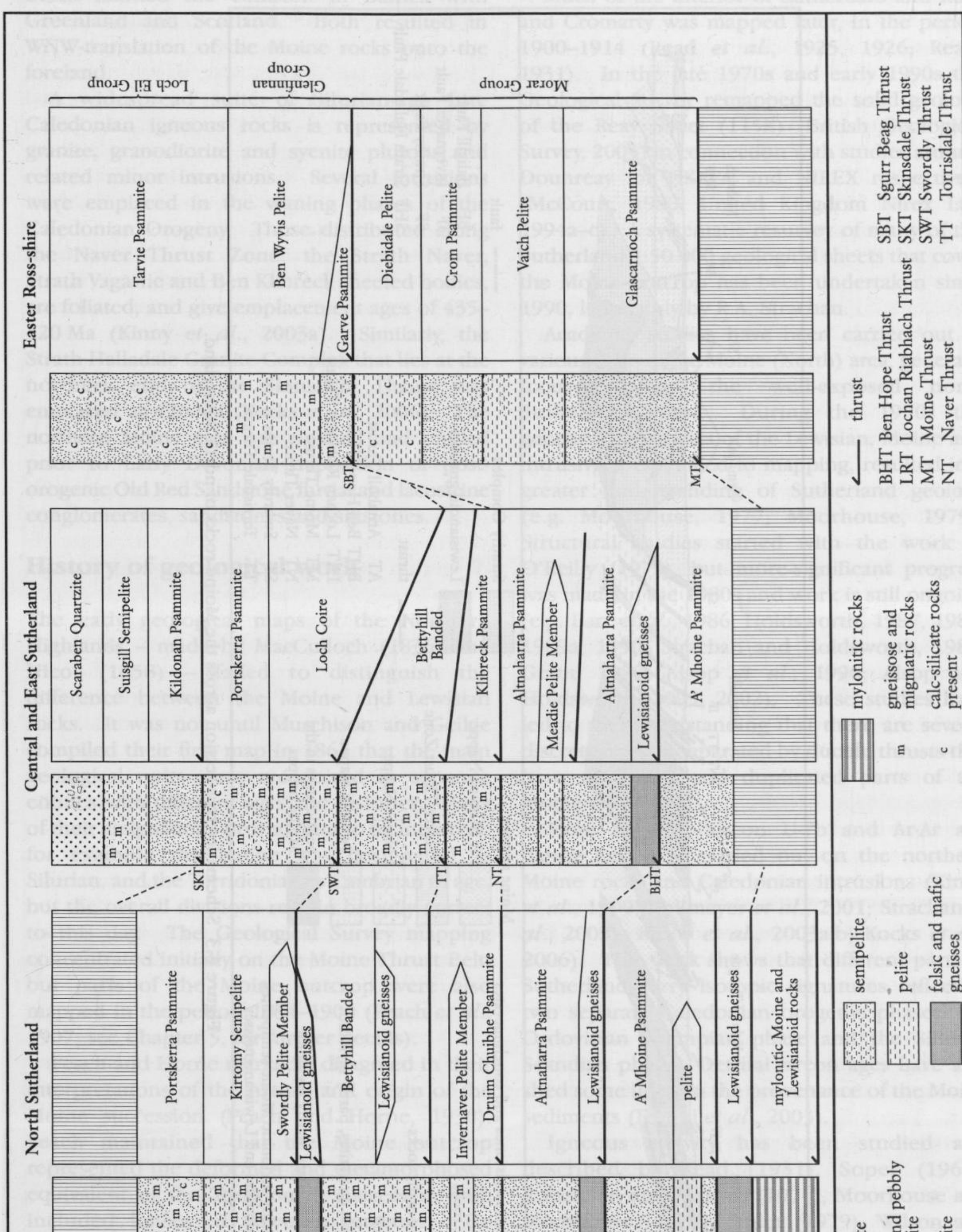

**Figure 6.2** Stratigraphy of the Moine Supergroup in Sutherland and Easter Ross.

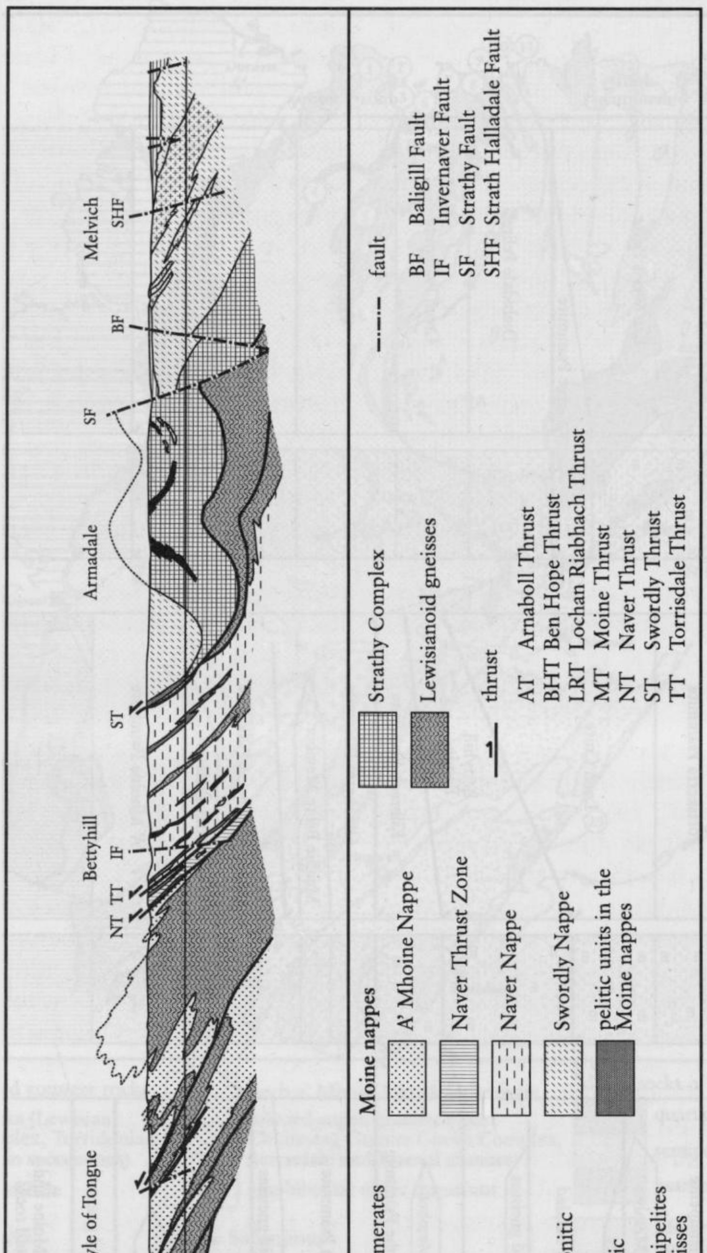


**Figure 6.3** Schematic cross-section across the Moine rocks of north Sutherland.

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 435–420 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 (Figures 6.3, 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.

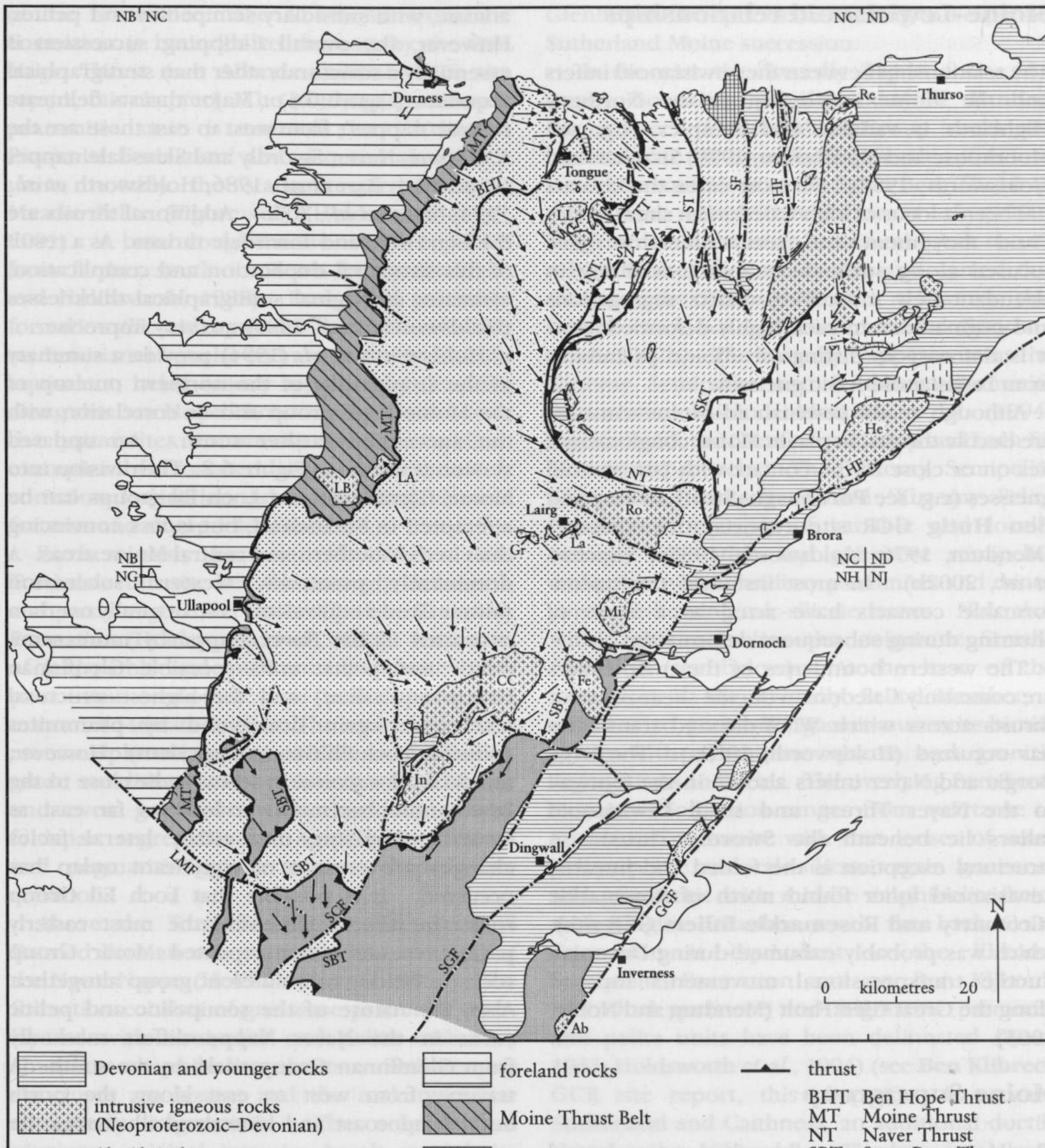


**Figure 6.4** Tectonostratigraphy of the Moine (North) area.

## 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 volcaniclastic 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 interlayered 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 semi-pelite, 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 hangingwall. 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' (Figures 6.1, 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 metasomatically 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 Mooorhouse, 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 Carn 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 Pelite 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 Rogart, 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 Rogart 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 (Johnson 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 mudstone 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 stromatolitic 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 (Figures 6.1, 6.2, 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 North-west 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 al.*, 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 pre-existing 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, 2–4 km 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 A' 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 A' 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 **Allt 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 al.*, 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 Morar. 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 $^{40}$Ar-$^{39}$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 re-activation 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 cross-cut Mid-Devonian units with the latter structure acting as a basin-bounding fault to the offshore Mesozoic succession of the Moray Firth.

# BEN HUTIG (NC 540 652)

***J.R. Mendum***

## Introduction

Ben Hutig (408 m) is the most north-westerly outpost of the Moine succession on the Scottish mainland, with the Moine Thrust Belt lying only about 1 km to the west. The basal units of the Moine succession form its western slopes, and the summit crags display excellent examples of highly flattened and elongated pebbles and of strongly rodded quartz veins. The bedrock consists of psammites, locally conglomeratic, and garnetiferous pelitic and semipelitic schists of the A' Mhoine Psammite Formation (Figure 6.5). All lithologies are cross-cut by prominent quartz veins. The lithologies form part of the Morar Group that to the west overlies Lewisianoid gneisses and mylonitic Moine and Lewisianoid rocks. The sequence is affected by two main phases of deformation and recumbent folding, termed 'D2' and 'D3'. The strongly elongate pebbles in the metaconglomerate units and the prominent quartz rodding developed in quartz veins both give rise to lineations that plunge east and relate to both the F2 and F3 folding. An earlier deformation phase, D1, produced a bedding-parallel fabric, but no large-scale D1 structures have been recognized. However, the upper greenschist-facies mineralogy which represents the peak metamorphic conditions attained in these rocks, is associated with D1. Recent Sm-Nd ages on garnets from the schistose pelite by Loch Vasgo (see **Port Vasgo–Strathan Bay** GCR site report, this chapter) and garnet and hornblende from the Ben Hope Sill amphibolites near Tongue, imply that this metamorphic event occurred between 830 Ma and 788 Ma (Strachan *et al.*, 2002b). Hence there is evidence for Neoproterozoic Knoydartian and later Ordovician and Silurian Caledonian tectonometamorphic events.

B.N. Peach and J. Horne first mapped the Ben Hutig area for the Geological Survey in 1884 and 1888. The rodded and folded quartz veins of Ben Hutig were first recognized by Peach and Horne (1907, p. 603), but subsequently were described and discussed in detail by Wilson (1953) in his paper on mullion and rodding structures in the Moine rocks of Sutherland. To explain the overall structural pattern,

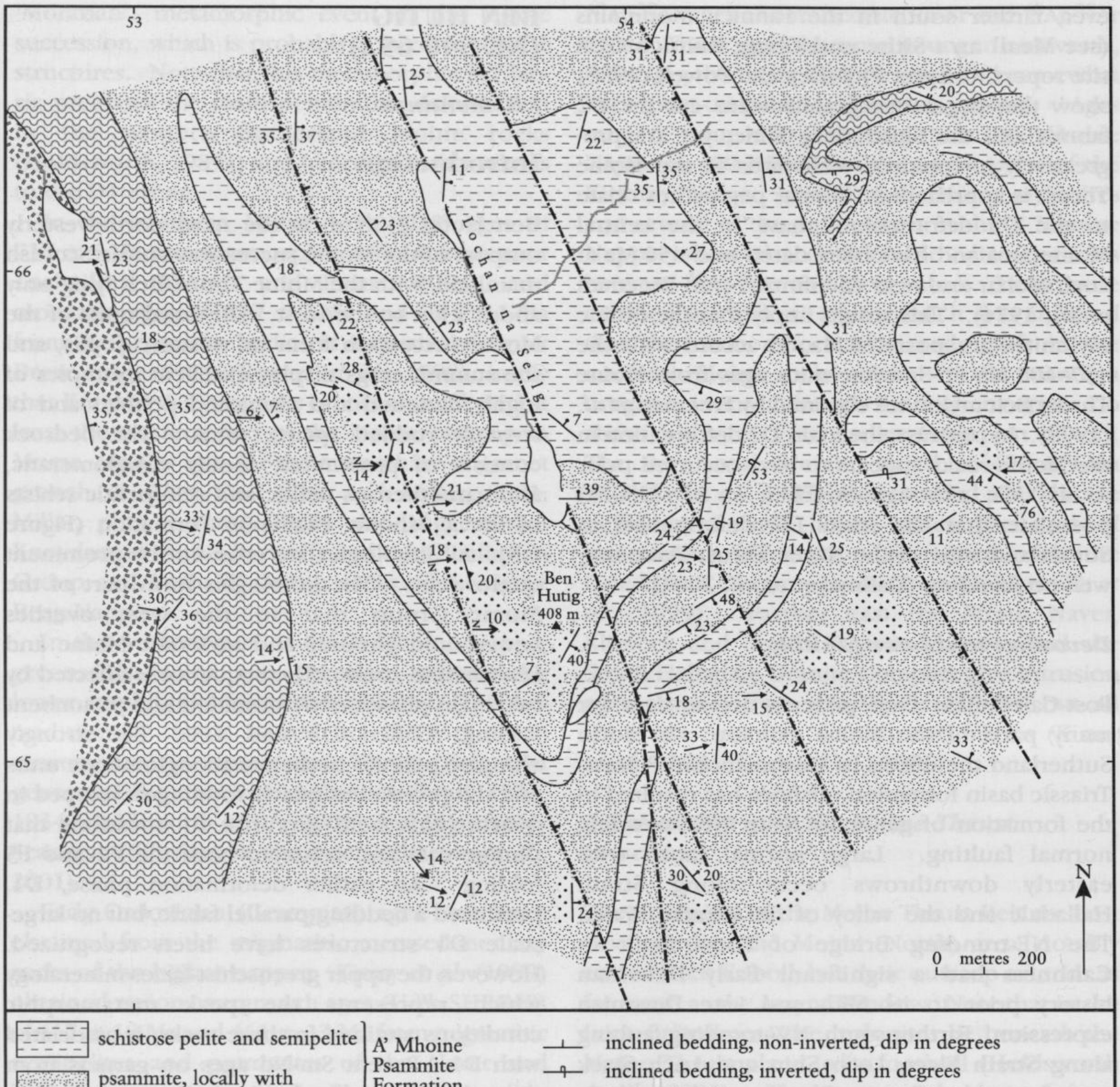


**Figure 6.5** Geological map of the Ben Hutig area.

Holdsworth (1987) proposed a model of progressive Caledonian thrusting and folding associated with translation of the Moine succession to the WNW (Holdsworth, 1989a, 1990; Alsop and Holdsworth, 1993). Alsop and Holdsworth (1993) also suggested that the later F3 folds in the Ben Hutig area 'rooted' downward into the thick zone of mylonites that forms part of the Moine Thrust Belt to the west.

## Description

The GCR site area includes the summit crags of Ben Hutig, its steep western slope, and its gentler eastern and southern slopes. They are underlain by dominantly feldspathic and siliceous psammites with interbedded meta-conglomerate and schistose, garnetiferous semi-pelite and pelite units of the A' Mhoine Psammite Formation (Figure 6.5). The psammites range from coarse-grained arkosic to fine- and medium-grained micaceous varieties. The meta-conglomerates occur as individual beds and lenses that range from a few centimetres up to 2 m or even 3 m thick. They are poorly sorted beds with originally sub-rounded pebbles of quartz and, more rarely, quartz-feldspar in a feldspathic micaceous psammitic to quartzose matrix. The pebbles are now strongly deformed, ranging from highly prolate to oblate in shape. Good examples are seen in the area just south-east of the summit of Ben Hutig (Figure 6.6), and for some 700 m along the broad ridge north-west of the summit. Trough cross-bedding with prominent mud drapes is locally common in the psammites and bedding-foreset angles are exaggerated up to 90° in fold hinges. Locally, the psammites have a strong planar fabric and contain abundant phengitic muscovite.

Finely to coarsely striped, cream, dark-green and grey, felsic and mafic gneisses with ultra-mafic and amphibolitic mafic pods are exposed in a 150–300 m-wide zone below the western cliffs of Ben Hutig (Figure 6.5). These Lewisianoid gneisses are sheared in part, but only become locally mylonitic adjacent to their contacts with the overlying Moine sequence above and the mylonitic rocks below. These latter rocks form a thick unit of gently E-dipping 'Oystershell Rock' (Peach *et al.*, 1907). In their more-eastern outcrops their Moine heritage is locally seen, with garnetiferous semipelites and gritty psammites present, albeit strongly deformed.

The quartz veins in the Ben Hutig area occur predominantly in the pelitic units and the micaceous psammites of the Moine succession. They range from pods and lenticles up to some 60 cm thick, arranged parallel to bedding and the main S2 schistosity, to pervasive anastomosing veins, discordant to the bedding and S2. In the psammites, quartz veins are less abundant but are generally thicker, with veins up to 1.3 m thick (e.g. at NJ 5417 6541). The veins are mostly of two distinct structural ages. The earlier veins

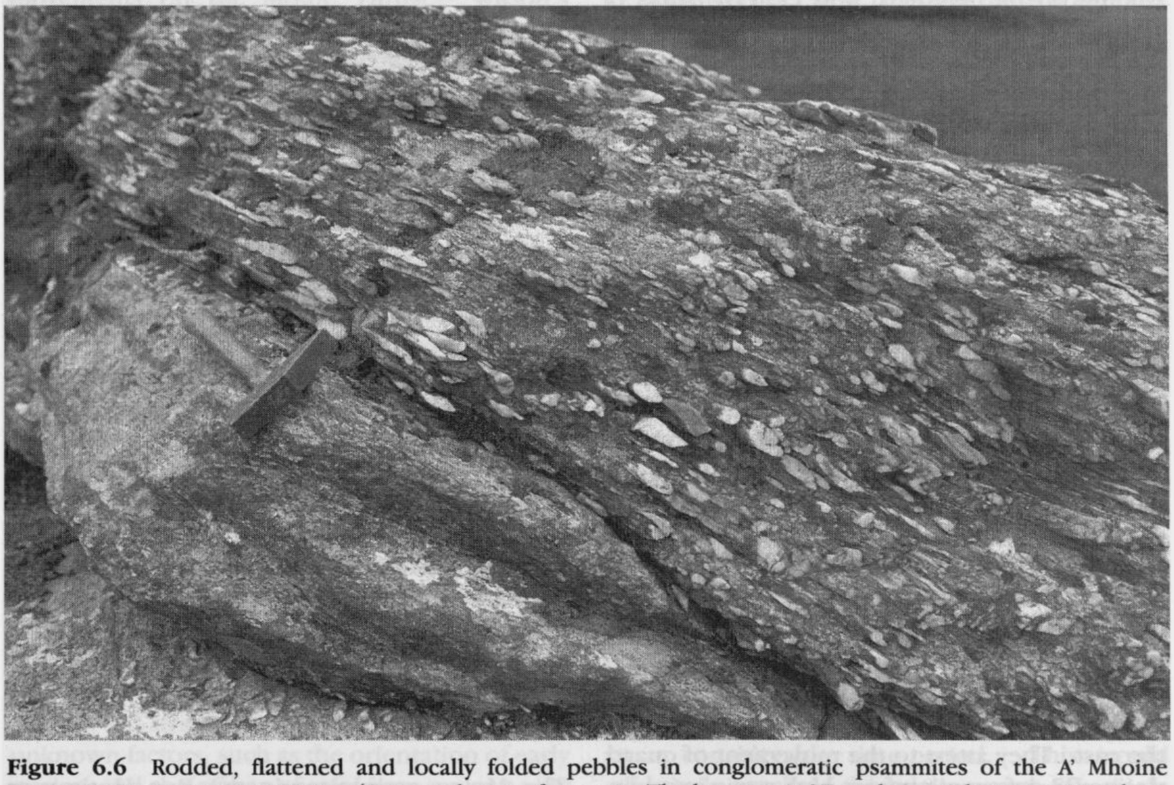

**Figure 6.6** Rodded, flattened and locally folded pebbles in conglomeratic psammites of the A' Mhoine Psammite Formation, Ben Hutig, 40 m south-east of summit. The hammer is 37 cm long. (Photo: J.R. Mendum, BGS No. P552316, reproduced with the permission of the Director, British Geological Survey, © NERC.)

either pre-date, or are synchronous with, the D2 deformation. They range from grey to white and show evidence of deformation during D2. The later prominent white veins are commonly discordant to the main S2 schistosity, but have been folded, lineated and recrystallized during the D3 deformation event. Hence they post-date D2 structures but pre-date the D3 event.

The rocks are affected by two main phases of deformation, D2 and D3. An earlier D1 event produced a bedding-parallel fabric and some quartz veining, probably coeval with the peak metamorphic conditions, which here attained upper-greenschist facies. D2 deformation produced both small- and large-scale, tight reclined folds with a gently E-plunging axial lineation and a pervasive, E-dipping, planar S2 fabric. D2 deformation was accompanied by greenschist-facies metamorphism. In the Ben Hutig area large-scale F2 folds, zones of platy psammite, and locally strong L2 lineations are all well seen. The lineations are coaxial with the fold axes and quartz rodding. In the crags 200–300 m east of the summit of Ben Hutig, a large-scale, upward-facing, tight F2 antiform is mapped. The structural pattern is dominated by a N-verging F2 fold pair, refolded by later F3 folding on the southern and eastern flanks of Ben Hutig. The deformed pebbles in the meta-conglomerate units are flattened in the S2 fabric and elongated along L2. In F2 fold hinge zones the pebbles are prolate but on the fold limbs they are generally oblate.

D3 produced open to tight asymmetrical folds that modified the pre-existing D1 + D2 structures. Immediately south and east of Ben Hutig summit, the S2 schistosity is folded and a penetrative S3 crenulation cleavage is locally developed. The F3 fold axes and related L3 lineations typically plunge gently to the north-east. The L2 lineation is commonly re-orientated into parallelism with L3. F3 folds vary in amplitude from a few centimetres to a few hundred metres.

The later, post-D2 quartz veins are prominently folded by F3 folds and exhibit a strong axial lineation (Figure 6.7). The quartz is strongly rodded but shows segregation within the fold profile into lenses and pods. All stages of this process, from minor necking of veins to complete segregation into pods, can be seen in the Ben Hutig area and for several kilometres to the east. They attest to the movement of quartz during D3 deformation from high-strain into low-strain areas. Care must be taken not to confuse

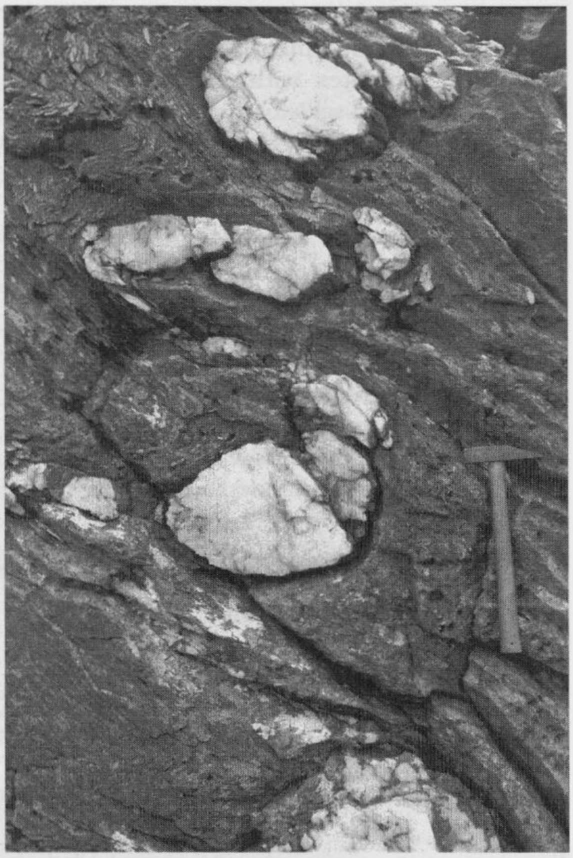

**Figure 6.7** Rodded, folded and segregated, originally discordant quartz veins in pebbly and gritty psammites of the A' Mhoine Psammite Formation. Ben Hutig, 100 m south-west of the summit. The hammer is 37 cm long. (Photo: J.R. Mendum, BGS No. P552315, reproduced with the permission of the Director, British Geological Survey, © NERC.)

the quartz vein structures with the deformed pebble beds that were deformed mainly during D2.

The mineral assemblages formed during the two greenschist-facies metamorphic events that accompanied the D1 and D2 deformations in the Ben Hutig area have been subjected to a pervasive late Caledonian retrogression at mid- to lower-greenschist facies (Read, 1931, 1934), probably related to the D3 event. Biotite and garnet have been altered extensively to chlorite, and new epidote, sericite and phengitic muscovite are widely developed.

## Interpretation

The Moine psammites in the Ben Hutig area contain poorly sorted conglomeratic and gritty units, but cross-bedding is also locally well preserved. The psammites are interbedded with pelitic and semipelitic schists with few transitional lithologies. These metasedimentary rocks represent periods of rapid deposition of mature sands and pebble beds followed by periods of quieter mud and silt accumulation. They may have formed in a shallow-marine or possibly fluviatile environment. Holdsworth (1987, 1989a) suggested that the conglomerate units at Ben Hutig, in Strath Melness, and at Traigh an t-Srathain (Strathan Conglomerate – see **Port Vasgo–Strathan Bay** GCR site report, this chapter) belong to the same basal Moine unit that has been repeated by folding and thrusting. However, lenticular conglomerate units apparently occur at several stratigraphical levels within the lower Morar Group succession in this area.

The key features of the Ben Hutig area are the excellent examples of conglomeratic beds, the quartz veins of two distinct ages, and the recognition of D2 and D3 deformation phases. In his detailed description and discussion, Wilson (1953) postulated that the rodding structures of Ben Hutig were related to SSW translation of the Moine rocks, unrelated to movements on the Moine Thrust. Wilson's interpretation of movement direction (tectonic transport) at right angles to the quartz rodding is no longer accepted. The historical interpretation of such structures and their kinematic significance are discussed in more detail in the **Oykel Bridge** GCR site report (this chapter). Wilson (1953) also failed to recognize the pebbly nature of the metaconglomerate on Ben Hutig, attributing all the quartz ellipsoids to segregation of quartz veins. Wood (1973) documented the conglomerate beds on Ben Hutig but implied that the structure and regional strain profile are simple. He recorded strongly prolate (constrictional) strain from measurements of the pebbles at seven localities, with a mean strain ellipsoid of $X:Y:Z = 25:1:0.9$. However, he failed to mention the quartz veining, and that the prolate strains occur generally in complex F2 hinge zones.

The finite strains obtained from the quartz pebble measurements result from the cumulative strain of three (D1 + D2 + D3) deformation events. D2 strain is dominant, but a number of unknown factors, such as the orientation of early strains, and the effects of refolding, make it very difficult to analyse the strain history. The overall shape of the finite strain ellipse changes from place to place within the area; moderately oblate (flattening) strains are recorded on F2 fold limbs, but elsewhere the finite strain is highly prolate. Note that finite strains are highly oblate in the deformed conglomerate at Strathan Bay, some 3.5 km to the east (Mendum, 1976; see **Port Vasgo–Strathan Bay** GCR site report, this chapter). The overall strain gradient increases downward towards the Moine Thrust in the west.

The quartz veining mainly occurred in two distinct phases; an early phase of segregation pods and veins synchronous with or perhaps post-dating D1; and a later more generally discordant phase that post-dates D2. Both types of vein are folded and lineated by the later D3 deformation. The lineation pattern in the psammites reflects both D2 and D3 phases of deformation, and the highly strained pebbles show clearly that this is the finite maximum extension direction. Segregation of the later quartz veins has occurred only during the D3 deformation. Hence, the prominent lineation developed in these later veins represents only the D3 deformation, but L3 generally lies subparallel to L2.

Holdsworth (1989a, 1990) proposed a model of overall W-directed, thrust-related, Caledonian deformation to explain the development of D2 and D3 structures in the Moine rocks of the Tongue–Ben Hutig area. He suggested that D1 was only manifest as a bedding-parallel fabric, but accompanied by upper-greenschist- to lower-amphibolite-facies metamorphism. Alsop and Holdsworth (1993) interpreted the later D3 folding as transient flow perturbations related to specific late-stage WNW-directed movements in the Moine Thrust Belt immediately to the west. Alsop and Holdsworth (2002) further refined this interpretation to suggest that the fold pattern represents a kilometre-scale F3 antiformal culmination with variations in minor fold vergence, facing, axial-plane and fold-axis orientation, all compatible with a large sheath-fold structure.

Structures related to two distinct deformation events are readily recognized on Ben Hutig, and the accompanying metamorphic events differ in grade. Hence, it seems probable that the D2 and D3 events are discrete and may be separated by a considerable time-period. This would effectively preclude them being parts of a single period of westward translation. Correlation of deformation events along the orogen is problematic and the age of D2 in Sutherland is not fully known. Strachan *et al.* (2002b) have shown that the S1 fabric and related peak metamorphic minerals formed between 830 Ma and 788 Ma. However, the D2 event in the Ben Hutig area is likely to be of Caledonian age, but it is currently unclear as to whether it is a mainly Grampian Event, as reported from the migmatitic rocks of the Naver and Swordly nappes to the east (Kinny *et al.*, 1999), or whether it is a Scandian Event. Dallmeyer *et al.* (2001) obtained a range of $^{40}Ar$-$^{39}Ar$ muscovite and hornblende ages and Rb-Sr muscovite ages from across the Moine succession in Sutherland. The ages ranged from 440 Ma to 410 Ma and were interpreted to show that the dominant deformation event in the A' Mhoine Nappe was of Scandian age, linked to movements on the Moine Thrust Belt (see also Strachan *et al.*, 2002a). Older ages of 450–490 Ma were obtained from muscovites in Moine rocks from the A' Mhoine peninsula, particularly from localities close to the Moine Thrust Belt. These muscovites are more phengitic (i.e. with higher Si and Mg content), and their corresponding Rb-Sr ages gave more-coherent values of around 420 Ma. The older $^{40}Ar$-$^{39}Ar$ ages were deemed anomalous due to excess radiogenic Ar.

## Conclusions

The Ben Hutig area is underlain mainly by Moine psammites, with some metaconglomerate lenses and pelitic and semipelitic schist units. The rocks lie in the lowermost part of the Moine Thrust Sheet in the A' Mhoine Nappe and form part of the basal unit of the Moine succession, the A' Mhoine Psammite Formation; inliers of the basement Lewisianoid gneiss occur nearby. Excellent examples of strongly elongated and highly strained quartz and quartzite pebbles are seen in metaconglomerate beds. Quartz veins, now tightly folded, stretched and locally even refolded, are common throughout the succession. The pebbles and the quartz veins serve as excellent strain markers. The overall strain, the majority of which relates to the D2 deformation, has resulted in prolate (cigar-shaped) and locally oblate (pancake-shaped) pebbles in the metaconglomerates, and strongly stretched, folded and lineated, quartz veins and pods. These veins and pebbly beds have been the subject of discussion regarding mechanisms of deformation and tectonic transport directions in the Moine succession for many years.

The proximity to the Moine Thrust Belt allows us to compare deformation, folding and metamorphic patterns within the Moine Nappe and the nearby thrust belt. The deformed pebbles have been used to determine the overall strains in the basal Moine metasedimentary units, and the folded, lineated and segregated quartz veins have provided an insight into the metamorphic and segregation processes accompanying deformation. The Ben Hutig area is one of national importance, and is of considerable teaching value. It remains an area suitable for further research.

# PORT VASGO–STRATHAN BAY (NC 572 659–NC 588 646)

***J.R. Mendum***

## Introduction

The Port Vasgo–Strathan Bay GCR site lies at the north-east end of the A' Mhoine peninsula in north Sutherland. It provides spectacular examples of the basal psammite, pelite and metaconglomerate units of the Moine Supergroup and their relationships to the underlying Lewisianoid gneiss basement, which occurs within the anticlinal Achnahuaigh Inlier (Figure 6.8). Amphibolitic mafic sheets of the Ben Hope Suite are intrusive into the Moine rocks. They were emplaced prior to deformation and metamorphism, and are well exposed along the coastal section between Talmine and Port Vasgo. Thin units of amphibolite and actinolite-bearing psammite are interbedded with the basal psammites of the Moine succession and may represent original mafic volcanic material. The geological structure of the site area is complex, with abundant reclined folding on several scales, numerous ductile thrusts, and extreme strain variations. The structures largely relate to the westward translation of the Moine rocks and Lewsianoid basement inliers during the Caledonian Orogeny. The metaconglomerate units have been used to obtain estimates of the strain affecting parts of the succession.

The succession was deformed and metamorphosed during Neoproterozoic events, but most structures date from the subsequent Caledonian Orogeny. The site area encompasses the Talmine

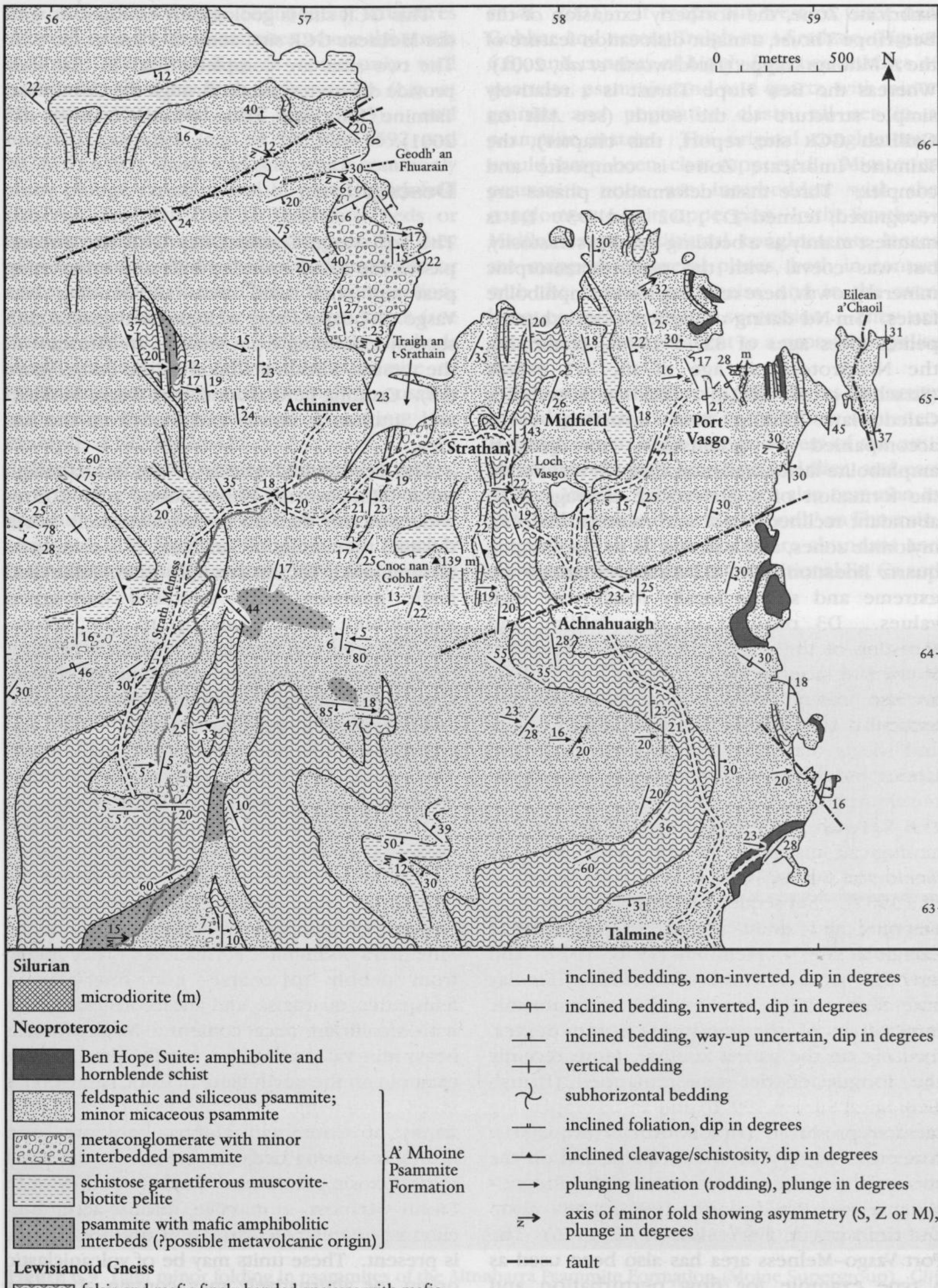


**Figure 6.8** Geological map of the Port Vasgo–Strathan Bay area.

Imbricate Zone, the northerly extension of the Ben Hope Thrust, a major dislocation feature of the A' Mhoine Nappe (Holdsworth *et al.*, 2001). Whereas the Ben Hope Thrust is a relatively simple structure to the south (see **Allt na Caillich** GCR site report, this chapter), the Talmine Imbricate Zone is composite and complex. Three main deformation phases are recognized, termed 'D1', 'D2' and 'D3'. D1 is manifest mainly as a bedding-parallel schistosity, but was coeval with the peak metamorphic mineral growth, here reaching lower-amphibolite facies. Sm-Nd dating of garnets from schistose pelites gives ages of 827 ± 19 Ma, confirming the Neoproterozoic age of the D1 events (Strachan *et al.*, 2002b). D2 was a complex Caledonian folding and thrusting event accompanied by greenschist- to epidote-amphibolite-facies metamorphism. It resulted in the formation of a penetrative cleavage (S2), abundant reclined major and minor folds (F2), mylonitic zones, and a strong, E- to SE-plunging quartz lineation, L2. D2 strain variations are extreme and strains locally reach very high values. D3 resulted in later folding and thrusting of the already deformed succession. Minor late monoformal structures and faulting are also present. The area contains several thin lenticular Late Caledonian microdiorite dykes and sheets that cross-cut the main folds and fabrics, but themselves are partially foliated and metamorphosed.

B.N. Peach and J. Horne carried out the first geological mapping in the area for the Geological Survey in 1884 and 1888 (Peach *et al.*, 1907). Subsequent investigations include mapping and strain analysis of the Strathan Conglomerate by Mendum (1976, 1979), and later PhD work by Holdsworth (1987). Findlay and Kerr (1979) studied the metamorphic mineralogy of the schistose Moine pelites, focusing on the garnet zoning. More recently the Tongue district was remapped (British Geological Survey, 1997b) and an accompanying memoir produced (Holdsworth *et al.*, 2001). Numerous papers have been published on the structural pattern and evolution of the Tongue–Talmine area (Holdsworth, 1989a, 1990; Alsop and Holdsworth, 1993; Alsop *et al.*, 1996). The Port Vasgo–Melness area has also been used as a type example for flow perturbation and complex sheath-folding, formed as a result of progressive shearing (Alsop and Holdsworth, 1999, 2002).

This GCR site is geologically contiguous with the **Melness** GCR site, some 2–3 km to the SSE. The two sites are complementary in that they provide different sections through the Caledonian Talmine Imbricate Zone (Holdsworth *et al.*, 2001).

## Description

The Port Vasgo–Strathan Bay GCR site encompasses the rocky rounded hills and intervening peat and shell sand areas surrounding Port Vasgo. It boasts a very well exposed coastal cliff-section extending from Geodh' an Fhuarain in the west to Eilean a' Chaoil in the east (Figure 6.8). Crofting land around Port Vasgo, Midfield and Strathan is mostly excluded from the site area.

The Lewisianoid gneiss of the Achnahuaigh Inlier (Holdsworth, 1989a) forms a 50–200 m-wide outcrop that tracks approximately north through the hamlet of Strathan. It is composed of laminated, locally strongly platy, felsic and mafic gneisses, with scattered dark-green amphibolite mafic pods up to 2 m across. Granitic veins and pegmatite lenses are present, but only rarely show good cross-cutting relationships. 'Apple-green' epidote is very abundant and commonly forms discrete layers. Biotite and chlorite are also abundant in the mafic pods. The typical Lewisianoid features are strongly attenuated by the superposed Caledonian D2 and D3 deformation. Both the eastern and western contacts of the inlier are highly sheared.

The Moine succession is dominated by psammites that concordantly overlie the Strathan Conglomerate in the basal part of the Altnaharra Psammite Formation. They range from pebbly to coarse- and finer-grained feldspathic, quartzose, and micaceous psammites with significant mica content. Magnetite-rich heavy-mineral bands are locally present, for example on the north flank of Cnoc nan Gobhar at NC 5740 6463. On the lower south-west flanks of Cnoc nan Gobhar, epidote- and actinolite-bearing beds are present in the basal gritty, arkosic psammites. Farther south-west in Strath Melness a massive, biotite-actinolite-clinozoisite-quartz-feldspar unit up to 2 m thick is present. These units may be of volcaniclastic origin, or alternatively may contain abundant detritus from mafic parts of the underlying Lewisianoid gneisses. Locally, clasts of Lewisianoid gneiss occur in the basal psammites (e.g. at NC 5778 6391). Sedimentary structures are well seen in the psammites where the strain is low. Cross-bedding is commonly well preserved, showing both right-way-up (e.g. at NC 5806 6432 and NC 5687 6595), and inverted examples (e.g. at NC 5689 6592 and NC 5751 6493). Early fold sets, which commonly show plunge variation and in parts sheath-fold patterns, are restricted to individual beds or specific parts of the sequence (Figure 6.9). They may represent syn-depositional slump-folds or convolute folds formed during compaction; alternatively they may be D1/D2 structures (see 'Interpretation', below). Only rarely do beds show grading from feldspathic psammite to micaceous psammite and semipelite, possibly indicating the direction of younging, for example at NC 5862 6427.

Highly strained metaconglomerate lenses, now ranging from some 10 cm to 40 m thick are common in the lower part of the psammite sequence. The Strathan Conglomerate Member is the thickest unit (Mendum, 1976; Holdsworth *et al.*, 2001). It crops out west of Cnoc nan Gobhar and across Traigh an t-Srathain (Figure 6.8), and consists of highly flattened cobbles of quartzite, psammite and vein quartz, with minor granite and pegmatite clasts, all set in a psammite matrix. The original conglomerate would have been clast-supported. Micaceous psammite units are interbedded with the conglomerate in its upper part. In the Strathan–Midfield area, additional conglomerate lenses are mapped in several places, both in contact with the Lewisianoid gneiss, and in the overlying psammitic Moine succession. They are commonly found adjacent to a prominent pelite unit.

Schistose garnetiferous pelite forms distinctive several metre-thick units in the Moine sequence. It crops out to both east and west of the anticlinal Achnahuaigh Lewisianoid Inlier, and east of Port Vasgo. Pelite units are also common in Strath Melness and north of Geodh' an Fhuarain. Garnets up to 10 mm across are abundant and show complex internal compositional Fe, Ca and

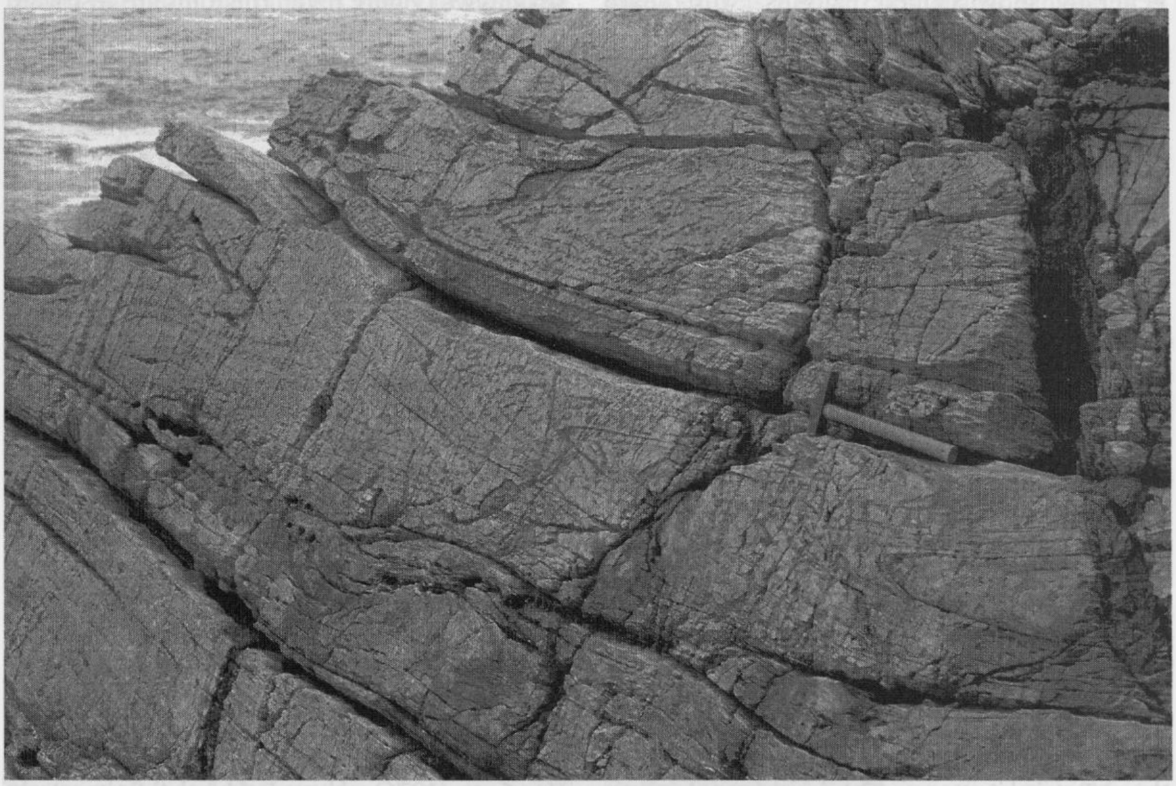

**Figure 6.9** Tight minor folding in psammites of the Altnaharra Psammite Formation (Moine Supergroup). Cliff face, *c.* 300 m east of Port Vasgo. Note variable fold profiles along axial surfaces and possible cut-offs by overlying bedding planes. Possible slump folds or F1 folds, tightened during the D2 deformation event. The hammer is 37 cm long. (Photo: J.R. Mendum, BGS No. P552297, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Mn zoning patterns that reflect the prograde metamorphic garnet-forming reactions (Finlay and Kerr, 1979). The main garnet growth occurred under lower-amphibolite conditions, synchronous with D1 deformation. The abundant chloritic rims are a product of the late retrogression. Garnetiferous semipelitic units occur higher in the succession on Meall Mòr, for example at NC 5828 6558.

Hornblende schist/amphibolite sheets are restricted to east of the Achnahuaigh Lewisianoid Inlier and are best seen on the coast section north and south of Port Vasgo. They are commonly garnetiferous, with garnets up to 4 cm across. They also show marginal reaction/alteration zones, for example east of Port Vasgo at NG 5887 6512, where discrete amphibole-, feldspar- and quartz-rich layers are developed. Dolomite veining and brown-weathering altered zones are present at some sheet margins.

Lenticular mafic microdiorite sheets and irregular pods of the 'Port Vasgo Microdiorite Suite' cross-cut the D2 and D3 structures in the Port Vasgo area (Holdsworth *et al.*, 2001). They generally show chilled margins, with sharp contacts discordant to the regional schistosity of the country rock. Locally they carry a fabric, which is generally parallel to that in the adjacent psammites. Where deformed, the igneous plagioclase has recrystallized into elongate, fine-grained albite aggregates, and together with brown-green biotite and green hornblende they form a new penetrative schistosity. The type example is a lensoid sheet up to 2 m thick at NC 5865 6505. Holdsworth *et al.* (2001) noted that microdiorite intrusions in this area are normally thin and schistose where parallel to the bedding, but thicken markedly and show discordance in lower strain areas, suggesting that the form of the intrusion is controlled by the pre-existing structure.

### *Structure*

The complex three-dimensional geometry of this area is the result of the original distribution of lithologies and their modification during three deformational events, D1, D2 and D3. Later faulting appears to have only minor effects on the structural pattern. The Lewisianoid inliers have been strongly affected by Caledonian deformation making their identification difficult in some areas. The Achnahuaigh Lewisianoid Inlier occurs as an anticline as shown by the presence of metaconglomerate lenses and the garnetiferous pelite in the basal parts of the Moine succession on both sides of the Lewisianoid contact. Cross-bedding in the psammites also shows that the Moine rocks become younger away from the inlier. Farther east on the craggy southern cliffs of Port Vasgo, a 2 m-thick sliver of Lewisianoid gneiss occurs in a shear zone of probable D2 age, close to a hornblende schist and garnetiferous pelite bed.

D1 deformation is manifest as a bedding-parallel fabric and related minor early structures. The lower amphibolite-grade peak metamorphic mineralogy, marked by garnet growth in pelitic rocks, is related to this event (Holdsworth, 1989a; Strachan *et al.*, 2002b).

On Creag Mhòr (NC 5846 6458) above Port Vasgo, spectacular examples of tight to isoclinal folds occur in mixed gritty and feldspathic psammites with subsidiary micaceous psammites (Holdsworth *et al.*, 2001). Along strike to the NNE on the coastal cliff-faces at NC 5878 6506 particularly prominent, larger-scale, close to isoclinal folds occur in the psammites (Figure 6.9). The folds are restricted to individual lenticular beds and have axial planes parallel to bedding/S1/S2. A penetrative, normally bedding-parallel, biotite fabric (?S1) is developed axial planar to the folds, which is unlike the platy mylonitic schistosity (S2) of nearby D2 high-strain zones. The laminae defining the folds are nebulous in parts and the fold profiles show extreme hinge and limb thickness variations. Dislocations and 'cut-offs' are present at some bedding surfaces. Fold axes generally plunge gently to moderately to the ENE, but in places plunge gently north. As discussed below, these folds may be interpreted as F1 folds, combined F1/F2 folds, or as slump folds/convolute bedding.

The effects of the main D2 deformation episode are manifest over most of this GCR site area as ductile high-strain zones, open to tight and rarely isoclinal folding, and related axial-planar penetrative fabrics and lineations. Both the intensity and type of D2 strain are highly variable.

Using the quartz and quartzite cobbles of the Strathan Conglomerate as strain markers, Mendum (1976) showed that the finite strain at Traigh an t-Srathain was an intense flattening (oblate) strain reducing the rock to some 10% of its original thickness. This conglomerate lies partly within a D2 shear-zone, but also shows evidence of D3 deformation and folding. In contrast, on a moderately attenuated F2 fold limb, south of Cnoc nan Gobhar at NC 5739 6415, lineated pebbly psammites imply that the strain is highly prolate ('cigar-shaped'), resulting in a finite strain ellipsoid with maximum stretching of the original pebbles reaching some 500%.

The F2 fold hinges are low-strain areas where cross-bedding is readily distinguishable. Foreset-bedding angles have locally been increased to more than 45° (e.g. at NC 5774 6398), due to differential rotation relative to bedding during D2 deformation.

F2 folds are typically tight, with asymmetrical profiles, thickened hinge zones (low strain), and attenuated limbs (high strain). The folds are reclined and generally face upwards to the south or SSW. Wilson (1953) records that between Melness and Ben Hutig most F2 folds verge (i.e. overfold) towards the SSW, but west of Strath Melness, some F2 folds do verge and face to the NNE. F3 refolding is only partly responsible for these reverses of D2 facing direction. The F2 folds are normally coaxial with the prominent L2 quartz lineation that plunges gently towards the ENE and ESE. This is commonly both an intersection and an extension lineation. F2 axial planes and the related penetrative mica cleavage, S2, mainly dip eastwards at between 20° and 30°. Their overall orientations lie close to the regional bedding. In parts F2 structures show sheath-type fold geometries with variably plunging axes. Holdsworth *et al.* (2001), describe such folds from Creag Mhòr and ascribe them to progressive rotation of fold axes during fold formation in areas of high D2 strain (Holdsworth, 1990). Alsop and Holdsworth (2002) further analysed the F2 and F3 fold pattern in the Port Vasgo–Strathan Bay GCR site area, and interpreted it as a product of flow perturbation during WNW-directed Caledonian layer-parallel ductile shearing (see discussion below).

D2 shear-zones either form discrete near-planar features, or lie on the long limbs of F2 asymmetrical fold stacks. They are marked by an intensely platy, locally blastomylonitic fabric, defined mainly by newly crystallized, aligned phengitic muscovite and recrystallized quartz. In mylonitic gritty psammites or felsic Lewisianoid gneisses, relict feldspar clasts are commonly preserved. Holdsworth *et al.* (2001) note that shear bands in the pelites at NC 5808 6547, together with mica 'fish' and other asymmetrical 'wrapping' textures from the Talmine area, all indicate a top-to-the-WNW sense of shear in these rocks. In the Port Vasgo area shear zones appear to repeat the succession and be associated with minor F2 folding. Farther west around Loch Vasgo and Cnoc nan Gobhar the shear zones locally anastomose around the Achnahuaigh Lewisianoid Inlier. On Cnoc nan Gobhar they also cut across the F2 fold stack in Moine psammites and pelites (Figure 6.8).

The D3 deformation event has had considerable effect throughout the Port Vasgo–Strathan Bay GCR site area. Medium- and small-scale, open to tight F3 folds are common and are generally coaxial with the F2 structures, i.e. their axes plunge gently eastwards. Where they refold D2 structures, they are readily recognized, but in many areas they merely reactivate and accentuate earlier D2 folds, fabrics or shear-zones. D3 structures are particularly abundant in parts of the Lewisianoid inlier where they fold an already attenuated gneissose layering. They typically form asymmetrical structures with prominent northerly vergence. The related S3 fabric, manifest as an axial-plane crenulation cleavage and locally as a penetrative planar schistosity, is generally developed only in the more-micaceous lithologies. Where minor F2 and F3 folds are developed, the latter typically have disharmonic profiles and show wide axial plunge variations (e.g. at NC 5845 6435). In other areas F3 axes and the coaxial L3 quartz lineations have more-consistent orientations. Locally F3 and L3 plunge at shallow angles towards ESE and can be distinguished from nearby F2 axes and L2 lineations, which plunge towards ENE. The orientation of F3 axial planes is locally variable – their strike ranges from north-east to north-west and their dip is shallow towards the south-east to north-east. In the Strathan Conglomerate quartz and quartzite pebbles, flattened in D2, are folded by F3 structures and show evidence of quartz segregation to form rods (e.g. at NC 5710 6535). Mendum (1976) attributed the folding and segregation to D2. However, the effects of F3 folding on D2 deformation features, and rodding of post-D2 quartz veins farther west and in the Ben Hutig GCR site area, make it clear these are D3 features (see also Holdsworth *et al.*, 2001). Holdsworth (1990) recognizes two distinct types of F3 structure in the Talmine area; curvilinear, close to tight, sheath-folds that refold D2 structures, for example at NC 5780 6408; and open to tight larger-scale folds that control the outcrop pattern.

Across the site area there is an overall steepening of the bedding and S2 schistosity eastwards, and this is attributed to later folding. Locally late monoformal folds affect the sequence and narrow zones of subvertical bedding and S2 occur. However, these appear to relate to post-D3 deformation episodes. At NC 5748 6581 a S-stepping monoform of some 40 m amplitude is developed in psammites beneath the Strathan Conglomerate; it can be traced for at least 1 km to the WNW. Late-stage faulting has only caused significant displacement of the outcrop pattern in two places; on the coastal section at Geodh' an Fhuarain (NC 5716 6590) and south of Creag Mhòr at NC 5875 6450. Both are ENE-trending faults locally marked by breccia zones and they downthrow to the NNW and SSE respectively. Small E- and ENE-trending faults also occur by Port Vasgo and on Meall Mòr. The faults are probably Devonian in age, but may be as young as Mesozoic.

## Interpretation

The structural complexity and wealth of exposure found in the Port Vasgo–Strathan Bay GCR site area have led to numerous interpretations of the geological history. The Caledonian structural history, which primarily reflects westward thrusting and folding (D2 + D3), has largely obscured earlier D1 deformation patterns and the original relationships between the Lewisianoid basement and dominantly metasedimentary Moine cover. Also it still remains unclear whether the main D2 deformation phase belongs to the Grampian (Ordovician) or Scandian (Silurian) orogenic event.

All workers agree that the striped mafic hornblendic and felsic (quartzofeldspathic) gneisses are of Lewisianoid origin, but discrimination between the Lewisianoid felsic gneisses and sheared arkosic or feldspathic Moine psammites is less clear-cut, particularly in or adjacent to the D2 shear-zones. The presence of local Lewisianoid detritus in the basal Moine rocks also confuses the situation. Farther west in the upper part of Strath Melness, an inverted contact between Moine metaconglomerate units and Lewisianoid gneiss is exposed at NC 5665 6292. Here, as in many instances, the Moine–Lewisianoid contacts appear to have been a locus for enhanced deformation and the rocks are strongly sheared and recrystallized. Quartz-feldspar pegmatite veins, lenses and pods are variably developed both in the slide zones and the adjacent Moine rocks (see also **Melness** GCR site report, this chapter). Holdsworth (1989a) interpreted felsic rocks containing amphibole or pegmatite veins and pods as Lewisianoid in origin, and thus has interpreted greater areas of Lewisianoid gneiss in the Port Vasgo–Strathan Bay area than are shown here (compare Figure 6.8 with fig. 6 of Holdsworth *et al.*, 2001).

Only the basal parts of the Moine succession are present in the Port Vasgo–Strathan Bay area, and these consist of originally proximal, lenticular, feldspathic sandstone units with conglomeratic and gritty lenses and thin but locally persistent pelitic units. The sandstones represent rapid clastic input, probably mainly from distant sources in the Canadian Shield (Cawood *et al.*, 2004). Friend *et al.* (2003) showed that the detrital zircon age spectrum from similar feldspathic psammites from Cnoc Eigil (NC 549 609), some 4 km to the south-west of the site area, contained very few Archaean-age grains. The pelites represent original shales, probably reflecting longer periods of low clastic input. However, detrital minerals such as epidote and actinolite are common locally in the basal parts of the Moine succession. They were probably derived from the local Lewisianoid basement and represent an extended period of erosion preceding Moine deposition.

Basic meta-igneous bodies, part of the Ben Hope Suite (Floyd and Winchester, 1983; see also Holdsworth *et al.*, 2001), were intruded originally as basalt and dolerite sheets and dykes into parts of the Moine succession, prior to D1 deformation. In the Port Vasgo–Strathan Bay area these amphibolites are restricted to the structurally higher levels, east of the Achnahuaigh Inlier. Their geochemistry implies that they were sub-alkaline basalts, and the range of compositions suggests that in-situ or high crustal level fractionation of the basaltic magma occurred (Winchester and Floyd, 1984). Discriminant plots show that they were tholeiites of continental within-plate to plate-margin affinities (Holdsworth *et al.*, 2001). In contrast, in Strath Melness, immediately overlying the Moine–Lewisianoid contact are finely interbedded amphibolites and psammites, and in parts amphibole-epidote-rich psammite units are seen. These are interpreted here as possible volcanic or volcaniclastic deposits, relating to the extensional episode that generated the rift basin in which the Moine succession was deposited.

The nature of the D1 event remains obscure. However, it is responsible for a bedding-parallel fabric and the peak metamorphic assemblages in the Moine rocks. Sm-Nd dates of 827 ± 16 Ma from garnets in the pelite units in this area imply that the metamorphism was Neoproterozoic in age (Strachan *et al.*, 2002b). Comparable dates from the metamorphic assemblages in the Ben Hope Sill and Meadie Pelite Member farther south appear to confirm the widespread nature of this early Neoproterozoic metamorphic event (Strachan *et al.*, 2002b). It is unclear whether this metamorphism links to an extensional or compressional event, and how it relates to the 870 Ma age of intrusion of the West Highland Granite Gneiss Suite farther south (Friend *et al.*, 1997; Rogers *et al.*, 1998).

Related to this issue are the problems of interpretation of D1 structures. The model erected by Holdsworth (1989a) to explain the structural development of this area involved Caledonian D2 thrusting and folding of a pre-existing, 'layer-cake' succession that lacked significant D1 structures. Certainly there are no significantly large areas of inverted strata that could be attributed to D1 folding or thrusting. However, Holdsworth (1989a) did suggest that there might have been a pre-existing basement high in the Talmine area. Alsop and Holdsworth (1993) cited the lenticular nature of the Strathan Conglomerate as evidence for significant sedimentary facies variation within the Moine in this area.

As described above, F1 folds appear to be restricted to individual beds or limited packages of beds, with excellent examples seen on Creag Mhòr (NC 5846 6458) and along strike on the coastal slabs east of Port Vasgo. The F1 fold axes plunge more north-easterly or even northerly than the normal F2 and L2 structures in the Port Vasgo–Strathan Bay area, whose plunge ranges from ENE to easterly. Indeed, Holdsworth *et al.* (2001) noted their anomalous axial orientations, although they still assigned them to F2. However, they appear to be early-formed structures with axial planes lying parallel to bedding/S1 cleavage (but note that S0/S1 is also commonly sub-parallel to S2). The early Neoproterozoic-age metamorphic fabric lies strictly axial planar to the F1 folds. If they are F1 structures, they are best explained as formed during a D1 extensional or compressional phase of folding accompanied by the peak metamorphism at epidote-amphibolite grade. It is also possible that they may be anomalous early F2 folds, but a preferred interpretation is that they are packages of slump folds with some convolute bedding. Unfortunately, it is difficult to specifically characterize slump folds and hence distinguish them from tectonic folds (see Elliot and Williams, 1988), particularly where the rocks have been severely deformed subsequently. Although no conclusive evidence is present, their mode of occurrence and geometry are compatible with gravitational collapse of rapidly deposited, partially consolidated sedimentary strata in a tectonically active environment. An analogue of similar scale, the Fisherstreet Slump, occurs in the Namurian sandstones and shales of County Clare in western Ireland (Strachan and Alsop, 2004).

Despite subsequent D2 and D3 sliding and the widespread development of mylonitic rocks, the unconformable nature of the Moine–Lewisianoid contact remains clear around the Achnahuaigh Lewisianoid Inlier. The Lewisianoid rocks lie in the hinge zone of a large-scale, tight F2 anticline that verges to the WSW and has been modified by late-stage D2 and subsequent D3 shearing. The complex folded zone on the northern and western flanks of Cnoc nan Gobhar (NC 5750 6432) forms part of the hinge zone and inverted limb of this D2 fold. Oversteepened cross-bedding foresets, thicker bedding, and only weak development of S2 mark the low strain in this area. Farther east at a structurally higher level on Creag Mhòr, similar low-strain features are seen. Here, the psammites lie on a complex 'short' limb of a large-scale D2 asymmetrical antiform that also verges and faces to the south.

Holdsworth (1989a) noted that the D1 lineation possibly controlled the subsequent development of the L2 lineation and even the development of F2 fold axes. It seems likely that the original stratigraphical template and D1 geometry did exert some control on the overall D2 and D3 structural pattern and its development (see Watkinson and Cobbold, 1981). The rocks had a south-easterly or southerly dip and an E- to SE-plunging L1 lineation prior to Caledonian thrusting and folding.

The mechanisms of D2 and D3 fold and thrust formation has also been the subject of numerous papers. Holdsworth (1989a, 1990), Alsop and

Holdsworth (1993), and Alsop *et al.* (1996) attribute all D2 and D3 structures to progressive WNW-directed transport during the Caledonian Orogeny. Alsop and Holdsworth (2002) subsequently modified this model such that the F2 + F3 fold pattern was interpreted as a product of coherent ductile flow with sheath folding, with the later open to tight F3 folds resulting from differential sinistral and dextral shear. They explained the F3 folds as late-stage flow perturbations developed during the ductile thrusting process. The perturbations are seen as focused on and adjacent to the pre-existing D2 thrusts, resulting in both transport-parallel and cross folding. However, Holdsworth (1990) noted that F3 folds appear to 'root' downwards into mylonitic zones and related them to the underlying Moine Thrust mylonites. This works only if the D2 and D3 folding are Scandian (Late Silurian) (see Kelley and Powell, 1985; see also the **Meall an t-Sithe and Creag Rainich** GCR site report, Chapter 7). $^{40}Ar$-$^{39}Ar$ step-heating ages and Rb-Sr ages obtained from muscovites and hornblendes of the A' Mhoine Nappe on north Sutherland by Dallmeyer *et al.* (2001) throw some faint light on this problem. A muscovite from Port Vasgo (sample no. 10) gave a $^{40}Ar$-$^{39}Ar$ plateau age of 451.8 ± 0.2 Ma. However, as it also gave an Rb-Sr age of 433 Ma, the older argon age was interpreted as due to excess radiogenic Ar. The overall data were interpreted to imply that D2 deformation in north Sutherland was of Scandian age.

## Conclusions

The Port Vasgo–Strathan Bay GCR site area exposes the lower parts of the Moine metasedimentary succession and the underlying Lewisianoid gneiss basement within a complex regional sheared and folded zone, termed the 'Talmine Imbricate Zone'. Farther south this complex fold-and-thrust zone passes into the Ben Hope Thrust (see **Allt na Caillich** GCR site report, this chapter). The zone was formed by the overall WNW translation of the Moine and Lewisianoid rocks in the A' Mhoine Nappe towards the foreland during the Caledonian Orogeny. The structural complexities are well displayed at outcrop scale and have been used to illustrate differing models for the formation of large- and small-scale sheath-folds. In addition, the site enables the relative timing of fold and shear-zone generation to be worked out, provides evidence of the original pattern of Moine metasedimentary rocks, and illustrates the strain variations associated with the main deformation phase, termed 'D2'. The area is notable for the remarkable changes in the degree of strain, with distinct sedimentary structures prominent only a few metres away from mylonitic high-strain zones.

The Lewisianoid felsic and mafic gneisses of the Achnahuaigh Inlier show evidence of a complex pre-Caledonian history, mainly at deep crustal levels, but have subsequently been severely affected by the Caledonian tectonic reworking. The Moine succession consists of psammites with subsidiary conglomeratic lenses, and thin garnetiferous pelite interbeds near its base. Locally Lewisianoid gneiss detritus is found in the lowermost Moine psammites. The conglomerate lenses now attain some 40 m in thickness but exhibit very high Caledonian strains such that their present thickness is only a quarter to about a tenth of their original thickness. Possible originally volcaniclastic units also occur in the basal parts of the Moine sequence. The Moine and Lewisianoid rocks contain numerous mafic sheets, now garnetiferous amphibolites and hornblende schists. They were initially intruded as differentiated tholeiitic basalt or dolerite sills and dykes in the Early Neoproterozoic and are part of the Ben Hope Suite. The Neoproterozoic Moine succession and mafic sills probably formed in an active, extending, marine, rift basin, underlain by continental crust.

The regional structure of the area is dominated by the gentle easterly dip of the bedding, the pervasive Caledonian schistosity (S2), tight reclined folding, and the main ductile thrusts. A very prominent quartz lineation (L2), that typically plunges gently eastwards in this area, reflects the main extension and westerly transport direction. It is parallel to the axes of the main F2 folds that plunge down the dip of their axial planes and verge (overfold) mainly to the south. Later Caledonian D3 thrusting, and associated F3 folding along similarly orientated axes and gently ENE-dipping axial planes, are superimposed on the earlier structures. This refolding, and the complex nature of the original template of basement highs and lenticular and varied basal Moine units in the Port Vasgo–Strathan Bay area, complicate the structural picture. The original Neoproterozoic-age D1 structural features have probably also exerted significant control over the form of the later Caledonian structures. The Moine rocks have been metamorphosed under lower amphibolite-facies conditions during the D1 event, and subsequently under epidote-amphibolite- and greenschist-facies conditions during the Caledonian thrusting and folding (D2 + D3).

The Port Vasgo–Strathan Bay GCR site is of national importance as it provides an insight into the relationship of the Moine cover to the Lewisianoid basement inliers. It also provides evidence of the somewhat enigmatic early structural and metamorphic Neoproterozoic events that affected these rocks. The excellent coastal and inland exposures provide a near-three-dimensional picture of the complex structures and strains developed during an extended period of Caledonian thrusting and folding. The area has been cited in several papers for its sheath folding and used in studies of their geometry and to erect models for their origin. Together with the **Ben Hutig** GCR site, it provides a link between the fold sequence in the internal Moine nappes and that in the Moine Thrust Belt in north Sutherland. The area is a natural laboratory for research and teaching in structural geology, that with further work will help to elucidate the stratigraphical, structural and metamorphic history of the Moine rocks of the North-west Highlands.

## MELNESS (NC 571 603–NC 586 624, NC 595 619)

*J.R. Mendum*

### Introduction

The Melness GCR site lies on the north-west side of the Kyle of Tongue and stretches north-east from Loch a' Mhuilinn to Cnoc an Airbhe and the peninsula of Ard Skinid. It provides a section through four inliers of Lewisianoid gneisses, which together with the adjoining basal Moine psammites and 'early' mafic sheets, have been tightly folded and thrust towards the west during the Caledonian Orogeny (Figure 6.10). Moine–Lewisianoid contacts are well exposed and are typically strongly sheared. The 'early' mafic sheets and pods have been metamorphosed to garnet amphibolite. The site also contains possible volcaniclastic rocks in the Moine succession and much pegmatite veining. It is complementary with the **Port Vasgo–Strathan Bay** GCR site area just to the north, but the rocks in the Melness area show less-extreme variations in the type and degree of Caledonian strain. The site straddles the entire Talmine Imbricate Zone, which links up with the Ben Hope Thrust to the south (see **Allt na Caillich** GCR site report, this chapter).

B.N. Peach and J. Horne first mapped the area for the Geological Survey in the 1880s. Several geologists worked in the area subsequently (e.g. Gilbert Wilson in the 1940s and 1950s), but the bulk of the published material stems from mapping and structural studies by Holdsworth (1987). This PhD work was included in the revised map of the Tongue area (British Geological Survey, 1997b) and accompanying memoir (Holdsworth *et al.*, 2001). The area has also been featured in several papers that have discussed the structural pattern and evolution of the northern Moine (Holdsworth, 1989a, 1990; Alsop and Holdsworth, 1993, 2002; Alsop *et al.*, 1996).

### Description

This area stretches north-east from Loch a' Mhuilinn across the low-relief rocky promontory immediately above Melness village, to Cnoc an Airbhe (NC 5847 6188) and the Talmine road. It also includes the well-exposed hilly peninsula of Ard Skinid farther east but excludes the intervening crofting land.

Lewisianoid gneisses form four main inliers that from west to east are labelled 'Loch a' Mhuilinn', Achnahuaigh–Cnoc an Airbhe', 'Dùn Buidhe' and 'Skinnet' (Figure 6.10). Their maximum thickness is about 150–200 m. Their component gneisses vary from finely striped hornblendic felsic gneisses to more-homogeneous quartzofeldspathic gneiss, and contain abundant mafic pods and lenses and rarely small ultramafic lenses. Pegmatitic and aplitic granite veins and pods and quartz veins and lenses are common. Representative lithologies are well seen in the crags east of the Loch a' Mhuilinn sluice at NC 5738 6126. Farther west in the Strath Melness Burn section pink marble is found, but unequivocal metasedimentary inclusions are very rare in these inliers. The original gneissosity has been strongly sheared and folded by Caledonian deformation. The Lewisianoid gneisses are more strongly platy towards their

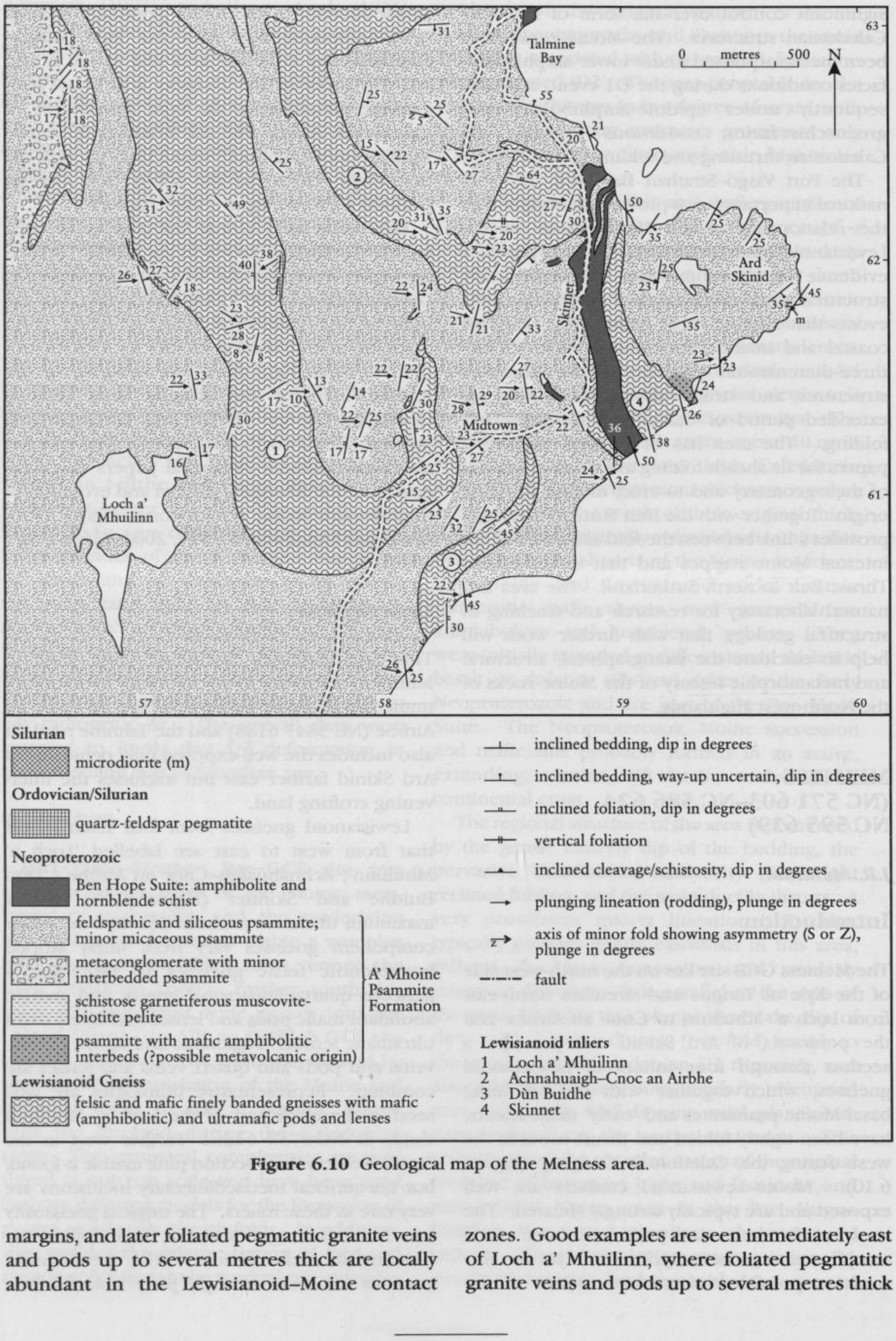


**Figure 6.10** Geological map of the Melness area.

margins, and later foliated pegmatitic granite veins and pods up to several metres thick are locally abundant in the Lewisianoid–Moine contact zones. Good examples are seen immediately east of Loch a' Mhuilinn, where foliated pegmatitic granite veins and pods up to several metres thick and abundant quartz veining are seen. These extend downwards from the slide contact for up to 70 m in the underlying pink, recrystallized, feldspathic and quartzose psammites.

The basal Moine rocks here belong to the Altnaharra Psammite Formation (Holdsworth *et al.*, 2001; see 'Introduction', this chapter). They consist of white to fawn and pale-grey, feldspathic psammites, locally gritty, with subsidiary thin, micaceous psammite interbeds. Only sparse thin semipelite and pelite interbeds occur in the psammite sequence in this area, typically close to Moine–Lewisianoid contacts. The psammites are best exposed in the wide hinge zones of medium-scale, ESE-plunging, reclined F2 folds on Ard Skinid. Here cross-bedding is preserved and in places small-scale, tight to isoclinal, possible slump folds are locally abundant (Figure 6.11). Both features imply that the sequence is locally inverted. The basal psammite beds adjacent to the Lewisianoid gneisses are commonly gritty and in places contain amphibolitic mafic gneiss fragments. Locally, they contain epidote-rich layers and magnetite lenticles (NC 5832 6049), implying derivation from the adjacent Lewisianoid rocks. In places, small lenses of Lewisianoid gneiss can be discerned in the basal parts of the psammite succession (e.g. at NC 5818 6125).

Garnetiferous amphibolite and hornblende schist forms both thick and thin sheets in the Moine and Lewisianoid rocks. These mafic bodies were originally cross-cutting intrusive dolerite sheets and sills, and some are still discordant to bedding and the Moine–Lewisianoid boundaries. A sheet *c*. 60 m thick trends north across the Melness area and is regionally discordant to the Skinnet Lewisianoid Inlier (Figure 6.10). Another highly garnetiferous hornblende schist unit occurs on the shore section at NC 5907 6114 close to the Moine–Lewisianoid contact. Its margins are sheared and show retrogression to biotite and chlorite with development of white plagioclase-quartz-rich veins. This sheet apparently cross-cuts the Lewisianoid gneiss inlier boundary to the north-west. Other thin amphibolite sheets are finely interlayered with gritty and epidotic basal

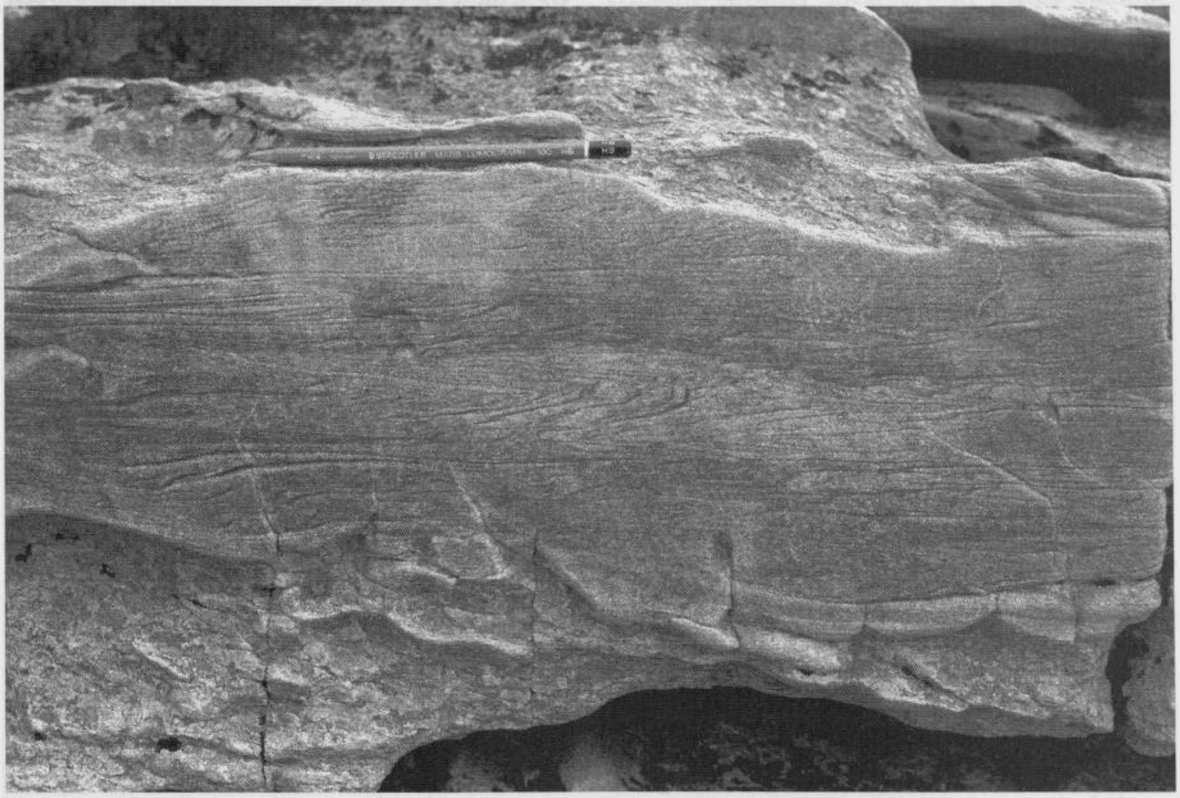

**Figure 6.11** Inverted slump-folds in the Altnaharra Psammite Formation, south end of Ard Skinid. The pencil is 16 cm long. (Photo: J.R. Mendum, BGS No. P552293, reproduced with the permission of the Director, British Geological Survey, © NERC.)

psammites, and may represent mafic volcanic material at the base of the Moine succession. The best examples occur immediately north-east of the Skinnet Lewisianoid Inlier, notably at NC 5934 6138, where pink and grey, laminated silicified 'cherty' units that show sheath folding are locally associated with the interlayered amphibolite and psammite. Similarly interlayered units are seen along strike on the coast south-west of Talmine Island around NC 5903 6222. Both massive and interlayered amphibolitic metabasic rocks have been affected by all the deformation phases (Holdsworth, 1989a).

Examples of the 'Port Vasgo Microdiorite Suite' (Holdsworth *et al.*, 2001) are seen on the south-eastern coastal section of the Ard Skinid peninsula at NC 5944 6155 and NC 5985 6175, and on the south side of Talmine Bay at NC 5864 6267. Although partially foliated and metamorphosed, the microdiorite dykes do retain chilled margins and cross-cut the D2 folds and ductile thrusts. They are further described in the **Port Vasgo–Strathan Bay** GCR site report (this chapter).

### *Structure*

The distribution of the Lewisianoid inliers in the Melness area is largely a product of Caledonian folding and thrusting. The original nature and geometry of the Moine–Lewisianoid contacts is particularly important but difficult to assess in many instances. The local abundance of epidote and other detrital material and rare conglomerate lenses in the basal Moine lithologies imply that the Moine succession was originally deposited unconformably on Lewisianoid basement gneisses. However, most Moine–Lewisianoid contacts have been strongly sheared and appear to have formed a locus for ductile thrusting. On the south-west side of Cnoc an Airbhe, around NC 5829 6185, highly deformed conglomerate lenses and psammites of the basal Moine units young away from the Lewisianoid inlier to the south. Although the Lewisianoid–Moine contact has been highly modified by shearing during D2, it appears to represent a modified unconformity.

As in the adjacent **Port Vasgo–Strathan Bay** GCR site, three main deformation and metamorphic events can be recognized. The D1 deformation phase was accompanied by peak metamorphic assemblages of lower-amphibolite grade, now dated as early Neoproterozoic in age (Strachan *et al.*, 2002b). Tight F2 folding and ductile thrusting are the dominant structures and F2 fold axes plunge gently east, down the dip of the S2 cleavage. They are co-linear with a strong, E-plunging quartz and hornblende lineation, L2. D2 deformation was accompanied by greenschist- to epidote-amphibolite-facies metamorphism. It occurred either during the Early Ordovician (Grampian) or the Late Silurian (Scandian) (Dallmeyer *et al.*, 2001; Strachan *et al.*, 2002a).

D2 shear-zones range from a few metres up to 40 m thick. They are strongly platy zones with a planar fabric defined by newly crystallized muscovite and recrystallized quartz and feldspar grains. They are found along Lewisianoid–Moine contacts, but have also developed on the highly attenuated limbs of D2 folds, particularly in the Moine psammites. Locally strongly foliated quartz-feldspar pegmatites are developed adjacent to the western lower Lewisianoid–Moine contact of the Loch a' Mhuilinn Inlier. The marginal shear-zone and pegmatites are apparently folded by a tight F2 fold, and subsequently have been refolded by a more-open F3 fold to give the current outcrop pattern.

The effects of the D3 deformation are mainly to modify the basic pattern, established during D2. However, F3 medium-scale folding of the thrust and folded pile is mainly responsible for the main strike swings and 'hook-shaped' Lewisianoid outcrop patterns, which resemble the type-3 interference patterns of Ramsay (1967). F3 minor folds are best seen in areas where their axial planes lie at a high angle to the S2 fabric, for example on the north-east and south-west ridges of Cnoc an Airbhe. A further example is seen in thinly interlayered psammite and garnetiferous amphibolite at NC 5934 6136. Here, tight F3 minor folds with a penetrative S3 axial-planar fabric, clearly refold the S2 fabric. The F3 folds are commonly almost coaxial and coplanar with the F2 and L2 structures, although their axial-plane orientations show more variation than those of F2 folds (see Holdsworth *et al.*, 2001, fig. 12b). Minor D3 shear-zones show westerly translation and appear to be related to the F3 folding, but more commonly D3 shear-zones have reactivated the earlier D2 structures. The D3 structures have formed under greenschist-facies conditions, and chlorite and biotite (after hornblende) mainly define the related S3 fabrics (Holdsworth *et al.*, 2001).

Two minor N-trending, steeply W-dipping normal faults are seen at NC 5933 6134 where they bound a 1.2 m-wide fracture zone. These may relate to Devonian or Mesozoic fault patterns, which dominate the offshore geology (see also **Coldbackie** GCR site report, this chapter).

## Interpretation

The area has similar problems of interpretation to those in the adjacent **Port Vasgo–Strathan Bay** GCR site area. In the Melness area the focus is on the nature of the Moine–Lewisianoid contacts and the overall D2 and D3 structural pattern.

Evidence for the unconformable nature of the Lewisianoid–Moine contacts is not as compelling as that found farther west in Strath Melness or in the **Port Vasgo–Strathan Bay** GCR site, as most contacts are strongly attenuated in the Melness GCR site. The Lewisianoid inliers are interpreted both as thrust-bounded sheets and as antiformal cores of kilometre-scale, tight F2 folds. The two easterly inliers, Dùn Buidhe and Skinnet, appear to have ductile shear-zones at their western margins and to wedge out northwards (Figure 6.10). In contrast the two more westerly 'hook-shaped' inliers, Loch a' Mhuilinn and Achnahuaigh–Cnoc an Airbhe, appear to result from F2 + F3 fold interference. The fold pattern in the wider Talmine area was analysed by Alsop and Holdsworth (2002), who modelled it as a product of Caledonian differential shearing and coeval generation of perturbations.

Abundant pegmatitic and quartz veins and pods, accompanied by recrystallization and pinkening of the underlying psammites, are best seen close to the western Moine–Lewisianoid contact of the Loch a' Mhuilinn Inlier (see above). These features suggest than the shear zone has been the site of considerable fluid movements, either during D1 or at an early stage of the D2 deformation. In contrast, the finely interlayered amphibolite and psammite lithology found immediately above the most easterly Skinnet Lewisianoid Inlier may represent thin metavolcanic units in the stratigraphically lowermost Moine rocks. Amphibole-rich mafic units occur in a similar stratigraphical position in Strath Melness, a few kilometres to the WNW.

## Conclusions

The Melness GCR site area in north Sutherland provides a section through a complex, ductile thrust zone, termed the 'Talmine Imbricate Zone'. This zone is a northern extension of the Ben Hope Thrust that itself lies within the A' Mhoine Nappe. The main units represented are Lewisianoid gneisses, which here form four inliers, the basal Moine psammites of the Altnaharra Psammite Formation, and 'early' mafic sheets, now metamorphosed to garnet amphibolite. The site is complementary with the **Port Vasgo–Strathan Bay** GCR site area to the north but the rocks in the Melness area show less-extreme variations in the degree of Caledonian strain.

The Moine rocks consist of locally gritty, feldspathic and micaceous psammites with cross-bedding and possible slumped bedding structures visible in lower strain areas. Moine–Lewisianoid contacts are well exposed and are typically strongly sheared. In places epidotic and other detrital material, and more rarely conglomerate lenses, are present, implying that the Moine rocks lie unconformably on the Lewisianoid basement inliers, at least in places. Thin amphibolite layers are intimately interlayered with basal psammites, and may represent basic volcanic material. The sequence, including the Lewisianoid gneisses, has been deformed and metamorphosed during Neoproterozoic times and subsequently tightly folded and thrust westward during two main phases of the Caledonian Orogeny. Two Caledonian fold phases, F2 and F3, are recognized; both have fold axes that plunge gently eastwards down the dip of their axial planes. A locally prominent quartz or hornblende lineation, L2, also plunges gently east, parallel to the F2 fold axes. The Caledonian D2 and D3 fold and ductile thrust patterns control the main outcrop pattern, with D3 folding responsible for some of the strike swings and 'hook-shaped' outcrop patterns. Quartz-feldspar segregations and pegmatite pods are common within the gneisses. The site is of regional importance and is ideal for further work on Moine–Lewisianoid relationships, the nature of Caledonian deformation, and for demonstrating structural features.

## ALLT NA CAILLICH (BEN HOPE) (NC 464 455)

***R.E. Holdsworth***

## Introduction

At the Allt na Caillich GCR site on the eastern flank of Strath More, a spectacular waterfall and cliff section through the Ben Hope Thrust is exposed. This structure is one of the main Caledonian ductile thrusts within the A' Mhoine Nappe in Sutherland (Figures 6.3, 6.4). It formed under lower amphibolite-facies conditions. It carries an intensely deformed sheet of Lewisianoid gneisses in its immediate hangingwall and, above this, the southernmost exposures of the 'Ben Hope Sill'. This Early Neoproterozoic, pre-metamorphic mafic sheet is one of the largest examples of the regional Ben Hope Suite. The asymmetric distribution of lithologies is typical of ductile thrusts in the Moine succession (Holdsworth, 1989a). During the primary mapping carried out in the region by the Geological Survey (Geikie, 1888; Peach *et al.*, 1907), a prominent belt of garnetiferous hornblendic and micaceous schists was recognized running southwards from the Kinloch River, around the northern and western flanks of Ben Hope, and down into Strath More. At least some of these rocks were considered to be of metamorphosed igneous origin (Geikie, 1888; Read, 1931); they became generally known as the 'Ben Hope Sill' (e.g. Moorhouse and Moorhouse, 1979). Read (1931, pp. 29 and 84) also suggested that a thrust ran around the western face of Ben Hope based on the reported occurrence of 'Eireboll Schists' (= mylonites?) by H.M. Cadell in 1886 in the north-west face of the mountain. Several authors refer briefly to the presence of a sheet of highly deformed Lewisianoid rocks on Ben Hope (e.g. Peacock, 1975; Floyd and Winchester, 1983; Evans and White, 1984; Winchester and Floyd, 1984), but more recently Holdsworth (1987, 1989a) and Grant (1989) have carried out detailed mapping of this Lewisianoid inlier and the Ben Hope Sill amphibolites. These authors have shown that the lower contact of the inlier is the Ben Hope Thrust, a structure that can be traced for over 25 km from the north coast (see **Melness** GCR site report, this chapter) to Allt na Caillich. Prior to orogenesis, the intrusion of the main sill occurred along the Moine–Lewisianoid unconformity, but Holdsworth (1987) showed that the Ben Hope Sill was both regionally and locally discordant. Geochemical studies of the Ben Hope Suite (Moorhouse and Moorhouse, 1979; Floyd and Winchester, 1983; Winchester and Floyd, 1984) showed that, despite pervasive amphibolite-facies metamorphism, the sills still have fractionated tholeiitic basaltic compositions with affinities to within-plate basalts, transitional towards plate-margin types. Evans and White (1984), Grant (1989) and Holdsworth and Grant (1990) describe textural and quartz c-axis orientation data from the psammites associated with the Ben Hope Thrust from the Kyle of Tongue southwards to Allt na Caillich.

## Description

The Allt na Caillich flows over a waterfall at the southern end of the NNE-trending cliffs of Leitir Mhuiseil (Figures 6.12, 6.13) at NC 464 455, some 5 km SSW of Ben Hope summit; most of the key exposures for this site lie within or adjacent to these cliffs. The Ben Hope Thrust overlies a thick succession of Moine psammite. In its hangingwall are the following units (from base to top): Lewisianoid-derived mylonites, a thin sliver of Moine psammite, the Ben Hope Sill amphibolite, overlain by garnetiferous mica schist. Above this lies another thick succession of Moine psammites. All the units have a shallow dip to the ESE and were deformed under lower-amphibolite- to upper-greenschist-facies metamorphic conditions. Exposed contacts are sharp apart from the boundary between the mica schist and the overlying psammites, which is gradational. The Lewisianoid gneisses, Ben Hope Sill and mica schist units all progressively thin towards the south and appear to peter out where the Ben Hope Thrust intersects the Allt Dornaigil stream section 0.5 km to the south of Allt na Caillich.

The Moine psammites below the Ben Hope Thrust comprise several hundred metres of cleaved, lithologically monotonous feldspathic psammites, which are well exposed in the Allt na Caillich stream section up to the waterfall. They are part of the A' Mhoine Psammite Formation (Holdsworth *et al.*, 2001). Traces of primary bedding are poorly preserved, although rare pebbly lenses and heavy-mineral layers are present locally. On approaching the thrust plane, the psammites become increasingly flaggy, finer-grained and more muscovite-rich,

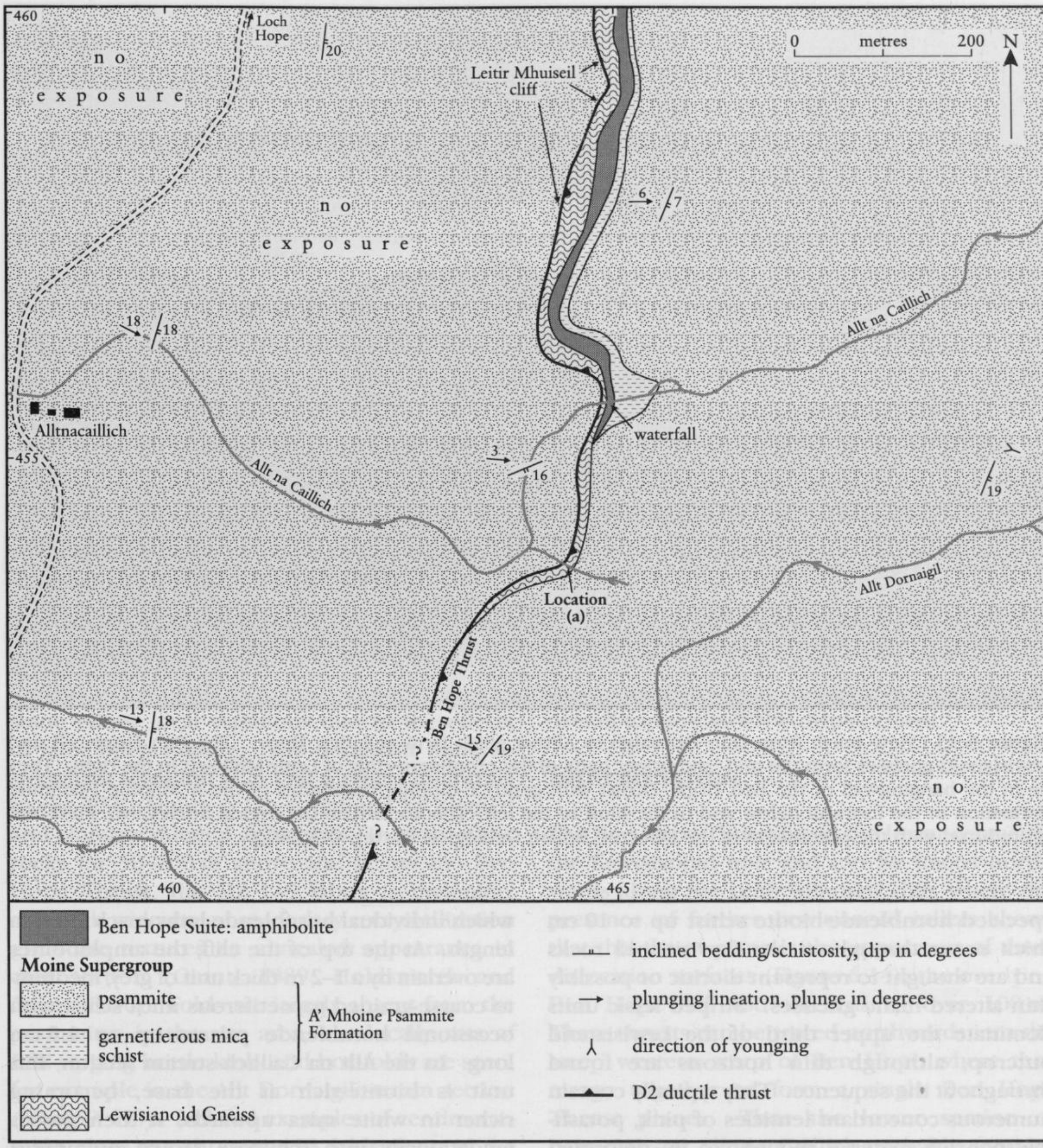


**Figure 6.12** Map of the Allt na Caillich GCR site.

reflecting the increasing strain, until all traces of original planar discordances disappear. The razor-sharp lower contact between the psammites and Lewisianoid rocks is well exposed in the waterfall section, in the cliffs of Leitir Mhuiseil for 250 m to the north and in the small, tributary stream section to the south (location 'a' in Figure 6.12). The Lewisianoid rocks comprise a heterogeneous sequence of mainly dark-coloured, fine-to medium-grained, laminated, sometimes platy schists derived from intense deformation and shearing of interlayered felsic and mafic gneisses. Dark green-black, schistose amphibolites form the dominant lithology in the lower two-thirds of the Lewisianoid unit. They differ petrologically from the Ben Hope Suite as they generally lack garnet and contain abundant pyrite and chalcopyrite crystals up to 2 mm across; large veins of coarse-grained calcite are also locally present. Lenses of

**Figure 6.13** View north from Dùn Dornaigil to Alltnacaillich farm and Ben Hope. The Ben Hope Sill and Lewisianoid gneisses form the mid- and upper parts of the prominent cliffs of Leitir Mhuiseil to the right. They lie in the hangingwall of the Ben Hope Thrust with gently E-dipping psammites of the A' Mhoine Psammite Formation in the footwall below and in the bluff to the left. (Photo: British Geological Survey, No. P002763, reproduced with the permission of the Director, British Geological Survey, © NERC.)

speckled hornblende-biotite schist up to 10 cm thick occur throughout the Lewisianoid rocks and are thought to represent dioritic or possibly thin altered mafic gneisses. Striped felsic units dominate the upper third of the Lewisianoid outcrop, although thin horizons are found throughout the sequence. They typically contain numerous concordant lenticles of pink, potash-feldspar-rich material thought to be deformed migmatitic segregations or granitic/pegmatitic veins (Holdsworth, 1987). Small, centimetre-scale hornblendite pods are a subordinate but characteristic additional lithology. In the waterfall and location 'a' sections, the 12–15 m-thick Lewisian sequence is overlain by 0.5 m of platy Moine psammite which is in turn overlain by a concordant, 2.0 m-thick unit of schistose garnetiferous amphibolite, the Ben Hope Sill (Figure 6.12). This comprises interlayered units of highly foliated fine- to medium-grained garnet-rich amphibolite and more-massive horizons of coarse-grained, garnet-poor amphibolite in which individual hornblende laths reach 2 cm in length. At the top of the cliff, the amphibolites are overlain by a 1–2 m-thick unit of grey, medium- to coarse-grained garnetiferous mica schist with occasional hornblende prisms up to 1.5 cm long. In the Allt na Caillich stream section, this unit is biotite-rich at the base, becoming richer in white mica upwards; it then passes gradationally into schistose Moine psammites above. A further thin (0.5 m), concordant unit of fine- to medium-grained garnetiferous amphibolite occurs within the psammites 140 m upstream. Otherwise, the upper sequence of Moine psammites is similar to the lower succession, although primary bedding structures and occasional cross-laminations are preserved showing that the sequence here is right-way-up (Figures 6.12, 6.14). These upper psammites are part of the Altnaharra Psammite Formation (Holdsworth *et al.*, 2001).

The main penetrative tectonic fabric (S2) defined by the alignment of mineral grains and

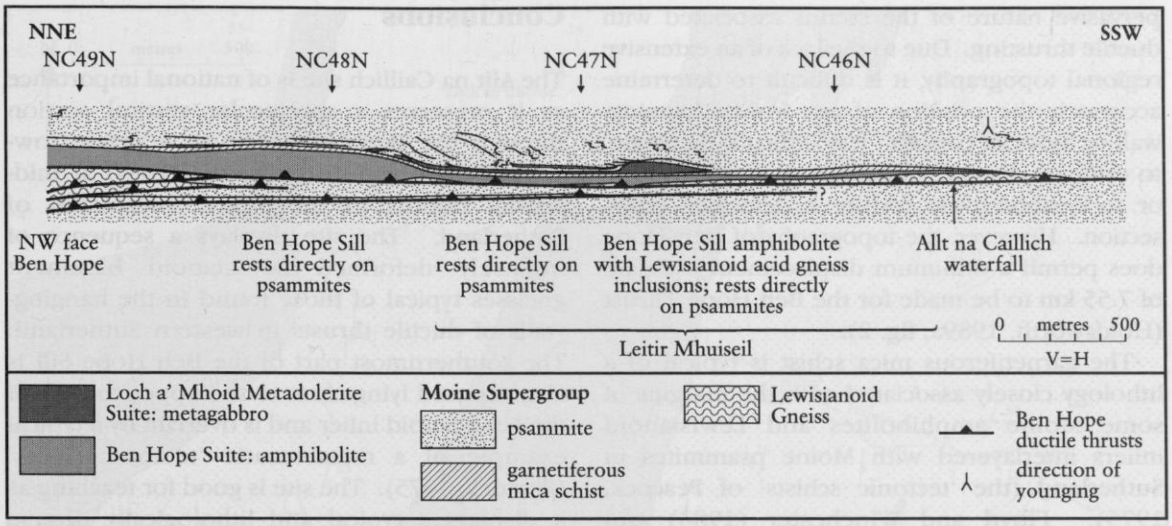


**Figure 6.14** NNE–SSW longitudinal cross-section showing thickness changes and lateral branching of the Ben Hope Thrust that occurs between the north-west face of Ben Hope and Allt na Caillich, including the cliffs of Leitir Mhuiseil. After Holdsworth (1989a, fig. 4).

elongate mineral aggregates lies mainly parallel to the bedding/layering, and dips are uniformly shallow towards the ESE, although there are some minor local variations due to the effects of later open folding. The dominant mineral-stretching lineation (L2) that plunges uniformly to the ESE (Figure 6.12) is defined by aligned and elongate mineral aggregates. In most of the rocks for 50–100 m above and below the Ben Hope Thrust, the D2 L–S fabric is mylonitic, although widespread secondary recrystallization gives the textures an annealed appearance in thin section (Grant, 1989; Holdsworth and Grant, 1990). Folds are largely absent from the psammites in the site area, but locally sets of ESE-verging brittle kink- and box-folds are seen, for example in the Allt Dornaigil stream section (NC 459 450). Isolated examples of centimetre-scale, close to tight minor F3 folds occur in the intensely deformed Lewisianoid gneisses and Ben Hope Sill amphibolite units, where they are seen to fold both S2 and L2. More-open F3 folds of this scale are also widespread in the garnetiferous mica schist unit. F3 plunge and vergence patterns are variable and the folds are typical products of progressive deformation in high-strain zones (Holdsworth, 1990). Some F3 folds are seen to be associated with discrete shear-zones orientated oblique to the main foliation which lead to the localized development of an anastomosing foliation in lower parts of the Lewisianoid unit (Grant, 1989). Shear-sense criteria visible in the field include shear-band fabrics, asymmetrical wrapping of porphyroblasts and F3 fold asymmetry; all consistent with overall top-to-the-WNW displacement.

## Interpretation

The Ben Hope Thrust lies at the lower contact of the Lewisianoid unit and can be traced northwards along the Leitir Mhuiseil cliffs where the presence of further Lewisianoid inliers shows that this thrust plane is the uppermost of three dislocation surfaces (Figure 6.14); the overlying Ben Hope Sill also thickens to over 100 m. These thrusts can be traced northwards into the steep western scarp of Ben Hope where they merge together to form a single Ben Hope Thrust plane. Thus the lower section of psammites at Allt na Caillich probably contains several ductile thrusts, but only the uppermost, and largest displacement surface is obvious due to the presence of the basement thrust slice and overlying Ben Hope Sill amphibolite. Ductile thrust ramp angles are uniformly low (< 5°) in the Leitir Mhuiseil–Ben Hope area, and at several locations the Ben Hope Sill amphibolite sits directly on the thrust plane (Figure 6.14). This may occur either because the thrust has cut up-section laterally in the hangingwall or because the original basic sill intrusively cut down into the Lewisianoid below. The low ramp angles are typical for the region and reflect the intense, pervasive nature of the strains associated with ductile thrusting. Due to the lack of an extensive regional topography, it is difficult to determine accurately the position of any frontal hangingwall or footwall cut-offs. It is difficult, therefore, to estimate displacements across ductile thrusts or to quantitatively restore a deformed cross-section. However, the topography of Ben Hope does permit a minimum displacement estimate of 7.55 km to be made for the Ben Hope Thrust (Holdsworth, 1989a, fig. 2).

The garnetiferous mica schist is typical of a lithology closely associated with the margins of some Moine amphibolites and Lewisianoid inliers interlayered with Moine psammites in Sutherland (the 'tectonic schists' of Peacock, 1975). Floyd and Winchester (1983) and Holdsworth (1987) have suggested that such schistose units form due to retrogression and metasomatism of amphibolites and adjacent psammites associated with the focused flow of hydrous fluids within shear zones.

The structurally simple nature of the platy rocks in the footwall and hangingwall of the Ben Hope Thrust is attributed to intense ductile deformation. The observed metamorphic assemblages (e.g. hornblende-biotite-garnet-albite-epidote in amphibolites) and annealed mylonitic textures are consistent with deformation under lower-amphibolite- to uppermost greenschist-facies metamorphic conditions (Holdsworth, 1987; Grant, 1989, Holdsworth and Grant, 1990). Evans and White (1984) measured the quartz c-axis orientations from a specimen of psammite adjacent to the Ben Hope Thrust and showed that they displayed asymmetric girdle patterns similar to those obtained from the mylonites of the Moine Thrust Belt. Grant (1989) carried out a detailed microstructural and quartz c-axis orientation study in the section between Ben Hope and Allt na Caillich. His results suggested that deformation associated with the Ben Hope Thrust was heterogeneously distributed, with distinct domains of coaxial and non-coaxial (mainly top-to-the-WNW) shear that changed location with time. He also found microstructural evidence for localized domains of top-to-the-ESE shearing, at least some of which formed late in the deformation history due to extensional reactivation along the foliation. This event probably relates to the late Caledonian phase of top-to-the-ESE shear recognized by Holdsworth (1989a) in the Kyle of Tongue region to the north.

## Conclusions

The Allt na Caillich site is of national importance as it preserves a spectacular vertical section through the Ben Hope Thrust, a major, low-angle Caledonian ductile fault formed at mid-crustal depths in the Moine succession of Sutherland. The site displays a sequence of intensely deformed Lewisianoid basement gneisses typical of those found in the hangingwalls of ductile thrusts in western Sutherland. The southernmost part of the Ben Hope Sill is also exposed lying close to the upper contact of the Lewisianoid inlier and is overlain by a typical example of a metasomatic 'tectonic schist' (Peacock, 1975). The site is good for teaching as it displays a typical and lithologically diverse sequence of annealed mid-crustal mylonites deformed under lower-amphibolite- to uppermost greenschist-facies conditions.

# ALLT AN DHERUE (NC 540 464–NC 535 443)

*J.R. Mendum*

## Introduction

The Allt an Dherue GCR site in central north Sutherland provides a wide cross-section across structurally interleaved and folded Moine psammites, garnet-staurolite-kyanite-bearing semipelites and pelites, and thick sheets of Lewisianoid gneisses (Figure 6.15). The area shows various aspects of the Moine–Lewisianoid relationships, the effects of major shear-zones on the succession, and is the type area for the Meadie Pelite Member and the so-called 'Meadie Schists'.

The geology is a southerly continuation of the complex zone of thrust and folded Lewisianoid inliers and Moine rocks found in the Tongue and Talmine areas to the north. The rocks have been strongly deformed and metamorphosed under amphibolite-facies conditions during Caledonian and earlier Neoproterozoic orogenic episodes. The deformation, metamorphism, widespread occurrence of shear zones, and local folding all serve to obscure the original Moine–Lewisianoid relationships in this area. The rocks are intruded by Neoproterozoic-age, partly garnetiferous amphibolites, mostly sills of the Ben Hope Suite. Ultramafic and mafic pods of the late Caledonian

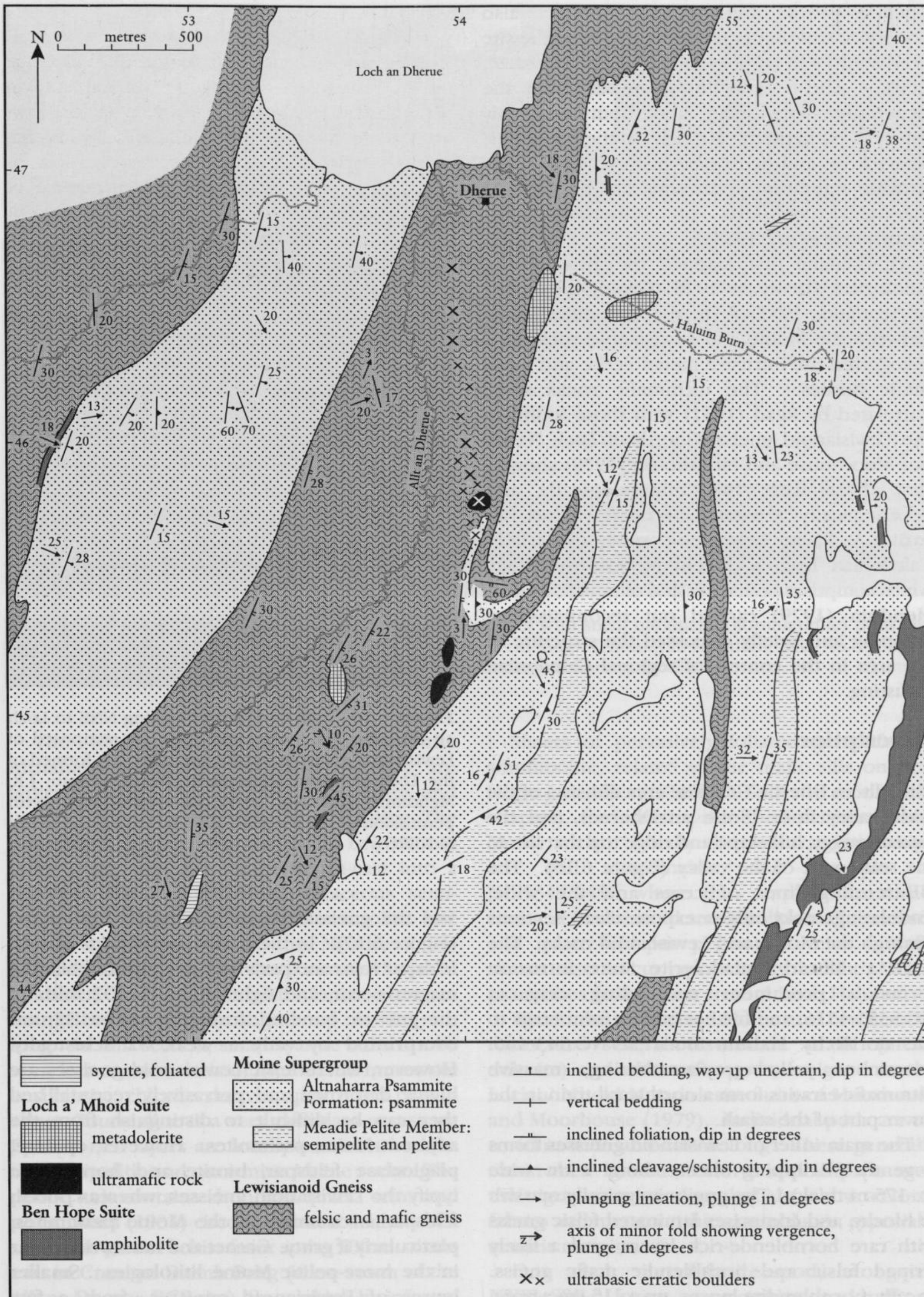


**Figure 6.15** Map of the Allt an Dherue GCR site.

Loch a' Mhoid Metadolerite Suite are also common, and immediately north-east of the site area is the Loch Loyal Syenite (Holdsworth *et al.*, 2001). These latter intrusions cross-cut the penetrative Caledonian fabrics but are partly foliated, particularly adjacent to their margins. The nature and geological history of the rocks provide significant constraints on the regional geological synthesis of Sutherland (e.g. Moorhouse *et al.*, 1988).

D. Haldane first mapped the area for the Geological Survey in 1926 (Geological Survey of Scotland, 1931). He did not differentiate between the Moine and Lewisianoid rocks, but recognized the intrusive metadolerite and ultramafic bodies. The ultramafic rocks were correlated by Read (1931) with those found in the Lewisianoid gneisses north of Loch Naver, but Moorhouse and Moorhouse (1979) showed that there were two mineralogically and geochemically separate ultramafic suites, an earlier Archaean Lewisianoid suite, and a later Caledonian Loch a' Mhoid Metadolerite Suite, which comprises both mafic and ultramafic bodies. Mendum (1979) carried out reconnaissance mapping and briefly discussed the structure of the area in the context of regional Caledonian thrusting.

## Description

The Allt an Dherue GCR site area consists of the wide valley floor (Srath an Dherue), and the tiered, craggy, hill-slope and ridge top that lies to the south-east of the valley (Figure 6.16). The NE-trending lines of crags and the wide, undulating rocky ridges expose clean sections through the Moine and Lewisianoid rocks. The Loch a' Mhoid Metadolerite Suite intrusion forms a prominent upstanding crag at NC 5351 4516, and further bodies form crags to the north by Haluim Burn at NC 543 466. Prominent yellow-grey-weathering, massive ultramafic erratics form a northward train in the lower part of the strath.

The main inlier of Lewisianoid gneisses forms a gently SE-dipping sheet, about 1 km wide (*c.* 175 m thick). The gneiss is typically massive to blocky, and comprises laminated felsic gneiss with rare hornblende-rich layers, and a finely striped felsic and hornblendic mafic gneiss. Locally, hornblendite lenses, up to 15 cm across, are present. The lower and upper parts of the inlier contain pervasive D2 deformation fabrics and the gneissic banding is highly attenuated (Figure 6.17). In the more-central parts quartz-feldspar veins and pods and irregular amphibolite masses occur, and tight minor pre-D2 folds of the gneissic banding, formed prior to D2, are overprinted by only a weak S2 schistosity. However, where felsic Lewisianoid gneisses are highly deformed and pervasively recrystallized they can be difficult to distinguish from the adjacent Moine psammites. However, epidote, plagioclase feldspar, biotite and hornblende typify the Lewisianoid gneisses, whereas potash feldspar is common in the Moine psammites, particularly if gritty. Garnet and muscovite occur in the more-pelitic Moine lithologies. Smaller lenses of Lewisianoid gneisses, from a few centimetres to tens of metres thick, occur within the Moine psammites outwith the main inlier.

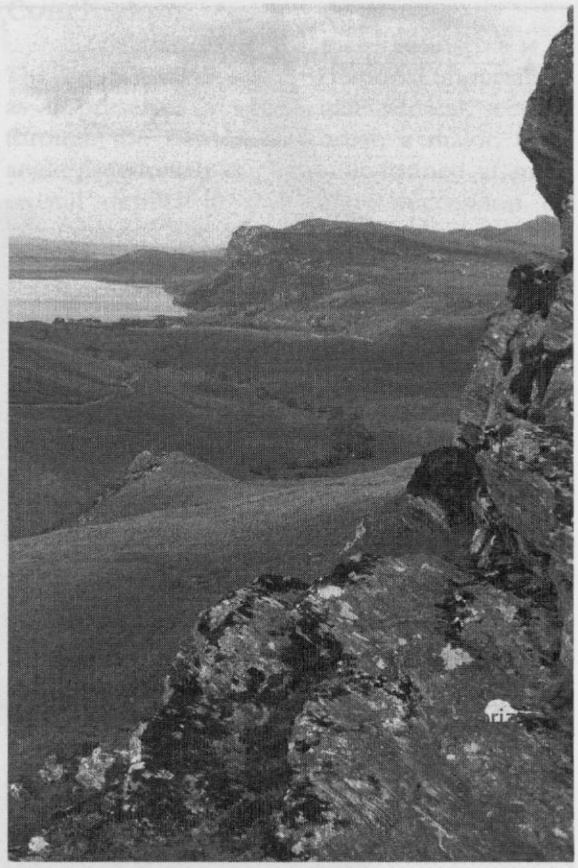

**Figure 6.16** Srath an Dherue, looking NNE to Loch an Dherue. The foreground crags are composed of Lewisianoid gneisses and the small knoll is formed of the Loch a' Mhoid Metadolerite Suite. (Photo: J.R. Mendum, BGS No. P552312, reproduced with permission of the Director, British Geological Survey, © NERC.)

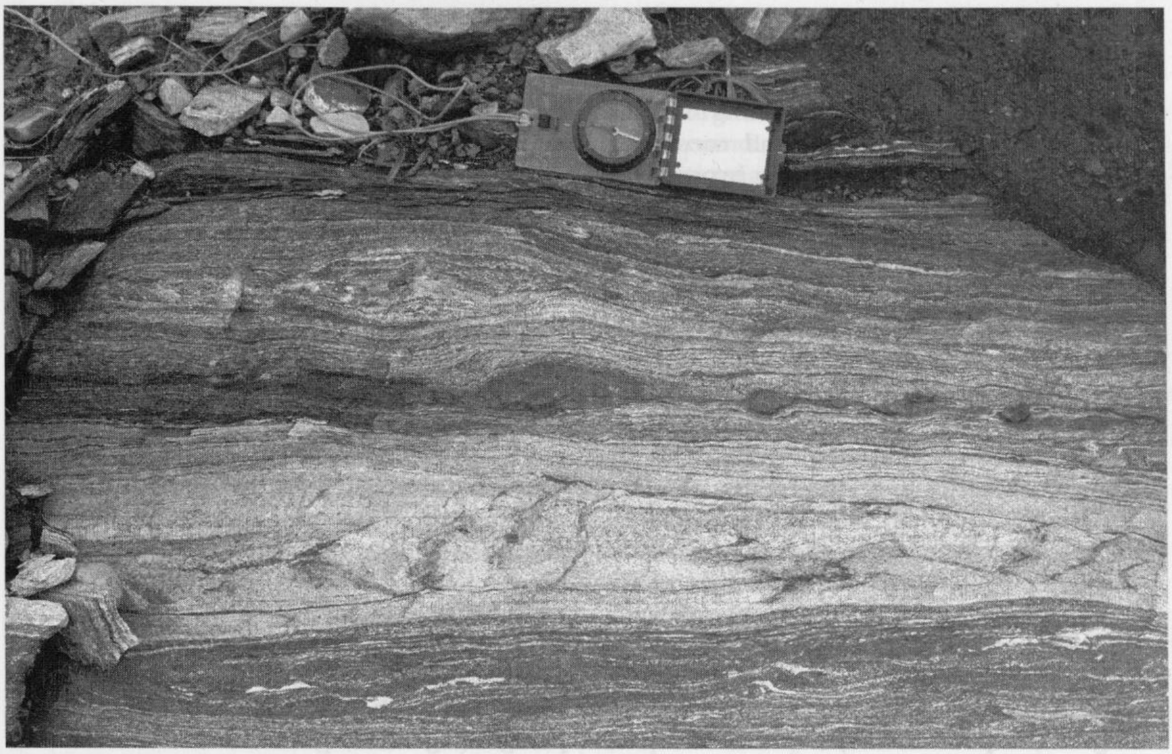

**Figure 6.17** Attenuated Lewisianoid felsic and mafic gneisses with small ultramafic (hornblendite) pods and lenses, 300 m west of Loch an Dherue. The compass is 18 cm long. (Photo: J.R. Mendum, BGS No. P552305, reproduced with the permission of the Director, British Geological Survey, © NERC.)

The Moine psammites belong to the Altnaharra Psammite Formation. They are typically poorly bedded and locally gritty, and generally carry a penetrative S2 schistosity. The psammites lying above the main Lewisianoid inlier grade upwards to the south-east into a mottled, massive, schistose, micaceous semipelite and pelite with garnet, staurolite and locally kyanite – this is the Meadie Pelite Member. Garnets range from 2 mm to 12 mm in diameter, and the staurolite forms elongate orange-brown porphyroblasts up to 2.5 mm long. In thin section, small kyanite laths can be seen in a coarse matrix of interleaved muscovite and biotite, chlorite sheaves, quartz and plagioclase. Tourmaline is a very abundant accessory. Epidote-rich layers are locally common both in the semipelitic and psammitic Moine rocks. The pelitic unit contains abundant quartz veins and pods. Read (1931) cited a chemical analysis of a staurolite-garnet schist from some 500 m south-east of Cnoc an Daimh Beag (4 km south of the Allt an Dherue GCR site), from which he inferred that the rock was originally a shale with an above average MgO and $K_2O$ content.

Sheets of pervasively foliated garnetiferous amphibolite, related to the mafic sills on Ben Hope (see **Allt na Caillich** GCR site report, this chapter), are intrusive into the Lewisianoid and Moine rocks. Locally discordant relationships are still discernable, for example at NC 5344 4486 where thin amphibolite sheets cross-cut Lewisianoid amphibolitic mafic gneisses and quartz-feldspar pegmatitic veins. Mafic sheets also occur sporadically in the Moine psammites farther east around Loch Haluim.

Within the interleaved Moine and Lewisianoid rocks are several discordant mafic (metadolerite) and ultramafic pods, assigned to the Loch a' Mhoid Metadolerite Suite of Moorhouse and Moorhouse (1979). Individual pods are up to 60 m wide and 200 m long. These generally retain their igneous textures and in parts even their igneous mineralogy, but also show tectonic fabrics and metamorphic assemblages, especially at their margins.

One such metadolerite pod, elongated NNW–SSE, forms a prominent knoll at NC 5351 4514 (Figure 6.16). Typically it is a mottled, very dark and pale grey-green, massive to blocky, medium-grained rock composed of hornblende, plagioclase feldspar (oligoclase-andesine), quartz, sphene, ilmenite and epidote. However, in its central part it is fresher, undeformed, coarser grained, and consists of plagioclase (andesine-labradorite), hypersthene (part altered to blue-green amphibole), biotite and minor opaques, identifying it as a norite. The western contact of this pod against the Lewisianoid gneisses trends NNE and is well exposed. The metadolerite is fine grained adjacent to the margin and markedly cross-cuts the gently SE-dipping foliation in the sheared Lewisianoid gneisses. To the north-east, the intrusion terminates at a SE-trending gully, possibly marking a fault or shear zone. Here, the metadolerite is distinctly foliated for some 10 m. NNE of this main intrusion further small meta-dolerite bodies occur in the lower part of the Haluim Burn.

Two ultramafic pods intrude the Lewisianoid gneisses at NC 5393 4524 and NC 5389 4509. They consist of yellow-grey-weathering, massive, dark-green, serpentinized and chloritized dunite and peridotite. They are composed of chlorite, tremolite, serpentine, relict olivine and altered enstatite. Magnetite and possibly chromite are present in patches, and some late-stage carbonate also occurs. 500 m NNE of the in-situ pods are a series of massive clean exposures of 'elephant-grey'-weathering, ultramafic rock that stretch north towards Dherue itself. The original survey joined up these exposures to form a large lenticular body (Geological Survey of Scotland, 1931) but Moorhouse *et al.* (1988) pointed out that they represent an ice-transported boulder train. However, the most southerly bodies are particularly massive and may constitute a third in-situ pod.

The structure of the area is dominated by the normally pervasive main schistosity, S2, which dips gently eastwards and locally intensifies into several shear-zones. Some of these shear zones apparently interleave Lewisianoid and Moine rocks. This broad zone, termed the 'Meadie Shear Zone' by Moorhouse *et al.* (1988), is a southerly extension of the Kyle of Tongue–Talmine Imbricate Zone (see **Melness** and **Port Vasgo–Strathan Bay** GCR site reports, this chapter; Holdsworth *et al.*, 2001). The degree of Caledonian strain varies from low in the internal parts of the Lewisianoid lenses to very high adjacent to some of the Moine–Lewisianoid boundaries. A distinct NE-trending shear-zone occurs around NC 5344 4434, but more-complex relationships are seen around NC 540 453. At this latter locality, close to tightly folded, thinly layered, felsic and mafic Lewisianoid gneisses exhibit a strong N-plunging rodding (L2) and lie adjacent to strongly foliated Moine psammites and schistose semipelites. Quartz and quartz-feldspar veins are abundant, particularly in the Moine rocks. The folded contact and striped Lewisianoid gneisses pass downwards with increasing strain into a planar shear-zone in the underlying psammitic and semipelitic Moine rocks. Although shear zones are generally located on attenuated major fold limbs and along Moine–Lewisianoid contacts, in some areas they diverge and lie wholly within Moine psammites or, less commonly, within Lewisianoid gneisses. Tight to isoclinal minor F2 folding occurs locally within these high-strain zones with the penetrative S2 schistosity axial planar to the folds.

A rodding lineation, L2, is developed over much of the area. It shows a gentle to moderate plunge (Figure 6.15) both to the north and south, but in the shear zones it commonly plunges to the SSE or south-east. However, in the north-western part of the Allt an Dherue GCR site area the lineation plunges gently to moderately east or ENE. In parts it represents the Caledonian extension direction, but more commonly it is formed by the intersection of S2 with an earlier planar fabric. It is difficult to separate or even recognize earlier and later fold phases, as folds of possible different generations are generally coaxial and parallel to the L2 lineation. In places the S2 fabric is locally folded, with the generation of a weak S3 schistosity.

## Interpretation

The nature of the relationship between Lewisianoid basement gneisses and the over-lying Moine rocks in the Allt an Dherue area remains unclear, despite the moderately good rock exposure, and the work done by several authors (Read, 1931; Moorhouse, 1977; Mendum, 1979; Moorhouse *et al.*, 1988). Where the layering in the Lewisianoid felsic and mafic gneisses is well developed, their identity is readily ascertained. In contrast, where the Lewisianoid gneisses are dominantly felsic and/or strongly sheared and metamorphosed, they are less easy to identify. Similarly, the

Moine psammites show diagnostic features in some areas, namely where bedding can be readily distinguished or where semipelitic units are present. However, where the psammites are not well bedded, or are strongly deformed, their identity is less clear.

Even the affinity of the garnet-staurolite-bearing semipelitic Meadie Pelite Member has been questioned. The Meadie Pelite is regarded here as representing originally Fe-Al-rich silty and shaly units of definite Moine parentage, but Moorhouse *et al.* (1988) noted that the geochemistry of the 'Meadie Schists' did not accord with either of the distinctive signatures of Moine and Lewisianoid lithologies elsewhere in Sutherland. Hence, they tentatively interpreted them as of Lewisianoid origin. Although Moine–Lewisianoid relationships are now strongly disrupted, it is probable that the Moine psammites and semipelites originally formed the basal units that lay unconformably on the Lewisianoid gneiss basement prior to Caledonian and earlier Neoproterozoic deformation and metamorphism. Some of the Moine–Lewisianoid contacts may well represent a modified unconformity (see also **Melness** and **Port Vasgo–Strathan Bay** GCR site reports, this chapter), but most now represent structural breaks.

The early garnetiferous amphibolite sheets represent sills and discordant sheets, originally of dolerite and basalt, that were intruded into the Moine and Lewisianoid rocks prior to the earliest deformation and metamorphism (Moorhouse and Moorhouse, 1979). They are linked to the Ben Hope Suite and their age of intrusion is bracketed at between 980 Ma and 830 Ma by the depositional age of the Moine rocks and the earliest metamorphic event (Strachan *et al.*, 2002b). Winchester and Floyd (1984) used their trace- and major-element geochemistry to infer that they were products of a differentiated sub-alkaline tholeiitic basaltic magma formed in a continental within-plate environment, possibly transitional to plate margin.

In contrast, the metadolerite body and the two ultramafic pods belong to the considerably younger Loch a' Mhoid Metadolerite Suite (Moorhouse and Moorhouse, 1979). Their geochemistry shows that they are mildly alkaline and on a Zr/Y vs Ti/Y diagram they plot in the within-plate basalt field (Moorhouse and Moorhouse, 1979). Their geochemistry suggests that early olivine and clinopyroxene fractionation of the magma was followed by late-stage ilmenite fractionation. Moorhouse and Moorhouse (1979) argue that the ultramafic pods represent olivine cumulates formed during fractionation of the basic magma. The central parts of the meta-dolerites retain their igneous textures and mineralogy, and the ultramafic pods contain relict olivine. The intrusions of the Loch a' Mhoid Metadolerite Suite are only partially deformed and post-date D2. Moorhouse *et al.* (1988) suggested that they were intruded towards the close of D2 deformation, but they may be later (or possibly even earlier) if the internal foliation cannot be correlated with the external structures, as seems probable. The intrusions represent a phase of probable Ordovician- or Silurian-age mafic and ultramafic intrusion during the waning stages of the Grampian Event or the Scandian Event.

The D2 structures in this area are dominated by the S2 schistosity and by shear zones. The Lewisianoid rocks form large lenticular masses, in part in thrust contact with the Moine psammites, but locally also tightly infolded with the psammites. The folds verge towards the west but there is no evidence of significant areas of inverted sequence. Some of the D2 folds are reclined, as they are farther north around Talmine (see **Melness** and **Port Vasgo–Strathan Bay** GCR site reports, this chapter) and farther south in Strath Oykel (see **Oykel Bridge** GCR site report, this chapter), but elsewhere they plunge north-east and northwards. There is a complex strain pattern in this area, with possible differential rotation in some lenticular zones during D2 and possible again during D3. D3 folding and fabrics are present, but are generally difficult to distinguish from the earlier pervasive D2 structures.

## Conclusions

The Allt an Dherue GCR site is of national significance as it represents an important area for the study of Moine–Lewisianoid relationships, Caledonian thrust-related ductile deformation features, and the nature and significance of the Loch a' Mhoid Metadolerite Suite of intrusive mafic and ultramafic pods. Within the Moine Altnaharra Psammite Formation is the Meadie Pelite Member, which contains the metamorphic index minerals staurolite, garnet and kyanite. This originally aluminous iron-rich siltstone has been metamorphosed during the Caledonian Orogeny and possibly earlier in Neoproterozoic times. Garnetiferous amphibolites, which represent early-formed intrusive basalt and dolerite sills, cross-cut the Lewisianoid and Moine rocks. They are Neoproterozoic in age and are linked to those on Ben Hope. Polyphase deformation is ubiquitous and several high-strain zones occur, commonly coincident with Moine–Lewisianoid contacts. Lewisianoid and Moine rocks are intruded by mafic and ultramafic pods, which form part of the late Loch a' Mhoid Metadolerite Suite. These intrusions apparently post-date the main Caledonian D2 penetrative deformation and metamorphism, and were probably intruded during the waning stages of the Grampian Event or the Scandian Event.

## COLDBACKIE BAY (NC 605 604–NC 612 606)

***J.R. Mendum***

### Introduction

Exposures in the bay and backing cliffs at Bàgh Challbacaidh (Coldbackie Bay) show folded, thrust and metamorphosed Moine psammites and semipelites with discrete lenses of Lewisianoid gneisses. They are overlain with marked angular unconformity by undeformed red-brown conglomerates and sandstones of probable Early Devonian age (Figure 6.18).

The psammites and semipelites form part of the Altnaharra Psammite Formation and belong to the Morar Group, the lowest group of the Moine Supergroup. Tight minor folds, ductile shear-zones and prominent mullion structures are well developed. These structures are attributed to the Caledonian deformation related to westward thrusting (Holdsworth, 1989a; Holdsworth *et al.*, 2001). More-brittle folds associated with shallow E-dipping detachments are also recorded in the bay at Coldbackie. These later-formed features are attributed to late Silurian or early Devonian uplift and extension (O'Reilly, 1971; Holdsworth, 1989b). The rocks lie close to the northern termination of the Tongue Lewisianoid Inlier, and within the site thin attenuated Lewisianoid gneiss lenses are in structural contact with the Moine psammites. Barr *et al.* (1986) documented the thrust interleaving of Lewisianoid basement and Moine metasedimentary rocks in Sutherland and attributed this to an Ordovician Caledonian event. However, they did recognize evidence of an earlier tectonometamorphic event (D1) of Neoproterozoic age. Subsequent work has shown that the early D1 fabrics were generally bedding-parallel, and have been accentuated by the Caledonian D2 and D3 folding and ductile thrusting (Strachan and Holdsworth, 1988; Holdsworth, 1989a, 1990). It is unclear as to the relative age and intensities of the Grampian and Scandian events in this area (see Strachan *et al.*, 2002a). The Neoproterozoic and Caledonian deformation events both occurred under lower amphibolite-facies metamorphic conditions.

B.N. Peach originally mapped the Coldbackie area for the Geological Survey in 1886. Peach and Horne (1914) suggested that the conglomerate and sandstone outlier occupied a NNW-trending valley with a faulted western margin. Although McIntyre *et al.* (1956) arrived at different conclusions, later studies by O'Reilly (1983) supported the early work and showed that the abundant red quartz-syenite boulders in the conglomerate were derived from Ben Stumanadh, some 8 km to the SSE. Three distinct units are recognized in the outlier: a basal breccia-conglomerate; an intervening sandstone; and an upper conglomerate. This fluvial succession may be of Devonian or possibly Permo–Triassic age. The nature of the conglomeratic sequence and its origin and age have been discussed by Peach and Horne (1914), McIntyre *et al.* (1956), Blackbourn (1981), O'Reilly (1983) and Holdsworth *et al.* (2001).

### Description

The GCR site area includes the sandy Bàgh Challbacaidh and its bounding cliffs and extends south to include the prominent road cut on the A816 at NC 610 601. The site is overlooked by the dramatic, massive, red-brown conglomerate cliffs of Cnoc an Fhreiceadain (Watch Hill) to the south (Figure 6.19).

#### *Lithology*

The Moine psammites and subsidiary semipelites form part of the Altnaharra Psammite Formation, the lowest unit of the Morar Group in this area (Holdsworth *et al.*, 2001). They consist mostly of thin- to medium-bedded, feldspathic and quartzose psammites with

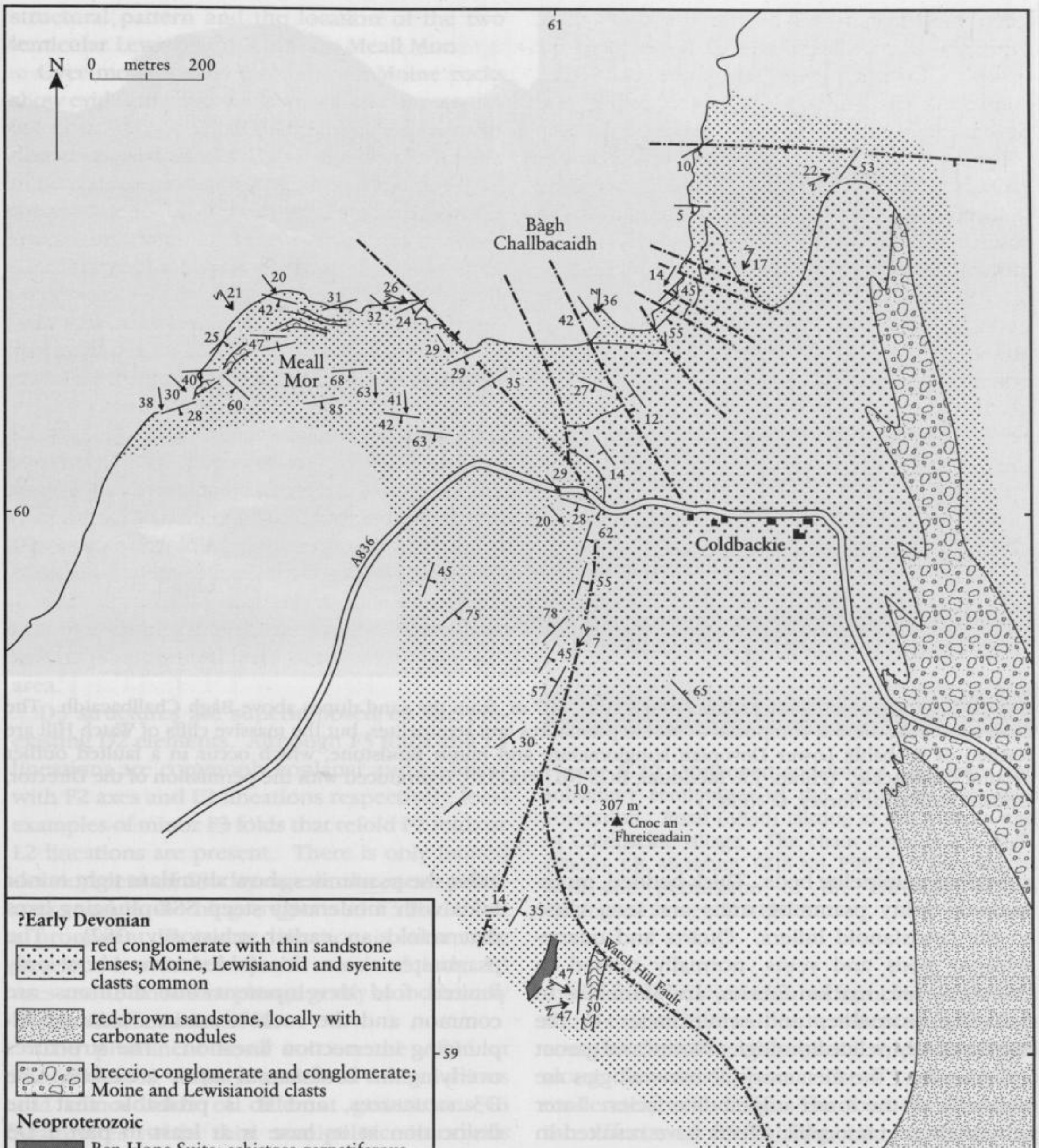


**Figure 6.18** Geological map of the Coldbackie Bay area.

**Figure 6.19** Cnoc an Fhreiceadain (Watch Hill), 307 m, from the sand dunes above Bàgh Challbacaidh. The road cut on the A836 is composed of Moine psammites and semipelites, but the massive cliffs of Watch Hill are formed of probable Lower Devonian conglomerate and minor sandstone, which occur in a faulted outlier around Coldbackie. (Photo: J.R. Mendum, BGS No. P552318, reproduced with the permission of the Director, British Geological Survey, © NERC.)

subsidiary semipelite beds. Thick-bedded, more-massive, gritty psammite units are seen close to the Lewisianoid inliers. Quartz and quartz-feldspar pods and veins, normally related to the main deformation fabrics, are abundant in both the psammites and semipelites. In the appropriately pelitic lithologies biotite and garnet are abundant; the metamorphic mineralogies are indicative of the lower-amphibolite facies. Later retrograde metamorphic effects have resulted in the formation of chlorite after biotite.

The Lewisianoid gneisses occur in lenses ranging from a few metres up to tens of metres thick within the Moine psammites. Lithologies range from finely layered gneiss with thin amphibolite units to more-massive quartzo-feldspathic gneiss. Thin quartz and quartz-feldspar pegmatite lenses are common. On Meall Mor at NC 6029 6020 a 3.5 m-thick lens of gneiss is in tectonic contact with the underlying Moine psammites, with the bedding in the psammites discordant to the contact. Immediately overlying this small Lewisianoid inlier the psammites show abundant tight minor folds with moderately steep SSE-plunging axes that refold an earlier schistosity (?S2). The psammites above this folded zone show only limited fold development but mullions are common and the rocks contain a strong SSE-plunging intersection lineation. The structures overlying this Lewisianoid 'inlier' are taken to be D3 structures, and it is probable that the dislocation at its base is at least in part a D3 structure. Some 20 m to the north-east by the HWM tight to isoclinal recumbent F2 folds occur in psammites below the Lewisianoid gneiss inlier.

### Structure

The Moine rocks around the bay dip gently to steeply southwards or south-eastwards. Cross-bedding and grading are seen in the psammites and show that most of the sequence is right-way-up and upward-facing, but narrow inverted zones also occur. Figure 6.18 shows the overall structural pattern and the location of the two lenticular Lewisianoid inliers on Meall Mor.

Over most of their outcrop the Moine rocks show evidence for two main phases of penetrative deformation and folding that have been termed 'D2' and 'D3' (Holdsworth, 1990). An earlier phase, D1, resulted in a bedding-parallel fabric, S1, best seen in pelitic rocks. More rarely, a related lineation, L1, is seen in psammites, and F1 minor folds are very sparse.

D2 structures are dominant in the area and comprise a penetrative S2 planar schistosity, a strong L2 rodding lineation, and close to tight, W- and SW-verging (Z-profile), minor- and medium-scale F2 folds. The S2 fabric is axial planar to F2 structures, and its orientation lies close to bedding and dips generally moderately to the south and south-east. L2 is mainly defined by quartz rodding, and plunges moderately south-east and south. Where minor folding is present, the rodding is coincident with F2 axes. Holdsworth *et al.* (2001) interpreted a major shear-zone structurally just below the Coldbackie Bay GCR area, but only small-scale examples occur within the site area.

D3 structures are superimposed on the pre-existing D2 elements. Although F3 folds and L3 lineations are commonly coplanar and co-linear with F2 axes and L2 lineations respectively, local examples of minor F3 folds that refold F2 folds or L2 lineations are present. There is only limited development of S3 cleavage in the more-pelitic rocks and in the hinge regions of F3 folds, but a prominent L3 quartz lineation is commonly developed, notable in quartz veins and pods. F3 axes and L3 lineations plunge gently to moderately to the south-east and SSE.

The prominent road cut on the A836 at NC 6105 6003 displays excellent fold mullions and minor folds of different generations in psammites with thin semipelitic interbeds (Figure 6.20). An F2/3 fold hinge and related L2/3 lineation that both plunge to the south-east are seen, yet in the low-strain hinge zone possible cross-bedding foresets are present (cf. **Oykel Bridge** GCR site report, this chapter). On the exposed top slab of the road cut, tight F2 folds with a fine SE-plunging quartz lineation and a strong axial-planar S2 schistosity are well seen. These folds form part of a complex F2 synform + antiform pair. The bedding-schistosity (S2) relationships on nearby Meall Mor and the sparse indicators of way-up suggest that the beds are largely inverted here. The overall form of

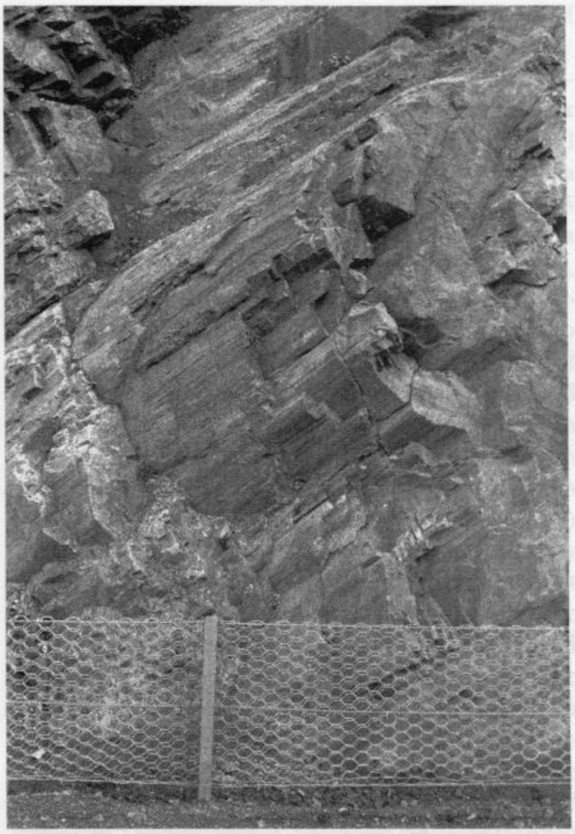

**Figure 6.20** Mullioned and folded psammites and subsidiary semipelites of the Altnaharra Psammite Formation. Road (A836) cutting at the western end of Coldbackie village. The chain fence is 2 m high. (Photo: J.R. Mendum, BGS No. P552317, reproduced with the permission of the Director, British Geological Survey, © NERC.)

the F3 folds is demonstrated in a crag some 40 m south-east of the road cut, where they show a complex S-profile with quartz veins developed along their axial plane. The F3 axes plunge moderately to the SSE. The road cut illustrates the effects of F3 folding on a pre-existing complex F2 fold profile. The mullions appear to result from coaxial F2 and F3 folding, albeit with differently orientated axial planes.

Late minor folds on Meall Mor refold the earlier D2 and D3 fabrics. Typically, they have gentle SW- or SSW-plunging fold axes, a south-easterly vergence (i.e. S-profile), and axial planes that strike north-east–south-west and have variable dips. Holdsworth (1989b) shows that such structures are also developed in lenticular NNE-trending zones parallel to the regional strike of the bedding and S2. Examples are found in out-crops at Bàgh Challbacaidh and farther north at

Scullomie Harbour (NC 619 615), where Holdsworth (1989b) documented several ESE-dipping detachments and brittle folded zones.

Late kink- and chevron-style-folds are also found in Moine psammites farther to the south, marginal to the bounding fault of the conglomerate outlier. Hence, at NC 6103 5975 small-scale Z-profile late minor folds, whose axes plunge gently to the SSW, are the dominant structures in gritty psammites. The folds may relate to movements along the bounding faults to the outlier, although Holdsworth (1989b) showed that such structures are developed in lenticular NNE-trending zones parallel to the regional strike of the bedding and S2.

### *Conglomerate–sandstone outlier*

The conglomerate that forms the bulk of the outlier exposed in the Coldbackie area is the highest member of a tripartite sequence (Peach and Horne, 1914). The sequence comprises a basal breccio-conglomerate member up to 30 m thick, a central red sandstone and marl member, up to *c.* 120 m thick, and an upper conglomerate member, 300 m thick. The upper conglomerate contains conspicuous, rounded, red quartz-syenite boulders that can be matched petrographically with the Ben Stumanadh intrusion farther south (O'Reilly, 1983). The upper conglomerate cuts across the two lower members and onlaps the Moine psammites in the northern part of the outlier. It is this upper conglomerate–psammite contact that is exposed on the east side of Bàgh Challbacaidh around NC 6122 6035. The conglomerate here lies in a small graben between two faults. It is a poorly sorted, clast-supported, cobble and boulder conglomerate with a coarse-grained silty sand matrix. Angular Moine psammite clasts of local derivation are abundant. Conglomerate exposures behind the sand dunes at NC 6110 6013 show a similarly clast-supported, cobble and boulder conglomerate with minor calcareous silty sandstone units. The overall bedding dips gently to the south-west. The clasts range from well rounded to moderately angular and consist of psammite, vein quartz, pegmatitic granite, feldspar, and red quartz-syenite. Lewisianoid gneiss clasts are typically small and fairly sparse. The upper 150 m of the conglomerate form the massive, widely jointed cliffs of Cnoc an Fhreiceadain that overlook Coldbackie (Figure 6.19). Bedding is crudely defined by cobble- and gravel-rich units up to 1 m thick, and dips up to *c.* 5° to the south-east. Moine psammite clasts are again sub-angular and are up to 30 cm long, but the rounded red quartz-syenite boulders are typically 20–30 cm across and locally up to 1 m. They lie in a purplish-brown, coarsely sandy matrix. Structures are rare in the sequence but a minor open Z-profile fold was seen with a subvertical short limb. Psammite clasts are rotated around the fold hinge and its axial plane strikes 016° and dips 38°W. The fold possibly drapes an underlying syn-depositional fault, but if so, the conglomerate succession must have been sufficiently thick to allow the lower units to behave in a relatively ductile manner. Alternatively, such structures may relate to the late chevron folds seen in the adjacent Moine psammites.

### *Faulting*

The majority of mapped faults in the Coldbackie area are steeply easterly dipping. Abundant minor faults occur on Meall Mor. Most show evidence of oblique sinistral + normal movement and small amounts of brecciation. The main faults at the western side of the conglomerate outlier can be inferred from the presence of eroded gullies at NC 610 602 and NC 614 587 and from the offset of features in the Moine psammites (O'Reilly, 1983). An easterly downthrow of at least 100 m is inferred. The southward continuation of this western bounding fault is exposed farther south in the waterfall (NC 621 639) immediately south of An Dubh-loch.

## Interpretation

The early D1 deformation, which apparently took place under lower-amphibolite conditions, appears to be at least partly responsible for the interleaving Lewisianoid and Moine rocks. However, it is clear that the Lewisianoid–Moine contacts were the locus for D2 and even D3 shearing, and were reactivated yet again during late Caledonian extensional movements (Holdsworth, 1989b). Angular discordances are still preserved between the Lewisianoid gneissic layering and bedding in the adjacent, locally gritty Moine psammites. The regional fold structure of the Coldbackie area is that of an overall reclined syncline, sandwiched between two major Caledonian shear-zones (Holdsworth *et al.*, 2001). Hence, the F2 and F3 fold pattern may cause repetition of the Lewisianoid inliers, such that the gneisses seen on Ben Tongue to the south-west link with the Lewisianoid lenses seen in the cliffs of Meall Mor. In detail, the structure is complex, but as the two Lewisianoid occurrences appear to link to the SSW, it seems likely that they form part of a single sheet. Holdsworth (1990) and Alsop *et al.* (1996) interpreted the F2 + F3 fold pattern as part of a progressive Caledonian W-thrusting sequence. The late-stage (post-D3) minor folds at Coldbackie were interpreted as Caledonian brittle structures, resulting from orogenic collapse and accompanying extension (Holdsworth, 1989b).

The presence of fold mullions in parts of the Coldbackie area requires some explanation. Mullion structure is named after the columnar forms found in the windows and internal columns of Gothic churches. Ramsay and Huber (1987) noted that fold mullions resemble a 'pile of wooden logs', and interpreted them as a type of cuspate-lobate structure, developed in a sequence of folded beds of different lithology (i.e. competence). Further discussion of fold mullions and their origin and significance is given in the **Oykel Bridge** GCR site report (this chapter). Mullion formation is undoubtedly favoured in areas of constrictional or prolate finite strain, particularly at high strains and where the stretching direction is prominent. This strain may result from local factors or merely from a particular combination of pure and simple shear. In the Coldbackie area, it is associated with westward translation during the Caledonian Orogeny, and in such cases fold axes tend to rotate towards the extension direction as deformation progresses (Sanderson, 1973; Williams, 1978). Alternatively the high prolate strains can be a product of coaxial F2 and F3 folding with the two fold episodes having separate axial planes.

At Coldbackie F2 folds appear to have formed as tight reclined folds with their axes plunging approximately down the dip of their axial planes, possibly as a result of a strong simple shear component during their generation. The axes so formed and attendant L2 extension lineation would create a 'stiff ribbing' that cannot easily be refolded or modified by later folding. The later fold phase, F3, is coaxial with F2, but F2 and F3 axial planes differ in orientation by some 30°. This would explain the structural features and orientations in this area and localized occurrence of the mullion structures.

The age and palaeogeography of the unfossiliferous conglomerate and sandstone outlier has been disputed over a long period and still remains problematical. The deposits occupy a distinct S–N-trending valley whose floor ranges from 120 m above OD in the south, to near sea level at Bàgh Challbacaidh (Peach and Horne, 1914). This valley probably had a steep fault-controlled western margin, which was also active at the time of deposition. The nature of the deposits suggests that they were deposited rapidly under tropical desert conditions from alluvial systems that originated to the south around Ben Stumanadh and flowed northwards or NNW along irregular valleys. O'Reilly (1983) infers that two such valleys existed and that they formed secondary feeders into a main valley that occupied the Kyle of Tongue. Peach and Horne (1914), Blackbourn (1981), O'Reilly (1983) and Holdsworth *et al.* (2001) all interpreted the outliers as Devonian (Old Red Sandstone) in age. They stressed the correlation with known Early and Mid-Devonian conglomerates to the east. McIntyre *et al.* (1956), Johnstone and Mykura (1989) and Carter *et al.* (1995) put forward a contrary interpretation that the rocks are Permo–Triassic (New Red Sandstone) in age. Zircon and apatite fission track dates from offshore borehole material and conglomerate from Coldbackie Bay have been interpreted to show that these are Permo–Triassic in age (Carter *et al.*, 1995). BGS boreholes offshore from the Kyle of Tongue have proved the presence of thick sequences of red-brown sandstones, in part conglomeratic. It is known that both Old and New Red Sandstone units lie offshore in the West Orkney Basin, but their thickness and extent is not well documented (Stoker *et al.*, 1993).

## Conclusions

The Coldbackie Bay GCR site contains complex folded and deformed Moine psammites with small enclosed Lewisianoid gneiss inliers seen on the cliffs of Meall Mor. In the road cut on the A836 fold mullions define a complex fold hinge within which cross-bedding structures appear to be preserved. This structure is interpreted as a product of the superimposition of two phases of ductile folding, F2 and F3, and related strains that constitute the major part of the overall

W-directed Caledonian ductile thrusting episode in this area.

Conglomerate and sandstones of Devonian (Old Red Sandstone) or possibly Permo–Triassic (New Red Sandstone) age unconformably overlie the Moine and Lewisianoid rocks; they are spectacularly exposed at Coldbackie. The conglomerate represents a coarse alluvial infill formed under tropical conditions and deposited on an irregular topographical surface. The inlier basically represents a fossil valley, whose western margin was controlled by normal faults. Quartz-syenite boulders in the conglomerate can be matched with the intrusion of Ben Stumanadh farther south by Loch Loyal. The age and palaeogeography of the conglomerate and sandstone sequence are important in interpreting the Devonian and Permo–Triassic evolution of the area and link to the offshore geology, such as the West Orkney Basin, which contains similar rocks. The GCR site contains features of national interest and is likely to be the subject of further study.

## STRATHAN SKERRAY TO SKERRAY BAY (NC 639 638–NC 667 636)

*R.A. Strachan*

### Introduction

This site provides excellent exposures of a major basement inlier within the Caledonian orogenic belt of north Sutherland (Moorhouse, 1976; Holdsworth, 1989a; Holdsworth *et al*., 2001). The basement Lewisianoid gneisses form part of the Borgie Inlier, tentatively correlated on lithological and geochemical grounds with the Lewisian Gneiss Complex of the Caledonian Foreland. Geochemical studies indicate that the inlier was affected by granulite-facies metamorphism, possibly equivalent to the Badcallian event of the Caledonian Foreland (Moorhouse, 1976). Subsequently, mineralogical evidence for this metamorphic event has been almost eradicated during the Neoproterozoic and particularly the Caledonian reworking. The western contact of the inlier with the Moine psammites is located in a zone of high tectonic strain but nevertheless is thought to represent a highly modified and inverted unconformity (Holdsworth *et al*., 2001). The Moine rocks and the bulk of the Lewisianoid gneisses display evidence for complex and polyphase Caledonian folding. Structural analysis indicates that the Lewisian inlier occupies the core of a major recumbent antiform (British Geological Survey, 1996, 1997b; Holdsworth *et al*., 2001), albeit modified by ductile shear-zones (see Figure 6.3). The site provides an appreciation of the nature of the sub-Moine basement and the pattern of reworking of that basement during the Caledonian Orogeny.

### Description

The westernmost part of the site, west of Port an t-Strathain, exposes medium-grained Moine psammites belonging to the Morar Group with thin discontinuous semipelite layers containing biotite, muscovite and locally garnet. Rare thin layers of feldspar grains may represent original gritty layers. Graded and finely cross-bedded units can be distinguished in lower strain areas. A prominent metamorphic foliation defined by regular colour layering and aligned micas dips moderately to the east. The layering is developed on a scale of 1–3 cm and represents bedding (S0) that has been strongly modified as a result of high tectonic strain marginal to the Borgie Inlier. Thin concordant quartz veins and segregations are abundant, as commonly found in such high-strain zones within the Moine succession. A few hundred metres to the west of the site, Moine psammites contain clear examples of inverted cross-bedding and it is probable that the psammites within the site are also mainly inverted although tight folding is present locally.

The contact between the Moine psammites and the structurally overlying Borgie Lewisianoid Inlier on the coast is marked by a brittle fault that dips steeply to the east (Figure 6.21). The fault dies out inland where the contact is represented by a sharp, concordant, moderately E-dipping boundary between Moine psammites and Lewisianoid hornblende-biotite schists (e.g. at NC 639 311). Both lithologies are strongly foliated adjacent to this boundary, which was obviously the focus of high tectonic strain.

The main lithology within the Lewisianoid Borgie Inlier is a layered, granodioritic to tonalitic felsic orthogneiss characterized by the alternation of quartzofeldspathic and biotite- or hornblende-rich layers (with rare garnet) on a scale of 0.5–2 cm. The felsic layers are typically

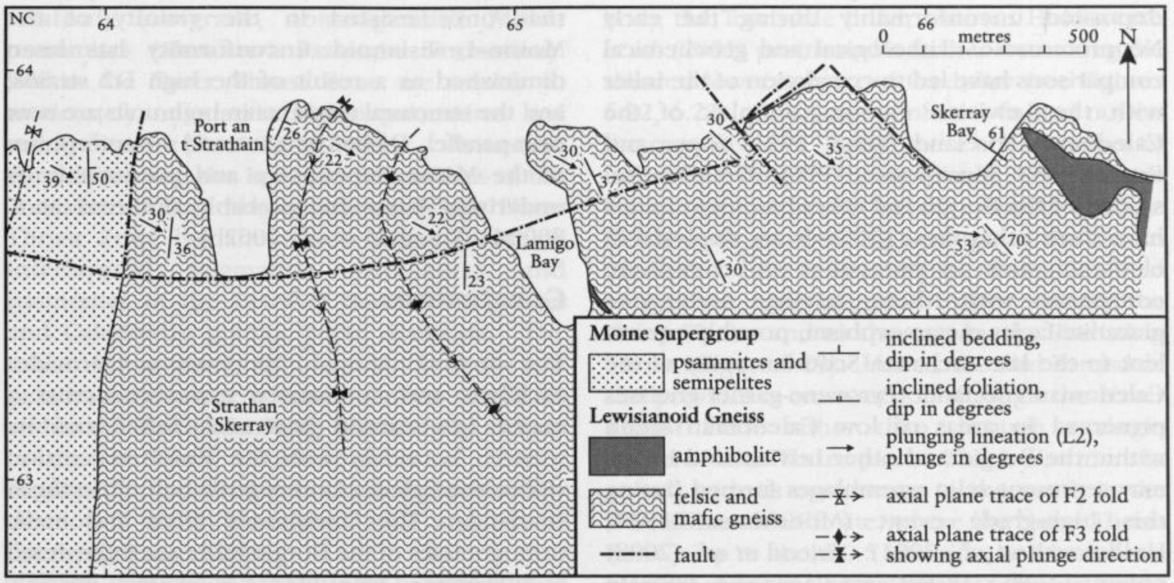


**Figure 6.21** Map of the Strathan Skerray to Skerray Bay GCR site.

interleaved with mafic gneiss, originally basaltic, now invariably amphibolite. Thicker mafic bodies are also common. The gneissic layering strikes north–south in the vicinity of Strathan Skerray but swings to north-west in Skerray Bay. Dips range from 20° to 70° to the east and north-east, generally increasing eastwards. Pods of ultramafic material, commonly now hornblendite, are scattered throughout the gneiss outcrop (e.g. at NC 651 639). An extensive sheet of foliated and lineated amphibolite outcrops south-east of Skerray Bay (Figure 6.21), and minor examples also occur in Lamigo Bay (NC 651 635) and west of Skerray Bay at NC 659 640. The margins of the amphibolites are locally discordant to the layering within the adjacent felsic orthogneisses. The amphibolites mainly comprise hornblende with subordinate plagioclase and quartz and are interpreted as deformed and metamorphosed basalt or dolerite igneous intrusions.

Three phases of deformation, D1–D3, have been identified in the Moine rocks (Alsop *et al.*, 1996; Holdsworth *et al.*, 2001). The main fold structures are of D2 and D3 age. F2 structures are generally highly attenuated, tight to isoclinal, reclined folds with axes parallel to a prominent ESE- to SE-plunging mineral and extension lineation (L2), defined by quartz-feldspar aggregates. A bedding-parallel S1 mica fabric is folded around F2 fold hinges, and in semipelitic horizons a closely spaced S2 crenulation cleavage is developed axial planar to the folds. Minor F1 folds are rare. D2 structures are locally refolded by open to tight, asymmetrical, reclined F3 folds whose axes generally plunge sub-parallel to L2. D2 and D3 structures are common throughout the outcrop of the Lewisianoid gneisses. The gneissic layering in the Borgie Inlier represents an original pre-Moine, high-grade foliation, which has been modified extensively during the D1–D3 tectonic events outlined above. A mappable F2 synform occurs *c.* 250 m to the west of the Moine–Lewisianoid boundary, and an F3 fold pair is developed within the Lewisianoid gneisses east of Strathan Skerray (Figure 6.21; Holdsworth *et al.*, 2001). Metamorphic grade is difficult to evaluate accurately due to a lack of suitable lithologies. However, the presence of syn-D2 garnets within Moine semipelites and an L2 hornblende lineation within the gneisses suggests that lower amphibolite-facies metamorphism accompanied Caledonian reworking. The Moine and Lewisianoid rocks are cut by late brittle faults that trend approximately both east–west and north-west–south-east (Figure 6.21); none show evidence of significant displacement.

## Interpretation

The Borgie Lewisianoid Inlier is interpreted as a part of the continental basement upon which the Moine metasedimentary rocks were deposited unconformably during the early Neoproterozoic. Lithological and geochemical comparisons have led to correlation of the inlier with the Lewisian Gneiss Complex of the Caledonian Foreland (Read, 1931; Soper and Brown, 1971; Moorhouse, 1976). Geochemical studies of the Borgie and other basement inliers have shown that these gneisses are depleted in elements such as potassium and rubidium, consistent with them having undergone granulite-facies metamorphism, possibly equivalent to the late Archaean Scourian event of the Caledonian Foreland. Pyroxene-garnet gneisses preserved in areas of low Caledonian strain within the Borgie and other Lewisianoid inliers may represent relic assemblages formed during this high-grade event (Moorhouse, 1976; Holdsworth *et al.*, 2001). Friend *et al.* (2008) obtained U-Pb SHRIMP zircon ages of *c.* 2880 Ma from the south-east part of the Borgie Inlier. This age was interpreted to date the formation of the Archaean igneous protoliths of the gneisses. The data showed evidence of significant isotopic disturbance at *c.* 1600 Ma. Some of the less-deformed mafic intrusions within the Borgie Inlier may represent reworked members of the mafic Scourie Dyke Suite (see Chapter 3). They exhibit doleritic textures and contain garnets with plagioclase coronas, features typical of metadolerites of the Scourie Dyke Suite that intrudes the Archaean gneisses of the foreland. They are unlike the amphibolites of the Bettyhill Suite that are prominent a little farther east (see **Ard Mor** GCR site report, this chapter), but when strongly deformed it is difficult to separate the two sets of intrusions.

The ESE- to SE-trending L2 mineral and extension lineations in the Moine and Lewisianoid rocks between Strathan Skerray and Strathan Bay are broadly traceable across north Sutherland into the Caledonian Moine Thrust Zone (Holdsworth *et al.*, 2001). Hence D2 and D3 folding and associated metamorphism are considered to be of Caledonian (Ordovician–Silurian) age. F2 and F3 folding have been interpreted to be the result of an essentially continuous, progressive deformation event (Alsop *et al.*, 1996), linked to Caledonian tectonic transport towards the WNW, parallel to L2. Tight to isoclinal interfolding of Lewisianoid basement and its Moine cover occurred widely during D2 (Holdsworth, 1989a; Holdsworth *et al.*, 2001; see also **Ben Klibreck** GCR site report, this chapter). Any angular discordance that once existed in the vicinity of the Moine–Lewisianoid unconformity has been diminished as a result of the high D2 strains, and the structural elements in both units are now near-parallel. D1 deformation and metamorphism of the Moine Supergroup and presumably its underlying basement probably occurred at *c.* 800 Ma (Strachan *et al.*, 2002b).

## Conclusions

The site is of national importance as it provides excellent and continuous exposure across a major Lewisianoid basement inlier and its western boundary with the Moine succession within the Caledonian orogenic belt of northern Scotland. The Lewisianoid felsic and mafic orthogneisses of the Borgie Inlier are interpreted as retrogressed granulite-facies gneisses, possibly originally contiguous with the Archaean Lewisian Gneiss Complex of the Caledonian Foreland. They represent part of the continental basement upon which the Moine Supergroup was deposited in the Early Neoproterozoic. Both Lewisianoid and Moine rocks were affected by polyphase folding and amphibolite-facies metamorphism during the Caledonian Orogeny. Tight recumbent interfolding of the Moine and Lewisianoid rocks was associated with WNW-directed translation towards the Caledonian Foreland. Pervasive reworking of the basement gneisses accounts for the general concordance of the metamorphic foliation in the basement with that in the Moine cover.

# AIRD TORRISDALE (NC 668 636–NC 683 623)

***V.E. Moorhouse***

## Introduction

The Aird Torrisdale GCR site provides coastal cliff-sections through the northernmost part of the Naver Thrust Zone, which separates the A' Mhoine and Naver nappes (Moorhouse, 1977; British Geological Survey, 1997b; Holdsworth *et al.*, 2001). The thrust zone is a significant structural boundary that telescopes different stratigraphical, tectonic and metamorphic levels within the exposed Moine succession in Sutherland. Below and west of the Naver Thrust Zone lies the A' Mhoine Nappe comprising relatively low-grade, non-migmatitic Moine psammites (Altnaharra Psammite Formation). Within the Naver Thrust Zone are weakly to moderately migmatitic Moine psammites and semipelites (Druim Chuibhe Psammite Formation) and the Lewisianoid gneisses of the Torrisdale Inlier. Above and east of the Naver Thrust Zone lies the Naver Nappe in which interlayered migmatitic semipelites and psammites of the Bettyhill Banded Formation and Caledonian granitic rocks dominate. The major shear-zones, lithological contacts and penetrative cleavage/schistosity in the site all lie within the Torrisdale Steep Belt and dip steeply to the north-east (Holdsworth *et al.*, 2001). Pegmatitic granite veins are prominently developed within the thrust zone and in the overlying Naver Nappe.

Aird Torrisdale is the most westerly and structurally lowest of four GCR sites (Aird Torrisdale; **Ard Mor**; **Farr Bay**; and **Glaisgeo–Farr Point**) that together effectively constitute a cross-section through the Naver Nappe of north Sutherland. Archaean high-grade felsic and mafic gneisses of the Lewisianoid Borgie Inlier are infolded with the psammites of the underlying A' Mhoine Nappe, and Lewisianoid gneisses also form smaller highly tectonized inliers in the overlying Naver Nappe (Figure 6.22). Early mafic sheets and dykes of the Bettyhill Suite, now foliated amphibolites, are notably abundant in the Naver Nappe. Pegmatitic granite and quartz-feldspar pegmatite veins and pods, in places up to tens of metres thick, are abundant both in the Naver Thrust Zone and in the overlying Naver Nappe. Appinitic mafic bodies also occur in the Naver Nappe, for example the Clerkhill Intrusion is a major feature of the **Glaisgeo–Farr Point** GCR site.

B.N. Peach first mapped the area around Aird Torrisdale for the Geological Survey in 1886. Moorhouse (1979) revisited the area in the 1970s, and the results of more-recent mapping of the Torrisdale area by I.E. Alsop, I.M. Burns and R.A. Strachan are incorporated in the revised geological map of the Tongue district (British Geological Survey, 1997b) and accompanying Sheet 114E memoir (Holdsworth *et al.*, 2001).

Previous geological accounts of Aird Torrisdale have described a discrete Naver Thrust rather than a zone of thrusting. Moorhouse (1979) placed the thrust along the sheared upper contact of a large Lewisianoid body, the Torrisdale Inlier, whereas Holdsworth *et al.* (2001) positioned it farther west along the sheared lower contact of the inlier (see Figures 6.22, 6.23). This latter contact is faulted out on the coast section. In fact there are a number of individual ductile thrust planes and narrow shear-zones exposed in the coastal section. Holdsworth *et al.* (2001) recognize the Druim Chuibhe Psammite Formation as being confined to a thrust zone bounded to the west by the Naver Thrust and to the east by the Torrisdale Thrust (Figure 6.23). Hence, the Aird Torrisdale site provides a cross-section through the Naver Thrust Zone rather than through a single discrete Naver Thrust plane. This is also more in accord with its occurrence to the south in the **Ben Klibreck** GCR site, where the Naver Thrust Zone is up to about 0.5 km wide, and includes a number of thrust dislocations together with tight Caledonian folding (Moorhouse, 1977; Strachan and Holdsworth, 1988). The thrust-bounded Torrisdale Lewisianoid Inlier strikes north-west and is faulted to the west against the larger Borgie Inlier.

## Description

There is continuous rock exposure all along the steep, but largely accessible E- to SE-trending coastline of Aird Torrisdale, and moderate rock exposure on the inland peat-clad hills that rise up to 100 m OD. The regional strike of lithologies is generally north-west, so the coastline provides an oblique cross-strike section. A traverse from Skerray Church (NC 6730 6243) north-east across Aird Torrisdale to the coast also provides an admirable cross-section through the main geological units. Moine psammites (Altnaharra Psammite Formation) and Archaean gneisses of the Torrisdale and Borgie Lewisianoid inliers in the A' Mhoine Nappe are exposed at the start of this traverse. The sheared contacts of the Torrisdale Inlier lie within the Naver Thrust Zone. The overlying migmatitic and gneissose Moine psammites and semipelites (Druim Chuibhe Psammite and Bettyhill Banded formations) of the Naver Nappe are beautifully exposed on the coastal cliffs and on the sand-blasted, glacially scoured outcrops at the north end of Druim Chuibhe (Figures 6.23, 6.24).

The rocks of Aird Torrisdale lie in the Torrisdale Steep Belt, where the regional bedding, gneissic foliation and main cleavage all dip between 50° and 75° to the north-east and east.

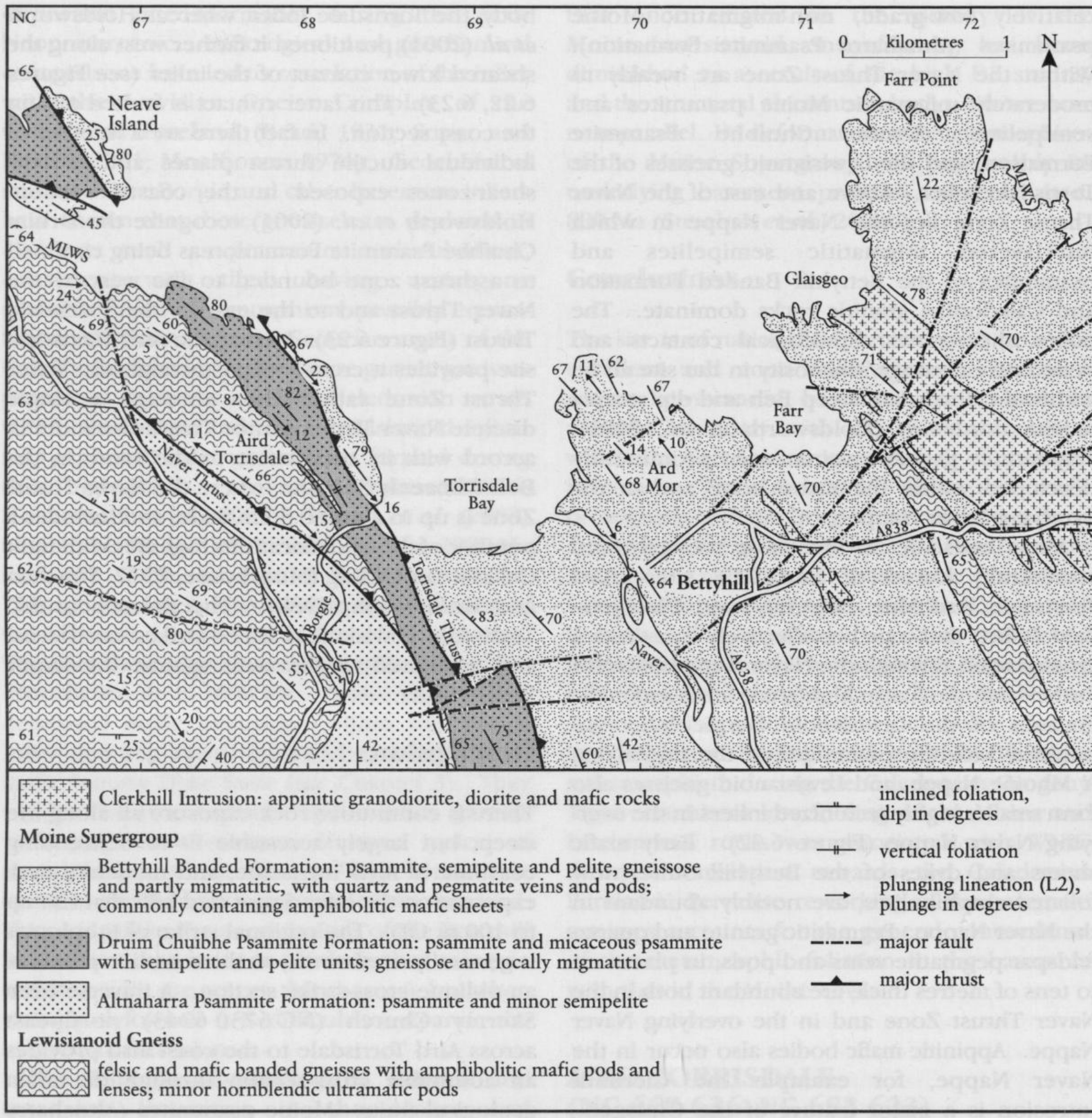


**Figure 6.22** Map of the Aird Torrisdale–Bettyhill–Farr area, showing the general geology encompassing the Aird Torrisdale, **Ard Mor**, **Farr Bay** and **Glaisgeo–Farr Point** GCR sites. Adapted from British Geological Survey 1:50 000 sheets 114E, Tongue (1997b), 115W, Strathy Point (1996), and Cheng (1942, 1943).

The compositional layering and foliation in Naver Nappe to the east mostly have a similarly steep orientation but the Torrisdale Steep Belt flattens out gradually southwards after about 10 km. Within the belt the dominant mineral lineations and fold axes plunge gently to the north-west and south-east, unlike the rocks farther west or east where the lineations and fold axes plunge predominantly down-dip.

Psammites of the A' Mhoine Nappe are exposed on both sides of the Skerray–Torrisdale road where, although deformed, they show prominent bedding; locally remnants of cross-bedding are seen. They are characterized by a steep NE-dipping, composite foliation and steep SE-plunging lineation, both attributed to the main regional Caledonian deformation events (D2 and D3). On the north-east side of the road at NC 6745 6257, non-migmatitic Moine psammites are structurally overlain by variably schistose biotitic and hornblendic mafic gneisses. Moorhouse *et al.* (1988) recognized

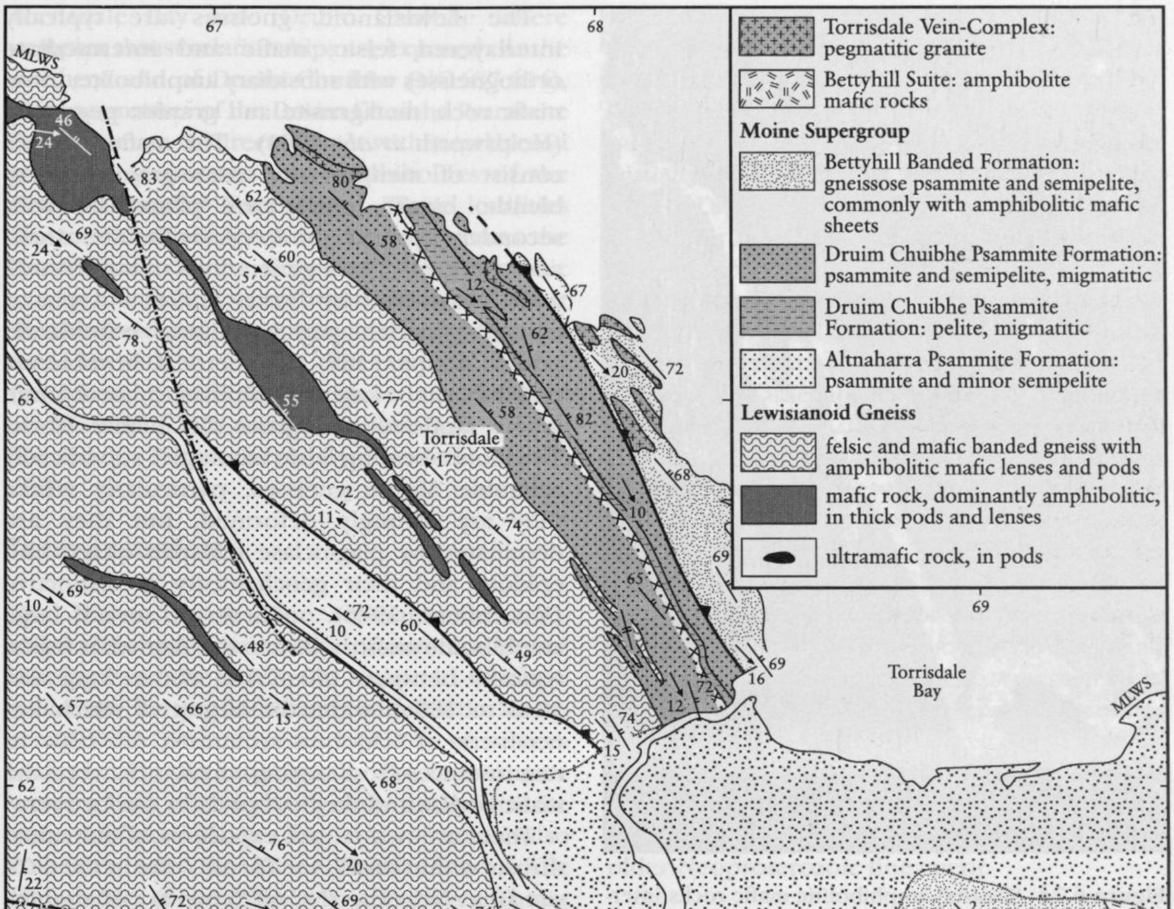


**Figure 6.23** Map of the Aird Torrisdale–Torrisdale Bay area. Compiled from data collected by G.I. Alsop, J.R. Mendum, C.G. Dyke and V.E. Moorhouse.

**Figure 6.24** Sheared amphibolitic mafic rocks interbanded with micaceous psammite and semipelite, showing tight F2 folds, cut by a quartz-feldspar pegmatite vein that is in turn deformed and folded by F3 folds. The hammer (37 cm long) is aligned with its handle parallel to the trace of the dominant planar fabric (S2). The exposure lies in the Naver Thrust Zone and Torrisdale Steep Belt. Druim Chuibhe, Torrisdale Bay (NC 6901 6167). (Photo: J.R. Mendum, BGS No. P581267, reproduced with the permission of the Director, British Geological Survey, © NERC.)

these highly deformed mafic rocks as part of the Torrisdale Lewisianoid Inlier. This NW-trending lenticular inlier is approximately 0.5 km wide, sandwiched between ductile thrusts in the Naver Thrust Zone. It is separated from the main Borgie Inlier towards its north-west end at Skerray village by a steep NNW-trending fault. It is possible that the Torrisdale Lewisianoid Inlier and the surrounding Moine psammites are disposed in a large NW-closing F2 fold that is truncated by this fault (Figure 6.23). The Torrisdale Inlier comprises highly deformed and folded felsic and mafic Lewisianoid gneisses.

The Lewisianoid gneisses are typically interlayered felsic, mafic and intermediate orthogneisses with subsidiary amphibolite, ultramafic rock, metagranite and granitic pegmatite (Holdsworth *et al.*, 2001). The mafic gneisses consist of medium- to coarse-grained hornblende, biotite, quartz and plagioclase with secondary epidote and accessory titanite, zircon and opaques. Three generations of hornblende were recognized by Burns (1994). A planar fabric, defined in part by aligned hornblende grains, wraps early asymmetrical hornblende poikiloblasts. Late sub-idioblastic hornblende grains randomly overgrow this planar fabric. The biotite-bearing felsic lithologies superficially resemble Moine gneisses, particularly where they are strongly deformed, but they are dominated by plagioclase feldspar, quartz and epidote and their geochemistry is distinctive (Moorhouse, 1976). There are several large amphibolite mafic bodies in the Torrisdale Inlier, typically between 150 m and 800 m long and 10 m to 100 m wide, the largest of which lies north-east of Achtoty at around NC 672 630. In rare instances cross-cutting contacts between the mafic bodies and the host gneisses can be seen.

There are two critical exposures of individual thrusts within the Naver Thrust Zone in the GCR site area. Near Lon (NC 6875 6040) a 10 m-thick sliver of sheared Lewisianoid hornblende schists and layered hornblende-biotite felsic gneisses, define the Naver Thrust that here separates non-migmatitic psammites with infolded Lewisianoid lithologies to the west from variably migmatized and gneissose psammites of the Druim Chuibhe Psammite Formation to the east. Examples of fold interference patterns are seen in the gneissose psammites. On the Aird Torrisdale coast at NC 6710 6358 a *c*. 1 m-thick zone of flaggy, striped, biotite-rich, schistose psammites with subconcordant quartzofeldspathic lenses marks a thrust that separates Lewisianoid gneisses of the Torrisdale Inlier from overlying, flaggy migmatitic psammites. Farther south-east on the coast of Aird Torrisdale at NC 6840 6234 a 3–5 m-thick unit of finely layered Lewisianoid hornblende-biotite gneiss separates gneissose psammites of the Druim Chuibhe Psammite Formation from overlying darker-grey, partly migmatitic micaceous psammites of the Bettyhill Banded Formation. Holdsworth *et al.* (2001) term this contact the 'Torrisdale Thrust' and hence it marks the upper boundary of the Naver Thrust Zone. It can be traced south-east across

Torrisdale Bay onto Druim Chuibhe where complex thrust relationships are exposed. At the northern end of Druim Chuibhe (NC 687 614), platy psammites of the Druim Chuibhe Psammite Formation are in direct contact with interlayered gneissose psammites and amphibolites of the Bettyhill Banded Formation. These localities illustrate the geological relationships across the Naver Thrust Zone. Coherent pink pegmatitic granite sheets and veins occur within the Naver Thrust Zone and are spectacularly exposed on Aird Torrisdale. Note that an extensional (detachment) fault that is exposed on the coast at NC 6837 6235 masks the location of the Torrisdale Thrust here (Holdsworth *et al.*, 2001).

## Interpretation

The Naver Thrust Zone separates the non-migmatitic predominantly psammitic Moine lithologies of the A' Mhoine Nappe in the footwall from the predominantly migmatitic Moine semipelites, psammites and pelites of eastern Sutherland in the hangingwall. The approximate western limit of abundant granite and pegmatite veins within H.H. Read's 'zone of veins' also coincides with the Naver Thrust Zone. The abundance of pegmatites in the Naver Thrust Zone may have resulted from enhanced fluid flow through the thrust system. The veins, part of the Torrisdale Vein-Complex, are described in the **Ard Mor** GCR site report (this chapter).

Relict garnet-pyroxene granulites locally occur as kernels in the amphibolites within the Torrisdale and Borgie Lewisianoid inliers. Moorhouse (1971, 1976, 1977) showed that these lenses are petrologically and geochemically similar to ones in Scourian gneisses of the foreland Lewisian. Similarly, the less-foliated and deformed amphibolites in these inliers may be equivalent to mafic dykes of the Scourie Dyke Suite seen in most of the foreland Lewisian outcrops. Moorhouse *et al.* (1988) inferred that the Lewisianoid gneisses originally formed a crystalline basement unconformably overlain by arenaceous Moine sediments and hence that the present inverted sequence is a result of Caledonian deformation.

The Naver Thrust Zone appears to have a complex and extended history, possibly commencing as early as the Neoproterozoic during Moine sedimentation. It has been the site of Caledonian ductile thrusting probably with major westward movement in both the Grampian (*c.* 470 Ma) and Scandian (*c.* 425 Ma) events (Kinny *et al.*, 1999; Friend *et al.*, 2000; Dallmeyer *et al.*, 2001). Kinny *et al.* (1999) carried out U-Pb SHRIMP analysis of zircons from partially blastomylonitic migmatitic psammites west of Druim Chuibhe at NC 688 614. The low U and Th clear rims of the zircons yielded an age of 467 ± 10 Ma, interpreted as dating metamorphism and deformation during the Grampian Event.

The characteristic steep dips in this area form part of the Torrisdale Steep Belt, which Holdsworth *et al.* (2001) interpreted as a result of rotation during late-stage (late D3) dextral transpression. Dallmeyer *et al.* (2001) obtained hornblende and muscovite $^{40}Ar$-$^{39}Ar$ plateau ages ranging from 417 Ma to 421 Ma from rocks of the Naver Thrust Zone 1–2 km south-east of Aird Torrisdale. They interpreted these Scandian ages as dating the formation of the Torrisdale Steep Belt. It is unclear as to whether these cooling ages also date the end of Scandian thrusting across the Naver Thrust Zone. What is clear is that late-stage orogenic movement and related strain have been focused along an earlier thrust zone, in turn possibly reflecting an even older Neoproterozoic lineament.

## Conclusions

The Aird Torrisdale site exposes the northern extremity of the Naver Thrust Zone, a major tectonic boundary within the Moine succession of Sutherland. The thrust zone separates the A' Mhoine Nappe in its footwall from the Naver Nappe in its hangingwall. Moine and Lewisianoid lithologies above and below the thrust zone, as well as individual thrust planes and folds within the zone are well exposed in accessible, cross-strike coastal sections and scattered inland exposures. Bedding, cleavage and all planar structural features dip steeply north-east and lie within the Torrisdale Steep Belt. The main Lewisianoid body, the Borgie Inlier, occurs below the thrust zone in the A' Mhoine Nappe whereas a smaller body, the Torrisdale Inlier, lies within the thrust zone. The Lewisianoid rocks consist of banded felsic and mafic gneisses of Archaean age with larger amphibolitic mafic bodies and small ultramafic pods.

The lithological differences in the Moine rocks above and below the Naver Thrust Zone are also manifest in the coast section. The thrust zone is responsible for stacking migmatitic Moine psammites, semipelites and pelites of the Bettyhill Banded Formation to the east on top of non-migmatitic Moine psammites, the Altnaharra Psammite Formation, and their Lewisianoid basement to the west. Most of the translation has occurred across ductile thrust zones and some of these have been dated as Early Ordovician (467 Ma) (Kinny *et al.*, 1999), but others are probably of Late Silurian age (*c.* 425 Ma). In the pelitic rocks of the Bettyhill Banded Formation migmatitic lits are pervasively deformed and feldspar porphyroblasts are present, resulting in augen gneisses. This implies that at least part of the major ductile movements post-dated the main migmatization event. The Moine psammites and semipelites within the thrust zone, the Druim Chuibhe Psammite Formation, are strongly cleaved, tightly folded and partly migmatitic (Holdsworth *et al.*, 2001). They contain abundant discordant pegmatitic granite veins as well as smaller quartzo-feldspathic segregation veins and pods.

The site is of national importance because it provides superb, readily accessible exposures across a major structural boundary within the Caledonian orogenic belt of northern Scotland. The ductile thrust contacts between the Lewisianoid inliers and younger Moine gneisses and within the Moine gneisses are readily seen and ideal for further work.

## ARD MOR (BETTYHILL) (NC 700 619–NC 704 628)

***V.E. Moorhouse***

### Introduction

Ard Mor is a small promontory at Bettyhill in north Sutherland that provides excellent coastal and inland exposures of strongly deformed, migmatitic, Moine metasedimentary rocks and intrusive igneous rocks of various ages (amphibolites, appinitic diorites and granitic sheets). The Moine rocks are part of the Bettyhill Banded Formation (previously termed the 'Bettyhill migmatites'). This coastal section lies within the Torrisdale Steep Belt in the structurally lower part of the Naver Nappe (Moorhouse, 1979; Holdsworth *et al.*, 2001).

The numerous pegmatitic granite intrusions form part of the Torrisdale Vein-Complex that were originally described by Read (1931, 1934), who termed them the 'zone of veins'. Cross-cutting relationships between variably deformed minor intrusions, as well as transposed planar fabrics and interference fold structures provide evidence for a polyphase history of deformation, metamorphism and igneous intrusion (Table 6.1).

The largest of the early mafic sheets, the Ard Mor Amphibolite, is well exposed on the highest point of the promontory (NC 6995 6270). It is part of the Bettyhill Suite of 'early Moine amphibolites', first recognized by Moorhouse and Moorhouse (1979). Evidence for its tectonometamorphic development is preserved within this site. The emplacement and structural age of the amphibolite are important in determining the age of deposition and deformation sequence of the Sutherland Moine succession. It is laterally equivalent to the intrusions of the Ben Hope Suite (see **Allt na Caillich** GCR site report, this chapter) and the early mafic intrusions in the Moine rocks farther south (see **Comrie** GCR site report, this chapter).

B.N. Peach first mapped the Bettyhill area for the Geological Survey in 1891–1892. Cheng (1943) later carried out pioneering work in this area, integrating geochemical, petrological and structural studies to try and unravel the complex metamorphic history. The area was remapped by I.M. Burns (1994) as part of a wider study of the tectonometamorphic history of the Naver and Swordly nappes. Friend *et al.* (2000) reported relict granulite-facies assemblages in some of the early amphibolite sheets, and Kinny *et al.* (1999) obtained zircon and monazite U-Pb age dates from the basal part of the Naver Nappe to the west, and from the Swordly Nappe to the east. The ages showed that the main migmatization event in both nappes occurred during the Grampian Event in the Early Ordovician.

### Description

The rocky promontory of Ard Mor provides a near-continuous, mostly accessible, coastal section and good inland exposure, including the highest point of Ard Mor (101 m) itself. This small site provides a cross-strike section through the varied Moine lithologies representative of the Bettyhill Banded Formation. They are dominantly flaggy, thinly interlayered, gneissose pink-grey psammites and subordinate darker-grey semipelites and pelites that strike NNW and dip steeply eastwards (Holdsworth *et al.*, 2001).

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

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

The layering is on a scale of 10–30 mm. All rocks are characterized by the presence of numerous concordant quartzofeldspathic segregations, which are particularly abundant in the pelitic units. Feldspar porphyroblasts are also common in the pelitic lithologies. Sedimentary structures are not preserved, in contrast to the psammitic rocks of the A' Mhoine Nappe to the west (see for instance **Aird Torrisdale** GCR site report, this chapter).

The Moine rocks are cut by abundant concordant to discordant sheets, dykes and lenticular bodies of amphibolite, pegmatitic granite, microgranite, and appinitic diorite (Figure 6.25). These intrusive rocks are very well exposed on the eastern side of Creag Ruadh (NC 6986 6310) and in the sea cliffs to the south-east. The amphibolites occur as sheets, mostly up to 3 m in thickness, but with larger bodies, such as the Ard Mor Amphibolite, reaching up to some 80 m thick. Although lenticular along strike, they are generally concordant with the compositional layering in the host Moine gneisses and contacts are sharply defined (Holdsworth *et al.*, 2001). In fact, the Ard Mor Amphibolite forms a linear array of NNW-trending discontinuous tabular outcrops through the centre of the site and continuing SSE (British Geological Survey, 1996, 1997b). It is a foliated garnetiferous amphibolite, partially retrograded to biotite and chlorite, and shows internal folding of early-formed fabrics. An early D1 metamorphic fabric is preserved in the moderately coarse-grained garnet-amphibolite in relatively low-strain areas, and is also recognizable in some F2 fold hinge zones. The D2 and D3 deformation and accompanying metamorphic events have progressively reduced this assemblage to fine-grained schistose amphibolite, notable on the fold limbs. The early S1 foliation is transposed in the fold limbs and the early garnets are retrograded to plagioclase feldspar and streaked out to become concordant with the regional foliation. Small, later garnets of possible D3 age locally overprint this composite S1–S2 fabric.

The Torrisdale Vein-Complex comprises a suite of pegmatitic granite intrusions that are very abundant in the Ard Mor area, where locally they comprise up to 50% of the outcrop (Holdsworth *et al.*, 2001). Individual intrusions vary from millimetre-thick veins to large, sheet-like bodies up to tens of metres thick, generally with sharp contacts. Most sheets clearly cross-cut the migmatitic layering in the host gneisses

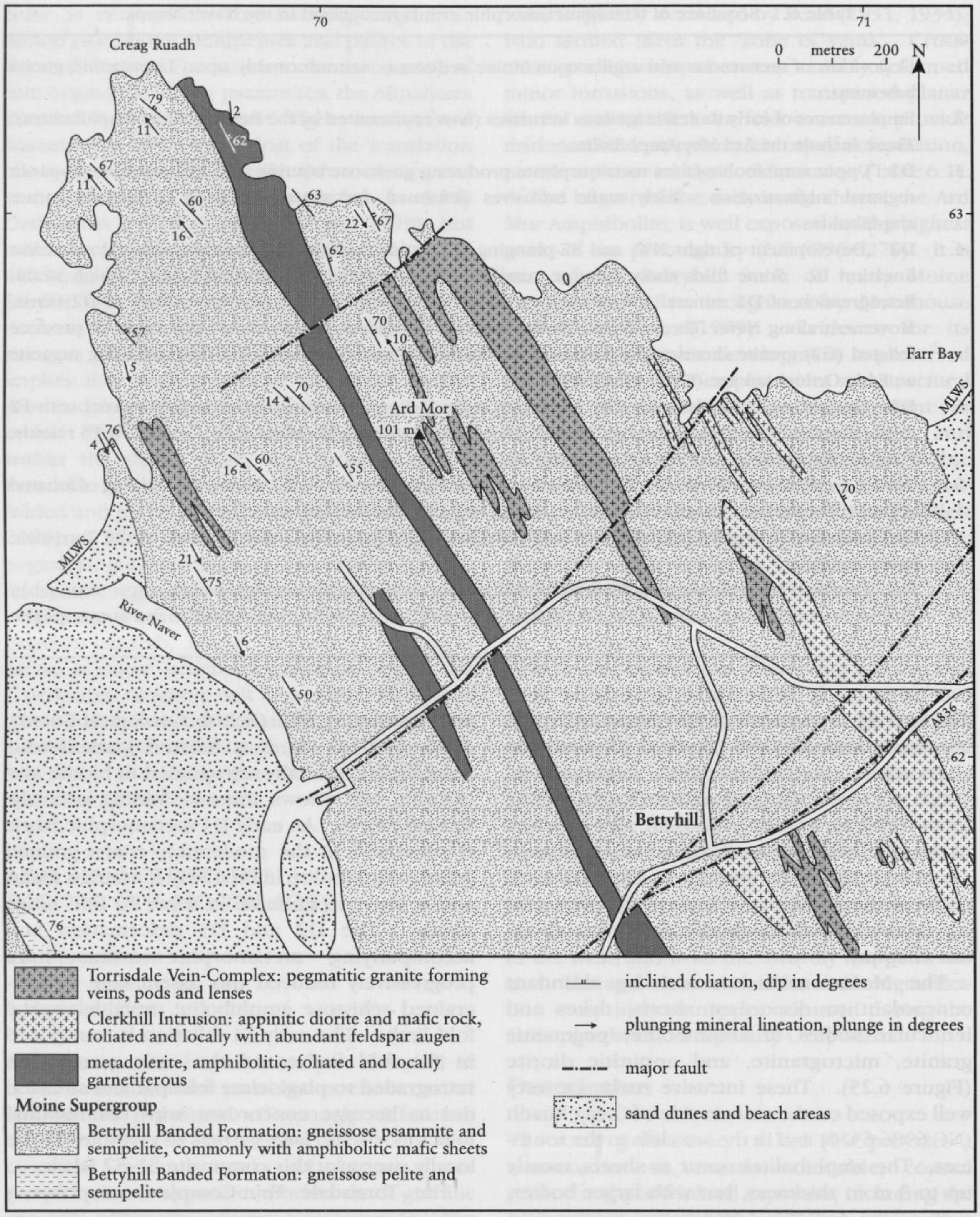


**Figure 6.25** Map of the Ard Mor GCR site. Compiled from data from British Geological Survey 1:50 000 Sheet 115W, Strathy Point (1996), Cheng (1943) and from mapping by G.I. Alsop.

(Moorhouse *et al.*, 1988). Where intrusions are markedly discordant to the gneissose layering in the host rocks they are generally folded. However, those at a low angle to the compositional layering are asymmetrically boudinaged, with their geometry implying a dextral sense of shear

(Holdsworth *et al.*, 2001). There are foliated and unfoliated granitic sheets representing a history of successive intrusive phases. For example, in a sea stack at NC 6993 6210 a pink, pegmatitic granite with a foliated marginal fine-grained zone cuts the migmatitic fabric in the adjacent amphibolite within the Bettyhill Banded Formation. Foliated granites tend to be concordant with, or slightly discordant to, the regional gneissosity/foliation, interpreted as a composite S1–3 fabric. Locally, subconcordant foliated granite sheets, locally termed 'G2', truncate the composite migmatitic fabric. A later phase of intrusive granitic veins, G3, cross-cuts F2 and locally F3 folds, and D2 fabrics. These G3 veins and sheets commonly have an L–S fabric defined by aligned quartz and feldspar aggregates and are folded where their orientation lies at a high angle to the regional fabric. A final phase, G4, comprises E–W-trending sheets of unfoliated microgranites and quartz-feldspar pegmatites that markedly cross-cut all the structures and lithologies, except for later minor faulting (Figure 6.26).

According to Holdsworth *et al.* (2001) the sheets and veins of the Torrisdale Vein-Complex vary from medium-grained to pegmatitic granites with varying proportions of perthitic K-feldspar, quartz and plagioclase with minor garnet, muscovite, biotite, apatite, zircon and opaque minerals. The central parts of the granite intrusions comprise mainly equant feldspars with extensive patches of marginal myrmekite and interstitial quartz aggregates. Sheet and vein margins are commonly highly strained with a penetrative L–S fabric defined by muscovite-rich laminae and quartz-feldspar aggregates that lie parallel to the composite planar fabric in the host gneisses. Feldspar porphyroclasts within the fabric are deformed in a brittle manner and show internal cracking and undulose extinction in thin section.

**Figure 6.26** Hook-shaped fold formed by superimposition of an upright F3 fold on an earlier tight recumbent F2 minor fold. A later non-foliated pegmatitic granite vein cross-cuts the refolded structure. On hillside above Creag Ruadh at NC 6982 6300. (Photo: V.E. Moorhouse, BGS No. P580517, reproduced with the permission of the Director, British Geological Survey, © NERC.)

A distinctive bluish-tinged, pale-grey, quartz-biotite rock is discontinuously developed along the boundaries of the Ard Mor Amphibolite and was noted by Cheng (1943) and Moorhouse (1979). The rock is an L–S tectonite with a strong, steeply E-dipping S2 planar fabric, concordant with the regional gneissosity, and a rodding lineation, locally coaxial with the later upright D3 folds that fold the S2 fabric.

At least four phases of deformation can be demonstrated within the Ard Mor site (Table 6.1). A pervasive regional migmatitic gneissose fabric, S1, is folded by tight, flat-lying F2 folds, themselves refolded by upright F3 folds. Examples of the upright F3 folds occur on Creag Ruadh (NC 6967 6306) where the excellent exposure allows hinge lines to be traced and composite fabrics to be studied in natural cross-sectional profiles. Penetrative schistose fabrics relate to the various fold phases. F2 folds locally form 'eye' structures; a good example of a hook-shaped fold interference structure (F2 + F3) occurs on the hillside above Creag Ruadh, where it is cross-cut by a late-stage, unfoliated pegmatite vein (Figure 6.26).

Holdsworth *et al.* (1991) recorded that linear structures within the Torrisdale Steep Belt have regionally anomalous orientations (see also **Aird Torrisdale** GCR site report, this chapter). L2 mineral lineations and F2 fold axes plunge gently SSE or NNW at $< 20°$ to the strike of the regional foliation. In contrast, to the west and south L2 and F2 generally plunge south-east and down-dip in the plane of the foliation. The F3 folds are mostly close to tight in style and their axes plunge similar to those of the F2 structures. They mostly verge to the ENE and are particularly strongly developed in this part of Sutherland. The latest (D4) deformation developed brittle-style folds and faults that affected all other folds and fabrics.

## Interpretation

The complex inter-relationships between the various structural and metamorphic fabrics in the migmatitic Moine metasedimentary rocks and the numerous minor amphibolitic, granitic, and appinitic intrusives within the Naver Nappe are readily studied within this site. Evidence of polyphase deformation and metamorphism is widespread, with examples of Type-3 fold interference structures (Ramsay and Huber, 1987) of particular note. As noted above at least four separate phases of deformation can be distinguished (see also Table 6.1).

The Ard Mor Amphibolite is part of a swarm of metamorphosed, early (pre-D1) tholeiitic intrusives ('early Moine amphibolites' of Moorhouse and Moorhouse, 1979). Note that the different mappers (B.N. Peach, Y.C. Cheng, V.E. Moorhouse, I.M. Burns and G.I. Alsop) disagree as to the exact position and extent of the various amphibolite outcrops. Amphibolite sheets and lenses of the Bettyhill Suite are abundant in the Moine succession, but it is difficult to define large individual masses or concentrations. Within the Ard Mor Amphibolite an early schistosity and associated garnet-hornblende mineral assemblage are folded, with original fabrics only preserved within some low-strain fold hinge regions. The early schistosity is transposed and garnets progressively retrogressed and streaked out into a composite planar fabric on the fold limbs. In parts this S1–S2 fabric is overgrown by small, euhedral garnets, probably of D3 age. Burns (1994) used equilibrium garnet-biotite assemblages to calculate the metamorphic temperature of about 550° C (assuming a pressure of 5 kbar) at the time of growth of these later garnets. Moorhouse (1979) interpreted the quartz-biotite rock, found locally adjacent to the Ard Mor Amphibolite, as a high-strain restite derived from psammitic gneiss. She inferred that under conditions of high D2 strain the migmatized psammitic gneisses were segregated or possibly partially melted to produce foliated granites and a quartz-biotite restite.

The migmatitic fabrics and abundant granitic minor intrusions exposed in the coastal cliff-sections of Ard Mor are a characteristic feature of the Naver Nappe. Although the migmatitic fabric is folded by F2 folds, and hence attributed to D1 deformation and metamorphism, the main fabric has been dated from zircon overgrowths at 467 Ma (Kinny *et al.*, 1999) implying its formation during the Early Ordovician Grampian Event. Its origin appears to be multi-phase with an earlier Neoproterozoic D1 amphibolite-facies metamorphic event overprinted by the Ordovician event. The G2 and G3 intrusive phases form the main part of the Torrisdale Vein-Complex and locally show dextral shear indicators. In places the granitic sheets and veins cut across F3 upright folds (including F2 + F3 refolds) and show little evidence of deformation.

Holdsworth *et al*. (2001) suggested that the Torrisdale Steep Belt formed during a localized, post-F3 dextral transpressive event to explain the strike and dip of structures in this belt, as well as the tightness of the minor F3 folds (see **Aird Torrisdale** GCR site report, this chapter). They also suggested that the Torrisdale Vein-Complex was emplaced over an extended time-period during the late stages of the Caledonian deformation event. Dallmeyer *et al*. (2001) obtained $^{40}Ar$-$^{39}Ar$ plateau muscovite ages of 419 Ma and 423 Ma from migmatitic Moine rocks sampled adjacent to the Ard Mor peninsula. They interpreted these ages as dating the late-stage Torrisdale Steep Belt fabric, implying that its formation was Scandian and hence Late Silurian in age.

## Conclusions

The Ard Mor coastal promontory provides good exposures of diverse, high metamorphic grade, Moine semipelites, pelites and psammites (Bettyhill Banded Formation), 'early' mafic amphibolite sheets, and later granitic veins and sheets within the Naver Nappe. The rocks record a complex history of deformation, metamorphism and emplacement of minor intrusions. Evidence of at least four separate phases of deformation and metamorphism can be distinguished, with excellent examples of refolded folds illustrating the polyphase orogenic history of these Moine rocks. Three phases of minor granitic intrusions, termed 'G2', 'G3' and 'G4', can be distinguished on the basis of their relationships to particular deformation episodes, with the oldest phase post-dating an early D1 migmatization. Granitic veins of the Torrisdale Vein-Complex (G3) were emplaced over a protracted time-period during the later stages of the regional Caledonian deformation, probably during the Scandian Event in the Late Silurian. The Ard Mor Amphibolite is part of the Bettyhill Suite, a swarm of metamorphosed tholeiitic basic intrusive sheets. It preserves evidence of early (D1) tectonometamorphic events and of progressive reworking by later D2 and D3 deformation events. The regional gneissosity/foliation can be shown to be a composite (S1–S3) fabric. The Ard Mor site is of regional importance and is an excellent place to start to unravel the complex geological history of the metamorphic Moine rocks of the Naver Nappe.

# FARR BAY (BETTYHILL) (NC 711 632–NC 719 624, NC 701 620–NC 724 615)

***V.E. Moorhouse***

## Introduction

The Farr Lewisianoid Inlier and adjacent migmatitic Moine metasedimentary rocks are well exposed in clean exposures along the high-water mark at the north-east end of Farr Bay. These rocks strike south-east through sand dunes and are next seen in inland cliffs adjacent to the lower part of the Clachan Burn, immediately south of the A896 road (Figure 6.27). Locally, excellent examples of fold interference structures in gneisses of the Bettyhill Banded Formation (Moine) are seen. There are also roadside exposures immediately south of Clerkhill, for example at NC 7160 6280, which show augen hornblende-granite gneisses, ultramafic (hornblende-pyroxene) rocks, and amphibolites belonging to the Clerkhill Intrusion, previously referred to as the 'Clerkhill Appinite Suite' (Moorhouse *et al*., 1988).

B.N. Peach first mapped the Bettyhill–Farr area for the Geological Survey in 1891–1892. Cheng (1942, 1943) subsequently studied the complex metamorphic and structural relationships between the hornblendic gneisses, the amphibolites and the Moine metasedimentary rocks. Cheng (1943) termed the Farr Lewisianoid gneisses 'Durcha Moines' (see 'Introduction' and **Allt Doir' a' Chatha** GCR site report, this chapter), but distinguished them from the Clerkhill and other mafic rocks of the Bettyhill area. V.E. Moorhouse remapped the area in the 1970s (Moorhouse, 1979; Moorhouse *et al*., 1988). More recently I.M. Burns studied the tectonothermal evolution and petrogenesis of the Naver and Swordly nappes (Burns, 1994).

## Description

Farr Bay is a NW-facing sandy bay that lies about 1 km north-east of Bettyhill. Rocky cliffs bound its outer parts and the bay is backed by extensive sand dunes. Although the degree of exposure in the bay varies yearly, dependent on the amount and distribution of blown sand, the exposures provide instructive sections across lithological strike and exhibit remarkable structural detail.

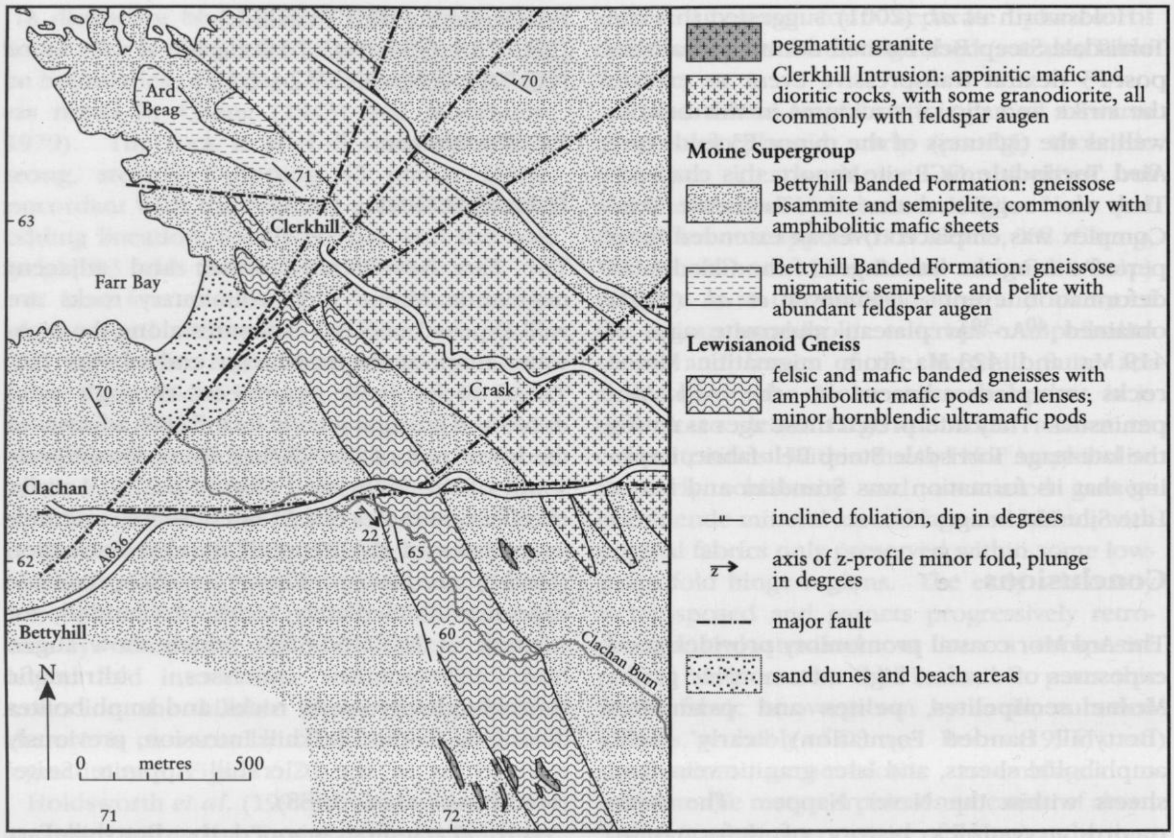


**Figure 6.27** Map of the Farr Bay GCR site. Based on Cheng (1943) and British Geological Survey 1:50 000 Sheet 115W, Strathy Point (1996).

The site also includes a well-exposed section in the lower rocky gorge of the Clachan Burn, and in the cliffs of Creag Clachain (NC 714 621) and Creag a' Bhodaich (NC 7230 6215), both of which lie immediately south of the main A836 road.

The dominant lithologies around the bay and in Creag Clachain and Creag a' Bhodaich are migmatitic, layered, gneissose Moine psammite and semipelite of the Bettyhill Banded Formation. On the east side of the bay are thinly layered hornblendic felsic and mafic gneisses of the Farr Lewisianoid sheet. This sheet is some 80–100 m wide adjacent to the sandy bay, but lenses out to the north-west (Figure 6.27). The sheet can be traced to the south-east for 3 km to just west of Loch Strathy (NC 777 471).

The primary compositional layering in the Moine metasedimentary rocks reflects the original bedding, but any evidence of sedimentary structures has been destroyed by the polyphase amphibolite-facies metamorphic events and related migmatization. These have resulted in a recrystallized, and in part segregated, foliation, with new mineral assemblages and textures. Pegmatite granite, quartz and quartz-feldspar veins, pods and stringers of various widths are abundant in these migmatitic rocks. The migmatitic layering and veining commonly show small- and medium-scale folding that varies in style from tight early folds to more-open later folds. A typical example is seen at NC 7177 6212 where Z-profile, close to tight folds show NNE- to SE-plunging axes. A prominent axial rodding and mullioning is seen, particularly in the quartz and quartz-feldspar segregation veins. The fold axial planes lie sub-parallel to the regional foliation and dip steeply to the ENE.

Evidence for the several deformation phases that have affected the Moine rocks is well seen in Farr Bay. Clean and etched exposures reveal tight F2 folds and more-open, upright F3 folds, which in places combine to form fold interference structures. At NC 7159 6272, situated at the top of a sandy scree slope, is a classic example of a type-3 fold interference structure (Ramsay and Huber, 1987) (Figure 6.28). Tight F2 structures with SE-plunging axes fold the fine-scale migmatitic layering and are refolded by close to tight F3 folds. The later F3 folds are almost coaxial with the earlier F2 structures but have ENE-dipping axial surfaces.

There are two small exposures of layered felsic and mafic gneiss of the Farr Lewisianoid Inlier at the high-water mark in the bay NC 7146 6266. More-extensive exposures are seen south of the A836 road in the lower Clachan Burn and here clinopyroxene-bearing mafic gneiss is recorded (Moorhouse, 1979). The Moine–Lewisianoid boundary is exposed at NC 7180 6210 and farther south-east in the Clachan Burn sections, but no obvious dislocation is observed. The Lewisianoid rocks are massive, cream, pink and dark green-black, thinly striped, hornblende-bearing acid and mafic gneisses with amphibolite pods and lenses. They show no sign of a strong superposed fabric near the margin of the inlier. The Farr Lewisianoid sheet is the only significant 'basement' body within the Naver Nappe (British Geological Survey, 1996), although smaller lenses of Lewisianoid gneiss occur farther to the SSE. Small inliers are also found in the footwall of the Swordly Thrust to the east.

Metamorphosed ultramafic (hornblende-pyroxene) rocks, amphibolites and dioritic gneisses with abundant pink K-feldspar augen, which together constitute the western part of the Clerkhill Intrusion, can be examined in roadside exposures near NC 7160 6280 (see **Glaisgeo–Farr Point** GCR site report, this chapter). The Clerkhill Intrusion is separated from the eastern boundary of the Farr Lewisian body by a thin zone of migmatitic psammitic gneiss (Figure 6.27).

## Interpretation

The Farr Lewisianoid sheet occurs in a relatively low-strain zone (evidenced by the local occurrence of fold interference patterns) and is structurally symmetrical with similar Moine metasedimentary rocks on both sides. Hence, Moorhouse *et al.* (1988) inferred that it occupies

**Figure 6.28** Tight F2 folds refolded by more-open F3 folds giving a type-3 interference structure. Top of sandy scree slope, Farr Bay, at NC 7159 6272. The compass is 18 cm long. (Photo: V.E. Moorhouse, BGS No. P580518, reproduced with the permission of the Director, British Geological Survey, © NERC.)

a complex fold core, similar to other Lewisianoid inliers in Sutherland (Strachan and Holdsworth, 1988). The lithologies exposed and geochemical evidence provided by Moorhouse (1979) suggest that the gneisses have affinities with the Scourian gneisses of the foreland Lewisian. However, recent isotopic data on the Farr Lewisianoid Inlier suggests that the gneisses cannot be correlated simply with the foreland Lewisian. Friend *et al.* (2008) obtained concordant zircon U-Pb SHRIMP ages of 2905 ± 24 Ma for the protolith of the Farr Lewisianoid gneisses. There was no evidence of the 2490 Ma granulite-facies Badcallian reworking event, but a discordant array suggested significant isotopic disturbance involving Pb loss as early as *c.* 1600 Ma.

The Farr Lewisianoid sheet is believed to be the structurally highest, unequivocal Lewisianoid inlier of any significant size in the Moine succession of Sutherland. Farther east small lenticular Lewisianoid gneiss bodies lie in the footwall to the Swordly Thrust and can be traced south to Ben Klibreck. The Strathy Complex (Moorhouse and Moorhouse, 1983) that structurally overlies the Swordly Nappe farther east has petrological and geochemical characteristics suggesting a lower crustal origin. However, it is petrologically and geochemically unlike the Lewisianoid inliers elsewhere in the Moine succession and its affinity is presently unclear (Moorhouse and Moorhouse, 1983; Moorhouse *et al.*, 1988; Burns *et al.*, 2004).

The type-3 fold interference structures here described above probably lie within a narrow zone of relatively low strain, possibly close to a major F3 hinge. These F2 + F3 coaxial folds (Moorhouse, 1979) demonstrate the polyphase nature of tectonometamorphic events within the Naver Nappe. It is tempting to correlate the D2 and D3 phases with the Early Ordovician Grampian and Late Silurian Scandian orogenic events respectively (Dallmeyer *et al.*, 2001). However, it is unclear as to whether the D2 phase is Ordovician, as there is considerable evidence farther south that D2 structures are Neoproterozoic in age (see 'Introduction', Chapter 8), and there is evidence for Knoydartian metamorphism farther west. It is clear that the area has been reactivated during several orogenic events but the exact age of the particular structures and their composite nature is difficult to determine. The area appears to be less affected by the Torrisdale Steep Belt, with F2 and F3 fold axes plunging to the south-east, rather than the SSE.

## Conclusions

The Farr Bay site provides clean exposures where the nature of the Moine and Lewisianoid rocks of the Naver Nappe can be easily studied. These pertain to basement–cover relationships, early igneous activity and the number and nature of the various orogenic events that have affected this part of the Moine succession. The basement comprises the Farr Lewisianoid body, the main Lewisianoid inlier within the migmatitic Moine rocks of north-east Sutherland that lie east of the Naver Thrust Zone. The Moine rocks are migmatitic psammitic and semipelitic gneisses of the Bettyhill Banded Formation. Superb refolded folds and minor folds in Moine psammites can be readily examined in several sand-blasted and etched rock pavements. The site is one of the few places where the three main groups of hornblendic rocks found in Sutherland are juxtaposed and thereby readily compared. These are the hornblendic mafic gneisses of the Lewisianoid inlier, the 'early Moine' amphibolites of the Bettyhill Suite, and the later hornblendic mafic and dioritic members of the Clerkhill Intrusion. The site is of national importance and is likely to remain an important locality for further study and for teaching purposes.

# GLAISGEO–FARR POINT (NC 713 635–NC 727 640)

***V.E. Moorhouse***

## Introduction

The peninsula of Farr Point and its adjacent rocky bays and geos provide an impressive across-strike section through the Clerkhill Intrusion and the migmatitic psammites and semipelites of the Bettyhill Banded Formation including the Farr Pelite Member (Figure 6.29). The Clerkhill Intrusion is a deformed and metamorphosed, appinitic, ultramafic to mafic and felsic body that is unique to Sutherland. In parts it shows spectacular development of potash-feldspar porphyroblasts, commonly aligned to give an augen texture. The bulk of its component lithologies are foliated, but they are cross-cut by numerous undeformed

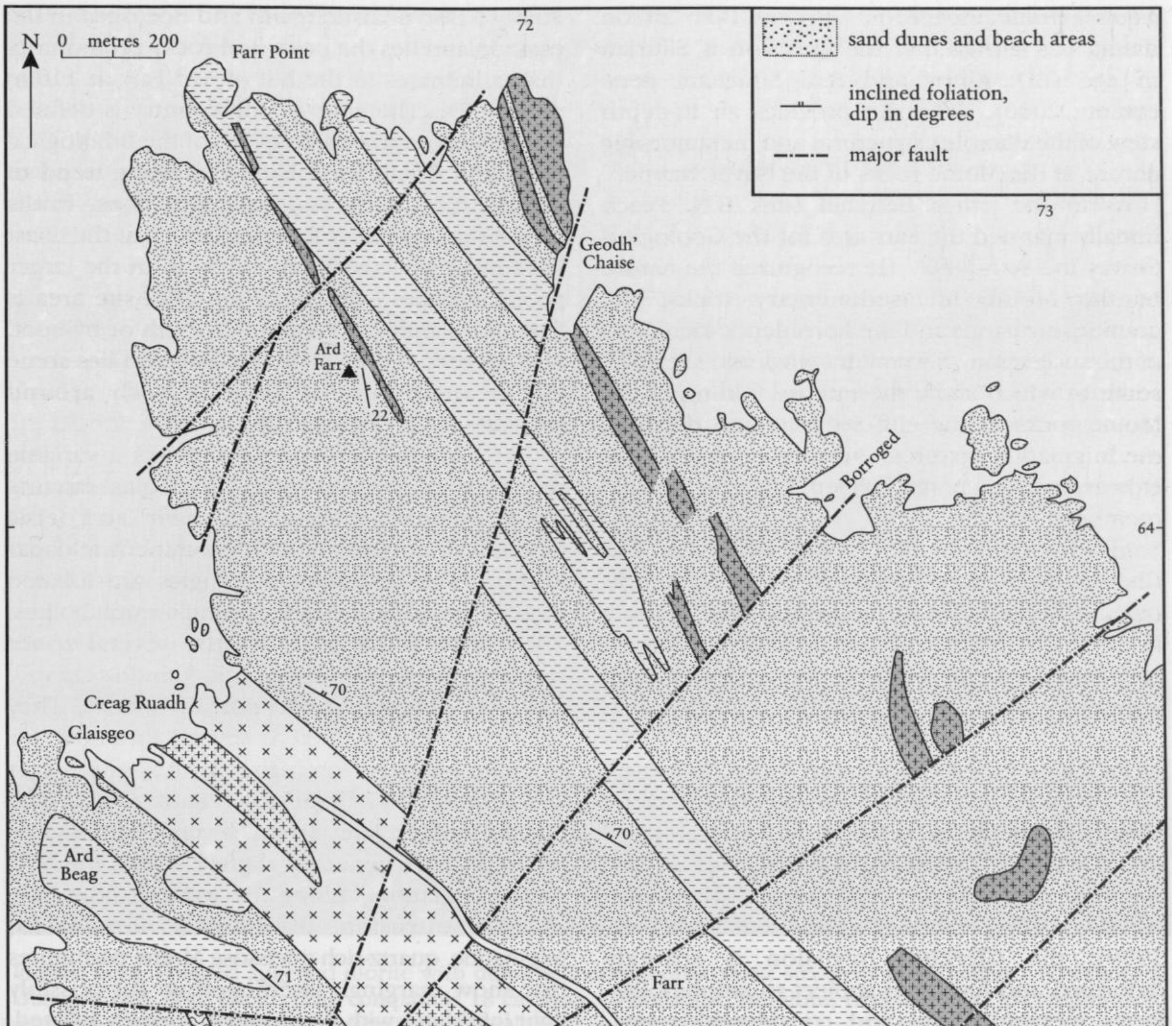


**Figure 6.29** Map of the Glaisgeo–Farr Point GCR site. Based on Cheng (1943) and British Geological Survey 1:50 000 Sheet 115W, Strathy Point (1996).

small granitic intrusions. Recent U-Pb zircon dating has shown that the intrusion is Silurian in age (P.D. Kinny and R.A. Strachan, pers. comm., 2006). The site provides an in-depth view of the complex structural and metamorphic nature of the Moine rocks of the Naver Nappe.

As in the other Bettyhill sites B.N. Peach initially mapped the Farr area for the Geological Survey in 1891–1892. He recognized the nature of the Moine metasedimentary rocks, the granitic intrusions and the hornblende-rich parts of the succession. Several drawings and sketches, some of which show the intense folding of the Moine rocks in the cliff sections and detail of the migmatitic textures, enhance his field slips. However, others portray sheep, cattle and female members of the local crofting population. Somewhat later, in the 1930s, studies by Y.C. Cheng focused more intently on the different rock-types. Cheng (1942) recognized the coarsely hornblendic nature of the Clerkhill Intrusion and termed it the 'Hornblendic complex with appinitic types'. Moorhouse (1979) also mapped the body, and Moorhouse *et al.* (1988) termed it the 'Clerkhill Appinite Suite', reflecting the presence of coarse hornblende-pyroxene rocks. Although the texture and mineralogy of the constituent rocks have similarities to the Appinite Suite in its type area (Wright and Bowes, 1979; Platten in Stephenson *et al.*, 1999), the Clerkhill Intrusion is strongly deformed and has been subject to amphibolite-facies metamorphism and considerable meta-somatism (Cheng, 1942).

Migmatitic Moine semipelites and psammites are exposed on the south-western side of the Clerkhill Intrusion, and mixed psammitic and semipelitic lithologies occur widely on its north-east side towards Farr Point. A foliated migmatitic and gneissose biotite-rich pelite is exposed on Farr Point and inland along the spine of the Ard Farr peninsula. Cheng (1943) designated this unit the 'Ard Farr pelitic gneiss' and it was one of the main lithologies studied in his pioneering work on the geochemical effects resulting from migmatization and metasomatism. In this account it is termed the 'Farr Pelite Member' of the Bettyhill Banded Formation.

## Description

The GCR site area encompasses the indented, steeply cliffed coastline and small bays that stretch from Glaisgeo in the west, around Farr Point to Borve Castle (ruin) and Borroged in the east. Inland lies the peaty and rocky promontory that culminates in the hill of Ard Farr at 110 m above OD. The grain of the country is defined by the steep north-easterly dip of the lithological units and dominant foliation, and the trend of the granitic, dioritic and mafic intrusions. Faults are marked by linear features, which at the coast have been selectively eroded to form the larger geodh features. Access to the CGR site area is from the hamlet of Farr to the south or by boat. A small part of the site is separate and lies some 200 m south-west of Swordly Loch around NC 7285 6275 (Figure 6.29).

The Clerkhill Intrusion comprises a variable sequence of metamorphic lithologies ranging from ultramafic through to mafic and felsic 'appinites', commonly with prominent feldspar augen. The dominant lithologies are foliated diorites, granodiorites and appinitic amphibolites. The augen lithologies comprise several zones crammed with prominent pink, 'dent de cheval', perthitic potash-feldspar porphyroblasts. They are beautifully exposed at several localities, for example between the high- and low-tide marks at Glaisgeo (NC 7131 6340) (Figure 6.30). The feldspar augen are up to several centimetres across and are generally aligned within the NW-striking foliation. Along the western boundary of the intrusion are highly attenuated, migmatitic, quartz-rich gneissose Moine psammites that show marginal 'interfingering' (or possibly tight infolding) with fine-grained, strongly foliated, hornblende-rich lithologies. In contrast, the eastern contact of the Clerkhill Intrusion against gneissose Moine psammites and semipelites is sharp, where it is seen in the coastal section by Creag Ruadh at NC 7148 6371. However, minor lenticular ultramafic 'pods' are present in the adjacent semipelites.

An exposure south-west of Swordly Loch provides critical evidence for the emplacement age of the Clerkhill Intrusion relative to the tectonothermal history of the Naver Nappe. Here, stringers and veins of 'appinitic' amphibolite with feldspar augen belonging to the Clerkhill Intrusion cut the early stromatic migmatitic banding (S1) in the surrounding psammites and semipelites of the Bettyhill Banded Formation. In addition, a foliated K-feldspar-bearing amphibolite sheet of the Clerkhill Intrusion is folded along with the migmatitic psammites and semipelites into tight upright (F3) folds. These structures clearly fold an earlier penetrative

**Figure 6.30** Foliated augened diorite with deformed amphibolitic mafic stringers and lamellae. Foreshore at Glaisgeo (NC 7142 6362). The compass is 18 cm long. (Photo: J.R. Mendum, BGS No. P577534, reproduced with the permission of the Director, British Geological Survey, © NERC.)

foliation in both the Clerkhill Intrusion and in the Moine metasedimentary rocks that is interpreted as a combined S1 + S2 fabric. Farther south-east by Loch Salachaidh at NC 7331 6212 the main foliation is cross-cut by a foliated granite body whose deformation is ascribed to late D3.

## Interpretation

Geochemical studies by Moorhouse (1979) suggest that the rocks of the Clerkhill Intrusion show similarities with the Appinite Suite rocks of Argyll (Wright and Bowes, 1979; Platten in Stephenson *et al.*, 1999) and the Ach'uaine Hybrid intrusions of central and south Sutherland (Read, 1931). Both sets of intrusions show enrichment in K, Sr, Ba, Ni, Cr and light REE. Recent zircon age dating also suggests that the diorites and granodiorites were intruded during the Silurian (P.D. Kinny and R.A. Strachan, pers. comm., 2006) and may link to the Strath Halladale Granite Complex farther east (Kocks *et al.*, 2006). However, the foliated and metamorphosed nature of the Clerkhill rocks suggests that they pre-date the Late Silurian Appinite Suite (*sensu stricto*), and hence are considerably older. The field relationships noted above suggest that the Clerkhill Intrusion was emplaced after the imposition of the early (D1) gneissose fabric in the Moine rocks but before tight folding related to the D3 deformation events, which are probably linked to the Grampian and Scandian orogenic events respectively (Kinny *et al.*, 1999). The pervasive foliation in the Clerkhill rocks has been correlated with the main S2 schistosity/foliation in the adjacent Moine rocks, thus implying a pre- or syn-D2 emplacement of the intrusion (Moorhouse *et al.*, 1988), but the recent U-Pb age dating suggests that this correlation is incorrect. F3 folds and D3 deformation of the diorites and granodiorites appear to post-date the main fabrics within the Clerkhill Intrusion. In the Glaisgeo area there is no obvious change in F2 or F3 minor fold vergence across the augen gneisses of the Clerkhill Intrusion, suggesting that it does not occupy a major F2 or F3 fold hinge.

The Clerkhill Intrusion is a differentiated granodioritic, dioritic and metadoleritic body, smaller examples of which are found throughout the Naver Nappe. The age of the ultramafic pods is more equivocal.

The Moine metasedimentary rocks (Bettyhill Banded Formation) of the Naver Nappe have been subject to considerable whole-rock and trace-element geochemical studies. Moorhouse and Moorhouse (1983) suggested that geochemically they showed more affinity with the Morar Group rocks farther south rather than the Glenfinnan Group rocks. Similar conclusions were reached for the psammites and semipelites in the structurally higher Swordly Nappe to the east. Hence, they concluded that it was unlikely that the Naver or Swordly thrusts correlated with the Sgurr Beag Thrust to the south. However, the migmatitic nature of these rocks testifies to the influx of fluid phases at various times in their tectonometamorphic history (Burns, 1994; Watt *et al.*, 1996) so that correlations based on the geochemistry should be treated with caution.

## Conclusions

The Glaisgeo–Farr Point GCR site is of national importance as it provides good cross-sections across a large, deformed and metamorphosed, appinitic, felsic to mafic and ultramafic body, termed the 'Clerkhill Intrusion'. Lithologically it ranges from a granodiorite to a diorite and a dolerite, with subsidiary amphibole-rich ultramafic pods. Recent U-Pb zircon age dating supports correlation of the body with the classic Late Silurian appinites of the Appin area and the Ach'uaine Hybrid cluster of Sutherland, although its foliated and metamorphosed nature imply that it may be older. Potash-feldspar-rich augen are abundant and hornblende-granite gneiss sheets and various other hornblende-rich lithologies can be studied in outstanding coastal exposures at Glaisgeo and inland. The deformation fabrics and minor structures in the rocks of the Clerkhill Intrusion, and in the surrounding gneissose Moine psammites and semipelites, indicate that the Clerkhill Intrusion was emplaced into the Moine succession during the latter stages of the Scandian Event in a similar manner to the Strath Halladale Granite Complex and foliated granitic intrusion of Strath Naver.

The Glaisgeo–Farr Point coastal section is also nationally important in providing excellent exposures of the Moine metasedimentary rocks on either side of the Clerkhill Intrusion. These form part of the Bettyhill Banded Formation and lie in the central part of the Naver Nappe. The site area has been the subject of several geochemical studies on the effects of metamorphism, metasomatism and migmatization on the range of rock types present and remains suitable for further work.

# SGEIR RUADH (PORTSKERRA) (NC 876 667–NC 883 657)

***R.M. Key***

## Introduction

Adjacent to Portskerra in north-east Sutherland, a near-continuous coastal section is exposed on rock platforms and in cliffs at the Sgeir Ruadh GCR site. This section lies within the Swordly Nappe and illustrates the relationships between migmatitic Moine psammites of the Portskerra Psammite Formation, amphibolite sheets of the Bettyhill Suite, and the Strath Halladale Granite Complex. Middle Devonian sandstones and breccio-conglomerates unconformably overlie these Neoproterozoic and Early Palaeozoic rocks (Figure 6.31).

Good exposures of the northernmost part of the Silurian-age Strath Halladale Granite Complex occur on the rock platform south of Sgeir Ruadh and the contact relationships of this sheeted granitic complex with the Portskerra Psammite Formation can be studied at Sgeir Ruadh itself. Coastal exposures west of Rubha Bhrà reveal the typical gneissose and migmatitic character of the Portskerra Psammite Formation. There are also numerous examples of the amphibolite sheets and dykes that represent metamorphosed Neoproterozoic intrusive mafic sheets and dykes.

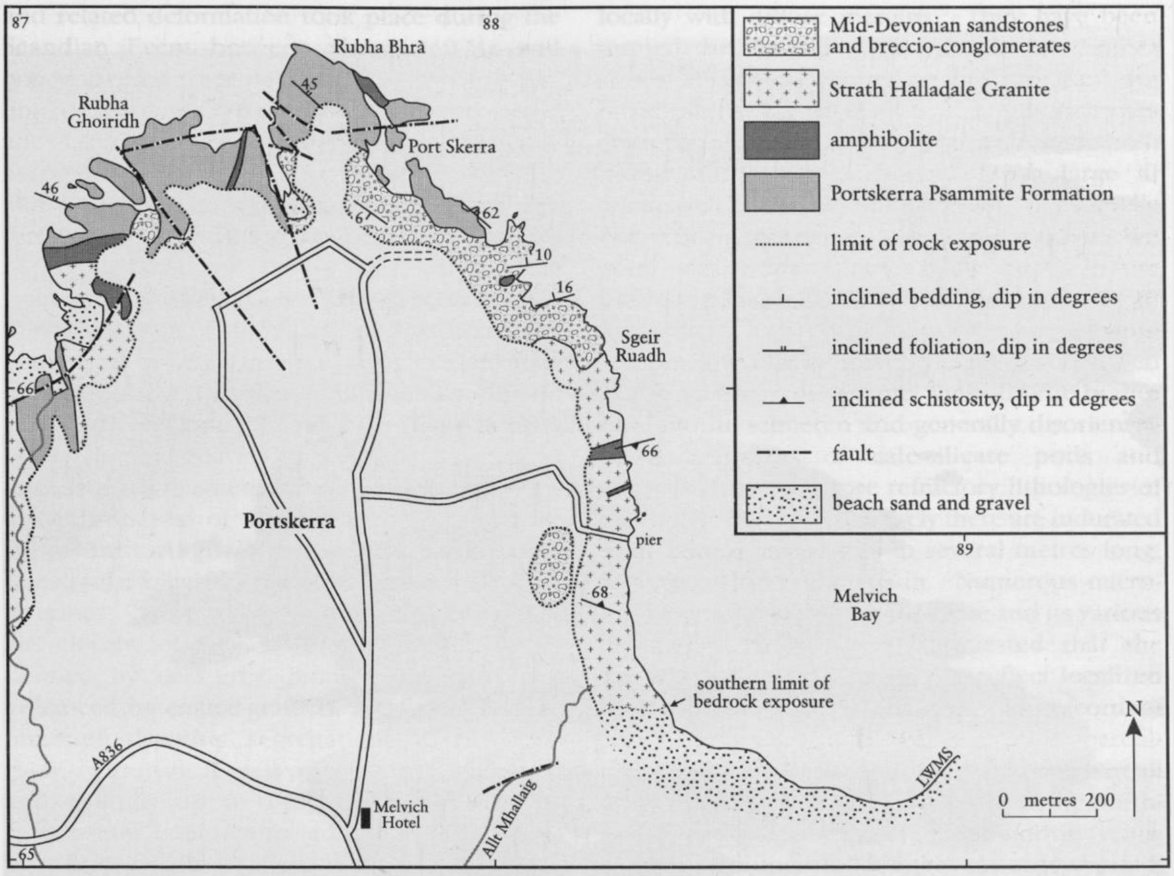


**Figure 6.31** Simplified geological map of the Sgeir Ruadh site.

The prominent basal unconformity of the Old Red Sandstone (ORS) Supergroup sedimentary rocks with the underlying Moine psammites and Strath Halladale granitic rocks is exposed at Sgeir Ruadh and at Port Skerra (Figure 6.31). These unmetamorphosed, Middle Devonian breccio-conglomerates and sandstones were deposited at the fringe of the Orcadian Basin. They underlie the gently undulating countryside around Portskerra village (Figure 6.32). A number of small faults are exposed, and their markedly different fault manifestations in the various lithologies can be studied in the coastal section.

Edward Greenly first mapped the area for the Geological Survey between 1890 and 1892, and Crampton and Carruthers (1914) gave a brief account of the geology. The migmatitic character of the Moine rocks of Portskerra was recognized by Read (1931) as being part of the Strath Halladale Granite Complex. More-recent work has divided the migmatitic Moine rocks into a series of smaller units, in part separated by significant ductile shears or thrusts (e.g. Moorhouse and Moorhouse, 1983; Fletcher and Key, 1991; Holdsworth *et al.*, 1994; British Geological Survey, 1996).

The Moine metasedimentary rocks contain numerous amphibolite sheets that form part of an extensive mafic sill-complex, part of the Bettyhill Suite (see Moorhouse and Moorhouse, 1979). These mafic intrusive rocks, originally dolerite and basalt sheets and dykes, appear to pre-date the earliest deformation and metamorphism and have been folded, boudinaged and partly migmatized during the extended deformation and metamorphic history. Only rarely do they still show discordant relationships.

The Strath Halladale Granite Complex forms a series of essentially concordant lenticular sheets within the Portskerra psammites. The intrusion was first recognized during the primary Geological Survey mapping (Crampton and Carruthers, 1914). Read (1931) recognized that metasedimentary (Moine) xenoliths occur throughout the main intrusion and noted the

**Figure 6.32** Oblique aerial photo of Rubha Bhrà and Portskerra. Mid-Devonian rocks, lying unconformably on the Moine succession, form the upper parts of the cliffs and underlie the higher parts of the peninsula. (Photo: BGS No. 21/6 (Fletcher and Key, 1991); reproduced with the permission of the Director, British Geological Survey, © NERC.)

intimate relationship of the intrusion and its country rock. McCourt (1980) recognized several generations of granitic intrusions in the Strath Halladale Granite Complex. Kocks *et al.* (2006) have recently published a U-Pb TIMS titanite age of 426 ± 2 Ma for the main Strath Halladale Granite, which is interpreted as dating the granite emplacement. There is no associated thermal aureole around the Strath Halladale granite sheets and they suggest that the granites were emplaced into hot country rock, roughly coeval with the regional Scandian tectonothermal event associated with the generation of the Moine Thrust Belt (see below).

The major ductile shears/thrusts in the Moine succession of Sutherland trend generally northwards with variable easterly dips and separate the succession into folds or nappes (Figures 6.3, 6.4). The gneissose psammites at Portskerra lie in the Swordly Nappe, the most easterly and one of the structurally higher nappes. Friend *et al.* (2000) have dated a high-grade metamorphic event that produced the migmatites in the underlying Naver Nappe at 467 ± 10 Ma (U-Pb SHRIMP zircon overgrowth age). In contrast, Ar-Ar and Rb-Sr isotopic studies on muscovite and hornblende from the lower A' Mhoine Nappe suggest that the pervasive W-directed thrusting and related deformation took place during the Scandian Event between about 440 Ma and 410 Ma (Dallmeyer *et al.*, 2001).

## Description

The GCR site encompasses the coastal section from Melvich Bay west to the rocky promontories of Rubha Bhrà and Rubha Ghoiridh and the steep gully of Allt na Clèite. The section lies just north and east of the village of Portskerra and consists of mainly intertidal, clean-washed rock exposures and platforms, with backing cliffs of till and bedrock up to 60 m high (Figures 6.31, 6.32).

Gneissose, magnetite-bearing psammites form the headlands of Rubha Bhrà and Rubha Ghoiridh. Aligned biotite flakes define a penetrative foliation parallel to the compositional layering. The beds dip steeply north-east and are closely jointed. The gneissic layering is defined by dark-grey, biotite-rich seams and enhanced by coarse-grained, locally pegmatitic, quartzofeldspathic segregations up to 5 cm thick. Individual segregations are lenticular and typically up to 1 m long. Thin biotite-rich pelitic laminations are preserved within mica-poor psammite beds. The laminations are mostly parallel to layering but locally define possible relic cross-bedding structures (e.g. at NC 8770 6663).

Dark grey-green to black amphibolite bodies are common in the psammites and also occur as xenoliths in the thick Strath Halladale Granite Complex (see below). They vary from thin sheets up to several metres in length to mappable lenses up to about 40 m thick that show some slight discordance to the compositional layering in the host psammites. They form part of the Bettyhill Suite of Moorhouse and Moorhouse (1979) (see **Ard Mor** GCR site report, this chapter) and have a penetrative foliation that may well be composite; their intrusion appears to pre-date all the deformation phases. The largest amphibolite bodies in the Strath Halladale Granite Complex are exposed north of Portskerra pier (Figure 6.31). Granite with amphibolite rafts is also exposed in the cliffs of Geodh' Geal to the north-west of Portskerra, where it is strongly jointed and faulted.

Several generations of minor granitic intrusions cut the psammites and amphibolites. The earliest of these are white granodiorites that occur as concordant and discordant sheets, locally with diffuse margins. They have been termed the 'Badanloch Granite Sheets' farther south in central Sutherland where they are more extensively developed. The granodiorites comprise quartz, sodic plagioclase (oligoclase), biotite and ilmenite/magnetite with large K-feldspars. The K-feldspar phenocrysts generally overgrow a pervasive 'ghost' foliation in the granodiorites that is defined by aligned biotite flakes and locally by ribbon quartz. However, at Sgeir Ruadh a fine-grained, foliated granodiorite contains potash-feldspar phenocrysts wrapped by the foliation. The larger granodiorite bodies have biotite schlieren and generally disoriented small xenoliths of calc-silicate pods and amphibolite – the more refractory lithologies of the host gneisses. More rarely there are indurated psammite inclusions up to several metres long, for example at Sgeir Ruadh. Numerous micro-granite veins cut this granodiorite and its various inclusions. It has been suggested that the diffuse patches of granodiorite reflect localized saturation by sodic fluids and the discordant sheets represent local mobilization of partial-melt material (Read, 1931; Brown, 1971). Small asymmetrical folds that verge towards the north-west post-date the early granodioritic veins. Fold axes plunge moderately towards the SSE and related axial planes dip some 35°–40° to the south-east. An axial-planar biotite foliation is only pervasive in the semipelitic layers. Larger-scale examples of these folds are present at Rubha Ghoiridh (NC 8730 6648).

A network of pink- or red-weathering grano-diorite to leucogranite veins of the Strath Halladale Granite Complex cross-cuts the white granodiorites. The pink granite veins increase in abundance towards the main Strath Halladale granite sheet, which is exposed near Portskerra pier. The veins comprise up to 50% of the rock volume, but individual veins rarely exceed 1 m in thickness. Shears and disharmonic open folds of more than one generation affect these granitic veins. For example, at NC 8823 6540 a late granite vein has been injected along a shear that offsets older veins. The late granite has an internal penetrative fabric, parallel to the host shear-zone. Highly discordant aplitic granite veins and rare quartzofeldspathic pegmatites cross-cut the pink granite vein network. Several generations of these late intrusions can occur in a single exposure; again they may be locally injected along shears that offset earlier veins.

A major sheet of the Strath Halladale Granite Complex is well exposed on both sides of Portskerra pier and also north-west of Portskerra (NC 871 663) (Figure 6.31). It is composed of pink, locally foliated biotite granite with prominent potash-feldspar megacrysts up to 3 cm long. The penetrative foliation is confined to narrow zones and wraps around the feldspar augen; it is itself locally tightly folded at NC 8819 6547. There are angular gneiss xenoliths and amphibolite rafts as well as late aplitic granite veins in the granite.

On the foreshore at Sgeir Ruadh, Strath Halladale granite is overlain unconformably by a veneer of Middle Devonian basal breccio-conglomerate, overlain in turn by buff coarse-grained sandstone. The strata mostly dip gently northwards and form cliffs up to about 30 m high. An uneven unconformity between the gneissose psammites and Devonian sandstone and breccio-conglomerate is well exposed at Port Skerra (NC 878 664). The breccio-conglomerate is matrix-supported with abundant granite and psammite clasts and subsidiary fine-grained sandstone clasts, in a coarse matrix resembling disaggregated granite. Farther west at NC 8731 6631 fawn to buff sandstone beds are draped over a small crag of psammite. The sandstones form laterally discontinuous beds up to 1 m thick, and basal breccio-conglomerate occurs in lenses up to 3 m thick. Sedimentary structures in the sandstones include ripple marks (indicating currents from the west), low-angle planar cross-bedding, pebble beds and dewatering structures.

Faults and parallel jointing control coastal geomorphological features including natural arches, great gashes in steep cliffs and inlets such as Geodh' Glas (NC 8755 6645). A series of NE-trending faults can be seen cutting granites in the cliffs to the north-west of Portskerra. Where faulted, the granite is friable, altered and commonly highly fractured. A small fault trending approximately east is exposed at NC 8770 6663, where an apparent downthrow of 10 cm to the south can be measured. This fault produces a 1 m-thick shatter zone where it cuts Devonian strata and also defines a gully in the underlying gneissose psammites. The psammites of Rubha Bhrà are strongly jointed with a dominant NE-trending set that dips moderately towards the north-west. Interplay between layering and joint planes breaks up the gneisses into rectangular blocks about 1 m$^2$ in cross-section. Individual joints are open, and locally they control the detailed shape of the coastline.

## Interpretation

Early metamorphic event(s) produced the gneissic fabric in the Moine rocks, defined by the sub-parallel quartzofeldspathic segregations and the early biotite foliation. Isotopic studies on the Moine rocks of Sutherland suggest that several early high-grade metamorphic events affected the succession. These may date back as far as 870 Ma (Friend *et al.*, 1997), but more probably occurred in the Neoproterozoic between 830 Ma and 790 Ma (Strachan *et al.*, 2002b) and around 470–460 Ma (Friend *et al.*, 2000). The white Badanloch granodiorite sheets were emplaced after these metamorphic events and were followed by the injection of the pink to red granitic veins and sheets of the Strath Halladale Granite Complex, dated at *c.* 426 Ma (Kocks *et al.*, 2006). This latter magmatism accompanied the generation of the Scandian fold–thrust sequence and associated amphibolite-facies regional metamorphic overprint. Various small aplitic and pegmatitic granite veins were intruded after the folding, in part associated with minor shear-zone development. Dallmeyer *et al.* (2001) obtained a hornblende $^{40}Ar$-$^{39}Ar$ age of 404 Ma for amphibolite at Rubha Bhrà, which they interpreted as dating uplift and cooling. This was consistent with muscovite and hornblende $^{40}Ar$-$^{39}Ar$ cooling ages of 423–410 Ma from farther west in the Naver and Swordly nappes.

The unconformably overlying Mid-Devonian sediments were laid down in a fluvial to lacustrine desert environment with coarse sediments flushed out over highly irregular basement topography. The main rock-type is mature quartz sandstone, with local cross-bedding, which contains lenses of breccio-conglomerate in the basal 3 m. The basal breccio-conglomerate spreads have variable thickness, particularly where they infill hollows in the existing landscape. They are dominated by locally derived clasts, for example at Sgeir Ruadh, and have been interpreted as basal lags to channel fills (Fletcher and Key, 1991).

The post-Devonian faulting and strong and regular jointing seen at Sgeir Ruadh is possibly associated with major faulting that controlled the extensional development of the major offshore Mesozoic sedimentary basins. A major fault, the Strath Halladale Fault, lies a few kilometres east of the site. Its trace strikes approximately north along Strath Halladale and into Melvich Bay, but some 6 km offshore the trace curves to strike north-east. Here, it forms the bounding fault to Permo–Triassic sedimentary sequences, downthrowing units to the east or south-east. By analogy with the Strathy and Bridge of Forss faults, it probably has both a Devonian and Permo–Triassic movement history, linked to basin deposition.

## Conclusions

The Sgeir Ruadh site is of importance because it demonstrates the regional migmatitic character of the Moine rocks of northern Sutherland, the nature of the early-formed Bettyhill Suite mafic intrusions, and their relationships to the Strath Halladale Granite Complex, a series of granitic sheets and veins of Late Silurian age. An early migmatitic event affected the Moine psammitic rocks and is characterized by quartzofeldspathic segregations mostly parallel to the gneissic layering. The migmatization may be linked to a Neoproterozoic-age Knoydartian event, as seen farther west in the A' Mhoine Nappe, or alternatively, the metamorphism and migmatization may reflect the Early Ordovician Grampian Event. White foliated granodiorite veins and irregular bodies, part of the more-widespread Badanloch Granite Sheets, are taken to be Ordovician in age. They are cut by pink to red granite sheets and veins that total several hundred metres in thickness, and form part of the Silurian-age Strath Halladale Granite Complex. The granite sheets are again foliated and were intruded during the later phases of the Scandian Event.

An angular unconformity between the various metamorphic and igneous rocks and overlying strata of the Middle Devonian Old Red Sandstone is well exposed at the site. The younger sedimentary rocks can be seen to drape over crags of gneissose psammite. A basal breccio-conglomerate is made up of eroded material from the immediately underlying bedrock, either completely broken down to a coarse-grained gravel, or into angular fragments up to boulder size that are supported in the gravel matrix. The overlying sandstones are typical of Old Red Sandstone material laid down by rivers that flowed across the strongly eroded Moine 'basement' in the desert landscape. The beds were deposited marginal to the main Orcadian lake basin succession that developed farther north-east.

A number of small faults that may be related to the development of the sedimentary basins developed offshore can be examined at the site. The faults have different expressions in the different lithologies. Fault breccias occur in the Devonian sandstones and conglomerates; the granites are intensely weathered along fault lines; and gullies have formed in the harder, but more-brittle Moine psammites.

# DIRLOT CASTLE (ND 123 484–ND 130 488)

*E.K. Hyslop*

## Introduction

Dirlot Castle in Caithness lies close to the western margin of the former Orcadian Basin, represented by a major sequence of Middle Devonian lacustrine and fluvial sedimentary rocks up to 6 km in thickness. At the GCR site small inliers of metamorphic basement rocks attributed to the Moine succession, cut by granitic veins, protrude through the Devonian Old Red Sandstone strata. This allows a glimpse of the rocks underlying the Orcadian Basin, and illustrates the nature of the unconformable contact at the base of the dominantly lacustrine sequence. The significance of the locality is long established. It was visited by Sir Roderick Murchison following the suggestion of the Caithness geologist Robert Dick (Murchison, 1859), and was subsequently described in detail by Crampton and Carruthers (1914), who interpreted it as representing an island within the Orcadian lake. More recently, the Dirlot Castle locality has been interpreted as representative of the marginal facies of a lacustrine system. Donovan (1973) and Parnell (1983) have described algal stromatolites and duricrusts from the site.

## Description

At Dirlot, about 20 km WSW of Thurso, two inliers of basement rocks are exposed in the gorge and banks of the River Thurso (Trewin and Hurst, 1994). The main outcrop is at Dirlot Castle, with a further smaller exposure a few hundred metres to the north-east (Figure 6.33). Murchison (1859) described these rocks as a 'boss of flag-like gneiss', and Crampton and Carruthers (1914) described grey-coloured gneisses aligned at high angles, intruded by numerous granitic veins. These early workers correlated the basement rocks at Dirlot with the metamorphic Moine rocks of the North-west Highlands.

The metamorphic rocks are best exposed in the river cutting immediately below the castle and churchyard (Figure 6.33). Here, interlayered gneissose semipelite, micaceous (biotite-rich) psammite and subsidiary feldspathic quartzite are steeply dipping and deformed by open folds with subhorizontal NW–SE-trending axes. Quartz segregations parallel to the gneissosity are

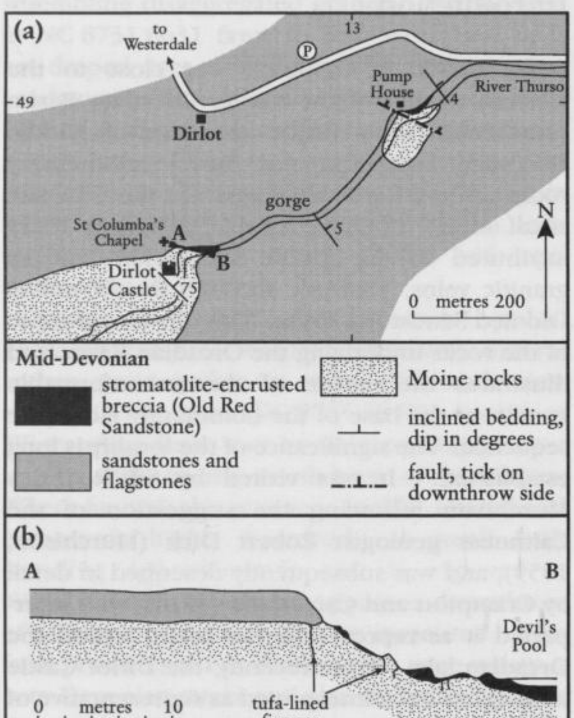


**Figure 6.33** Geological map of Dirlot Castle with sketch section through gorge. Based on Donovan (1973) and Trewin and Hurst (1994).

common. The rocks are intruded by numerous, unfoliated, medium- to coarse-grained granite and aplitic microgranite veins. The granite is highly reddened, the colouration increasing with weathering towards the contact with the overlying sedimentary rocks. In thin section, the feldspars are largely altered to fine-grained white mica (sericite), and the biotite is highly chloritized.

The basement rocks are overlain by a breccia conglomerate up to 60 cm thick, composed of pebble- to cobble-size clasts of the underlying Moine and granitic lithologies. The unconformity surface is irregular, with a shallow easterly dip that steepens to the east. The clast lithologies and their angular and unsorted nature suggest a locally derived scree-like deposit (Donovan, 1973). Occasional rounded pebbles indicate an additional source of more actively worked sedimentary material.

The breccia is cemented by carbonate, which in places takes the form of algal stromatolites. The stromatolites occur as clast coatings of concentrically layered rusty-brown ferroan dolomicrite, with minor calcite spar infilling irregular cavities. Individual stromatolite colonies are hemispheroids 5–15 mm across that are typically linked to form an irregular mat. Stromatolite coatings are perhaps best developed on the largest clasts, where they reach up to 8 cm in thickness. Fissures up to 2 m deep are seen in the basement rocks that contain stromatolitic encrustations. Sparse flakes of stromatolite are present in the breccia.

The breccia passes rapidly upwards into purplish and grey siliceous and micaceous thin-bedded alluvial sandstones in which stromatolites are absent. The sandstones are overlain by typical dark-grey 'flaggy' siltstones of the Orcadian Middle Devonian lacustrine succession, which are well exposed in the upper parts of the river gorge at the Dirlot Castle site.

## Interpretation

The rocks at Dirlot Castle represent a local basement high within the Mid-Devonian Orcadian lacustrine basin. These would probably have been small islands within the Orcadian lake, developed close to its margins. Mid-Devonian lacustrine breccias and sandstones unconformably overlie metamorphic and igneous basement lithologies typical of the Moine assemblage of east Sutherland. The basement rocks are similar to the rocks exposed in Strath Halladale some 20 km to the west. The outcrop of basement rocks implies that Moine lithologies extend from the western edge of the Orcadian Basin continuously eastwards under the Lower and Middle Old Red Sandstone sequences at least as far as Dirlot Castle, a distance of some 10 km.

The relationship between the crystalline basement rocks and the overlying sediments provides an insight into the sedimentary processes that occurred at the lake margins. The sharp relief, angularity and local derivation of clasts, and preservation of detrital stromatolite flakes in the breccia deposits all indicate a relatively low-energy environment. The presence of stromatolites suggests warm shallow-water conditions, with the minor fragmentation caused by relatively low-energy wave action or periodic dessication. The thicker coatings on the larger clasts indicate their stability. The fluviatile sandstones that overlie the sequence further indicate the marginal nature of the environment.

## Conclusions

The exposures at Dirlot Castle are an example of a Devonian lake-margin setting where both the sedimentary processes and the nature of the crystalline basement underlying the basin can be discerned. The basement rocks are gneissose Moine semipelites and psammites, which are folded and cut by numerous granitic veins and pods. Mid-Devonian breccias and sandstones unconformably overlie the Moine rocks and granitic intrusions, which show limited reddening and alteration. The thin lenticular breccias are interpreted as scree deposits whereas the sandstones are probably fluvial. The breccia is cemented by carbonate (normally dolomite) that locally forms concentric layers that coat individual breccia clasts. The carbonate was deposited by algal colonies, termed stromatolites, that lived in shallow water in the brackish Orcadian lake. Similar marginal facies are exposed in several other localities in the Orcadian Basin (e.g. see the Red Point and Yesnaby GCR site reports in *The Old Red Sandstone of Great Britain* GCR Volume; Barclay *et al.*, 2005), but at Dirlot Castle the nature of the Moine basement and its role as an upstanding island in the Orcadian lake are very clearly seen.

# BEN KLIBRECK (NC 574 343–NC 585 299)

*R.A. Strachan*

## Introduction

The Ben Klibreck site is an important area for the study of basement–cover relationships and ductile thrust tectonics within the Caledonian orogenic belt of northern Scotland (Moorhouse, 1977; Barr *et al.*, 1986; Strachan and Holdsworth, 1988). The site is also of historical importance because of its contribution to early studies of migmatites (Read, 1931). West of Ben Klibreck, psammites and semipelites of the Morar Group (Moine) are interfolded with highly reworked orthogneisses broadly correlated on lithological and geochemical grounds with the Lewisian Gneiss Complex of the Caledonian Foreland (Read, 1931; Soper and Brown, 1971; Moorhouse, 1977; Barr, 1983; Strachan and Holdsworth, 1988; Friend *et al.*, 2008). Eastwards and structurally upwards, these Lewisianoid gneisses are overlain by Moine psammitic and semipelitic gneisses that contain thin, highly tectonized slices of similar Lewisianoid basement orthogneisses. Three main ductile thrusts can be identified, the Naver, Torrisdale and Swordly thrusts. The upper slopes of Ben Klibreck are composed mainly of migmatitic Moine semipelitic and pelitic gneisses of the Bettyhill Banded and Loch Coire formations. Granites and pegmatites intrude this structural succession and become progressively more-abundant eastwards in the site area, particularly within the overlying migmatitic Moine rocks (Figure 6.34).

Differing opinions have been expressed on the nature of the boundaries between the various Moine rocks and on the origin of, and relationships between, the migmatites, granites and pegmatites. Read (1931) considered that there was a transition from unmigmatized to migmatitic rocks, and Soper and Brown (1971) concluded that this represents a prograde but inverted metamorphic gradient. Brown (1967, 1971) interpreted the geochemistry of the migmatites to indicate that they formed *in situ* as a result of sodium metasomatism, with the granites and pegmatites providing channel ways for the infiltration of sodic fluids. Contrasting mechanisms proposed for the formation of these

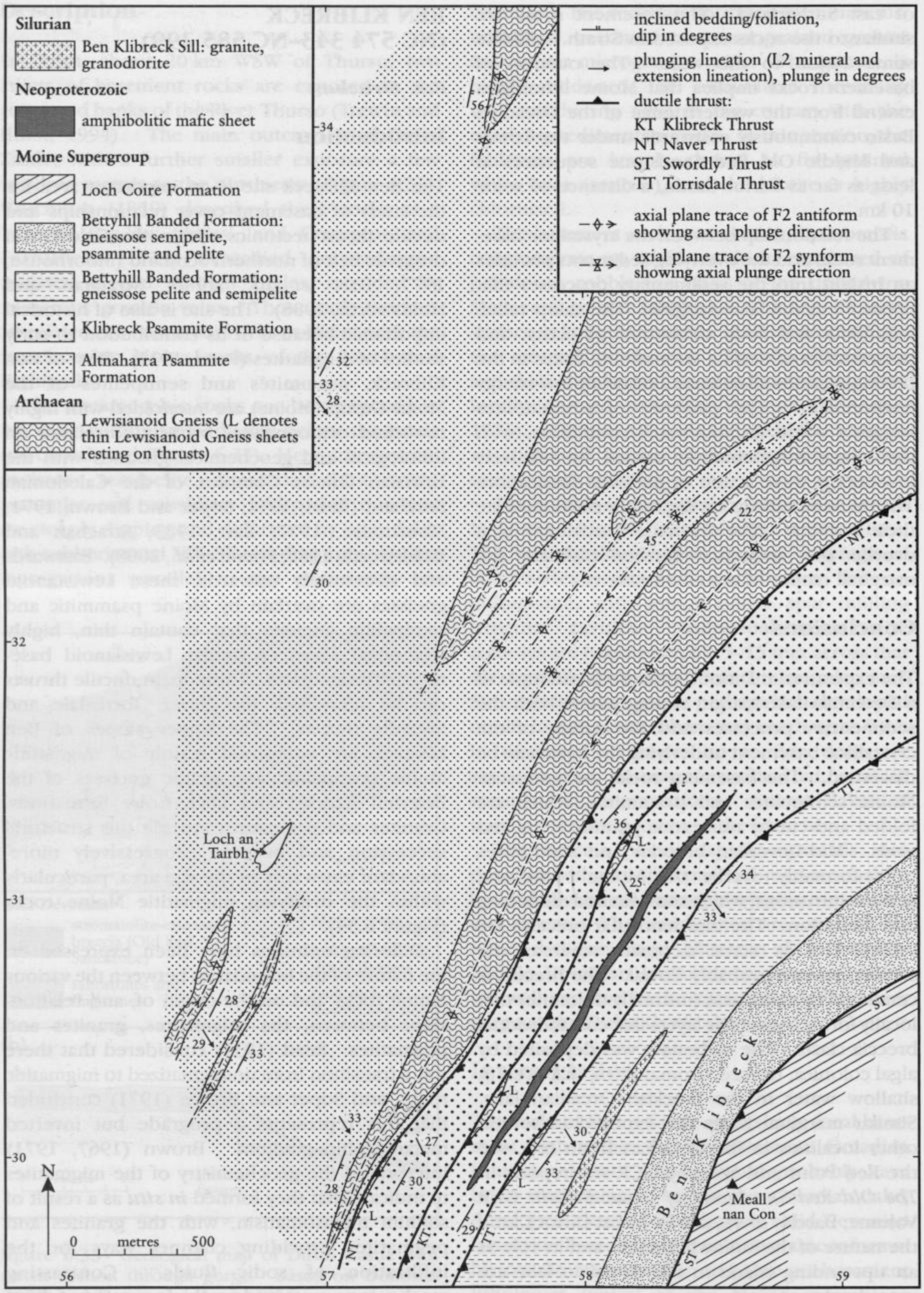


Figure 6.34 Geological map of the Ben Klibreck area.

and related migmatites in Sutherland include subsolidus segregation (Barr, 1985) and partial anatexis (Burns, 1994; Watt *et al.*, 1996). The present consensus view is that Caledonian displacement along the ductile Naver Thrust emplaced migmatitic gneisses onto unmigmatized rocks giving the apparent metamorphic inversion, and that the granites and pegmatites were intruded at various stages during and following thrusting (Moorhouse, 1977; Barr, 1983, 1985; Strachan and Holdsworth, 1988). If the Moine migmatites are mainly Neoproterozoic in age (cf. Barr *et al.*, 1986), then a genetic relationship between these and the Caledonian granites and pegmatites is clearly unlikely. U-Pb zircon isotopic data indicates that the Moine migmatites in Sutherland may well be Caledonian in age (Kinny *et al.*, 1999), and hence a re-appraisal of the petrogenetic relationship between the migmatites, granites and pegmatites is appropriate.

## Description

The site area stretches from the low undulating peaty ground on the eastern side of Strath Vagastie to the steep W-facing rocky slopes of Ben Klibreck up to its summit at Meall nan Con (961 m). The low undulating ground that lies west of Ben Klibreck is underlain mainly by Moine psammites but includes several Lewisianoid gneiss inliers (Figure 6.34; Moorhouse, 1977; Strachan and Holdsworth, 1988). The bedding and regional foliation within these rocks both dip gently to moderately to the ESE. The most extensive outcrops of Lewisianoid rocks form part of the Naver Inlier that thickens markedly to the north. The main lithology is a layered felsic and mafic orthogneiss characterized by the alternation of quartz-plagioclase feldspar and hornblende-rich (locally with garnet and biotite) layers normally on a scale of 0.5–2 cm (Figure 6.35). With increasing tectonic strain, the mafic gneiss takes the form of pods and layers of hornblende-biotite schist. Small pods of ultramafic lithologies are present locally, and include hornblendite (e.g. at NC 563 304), and talc-tremolite rocks with serpentine (e.g. at NC 591 336).

The Moine rocks in the western part of the site area belong to the Altnaharra Psammite Formation (Moorhouse, 1977), part of the Morar

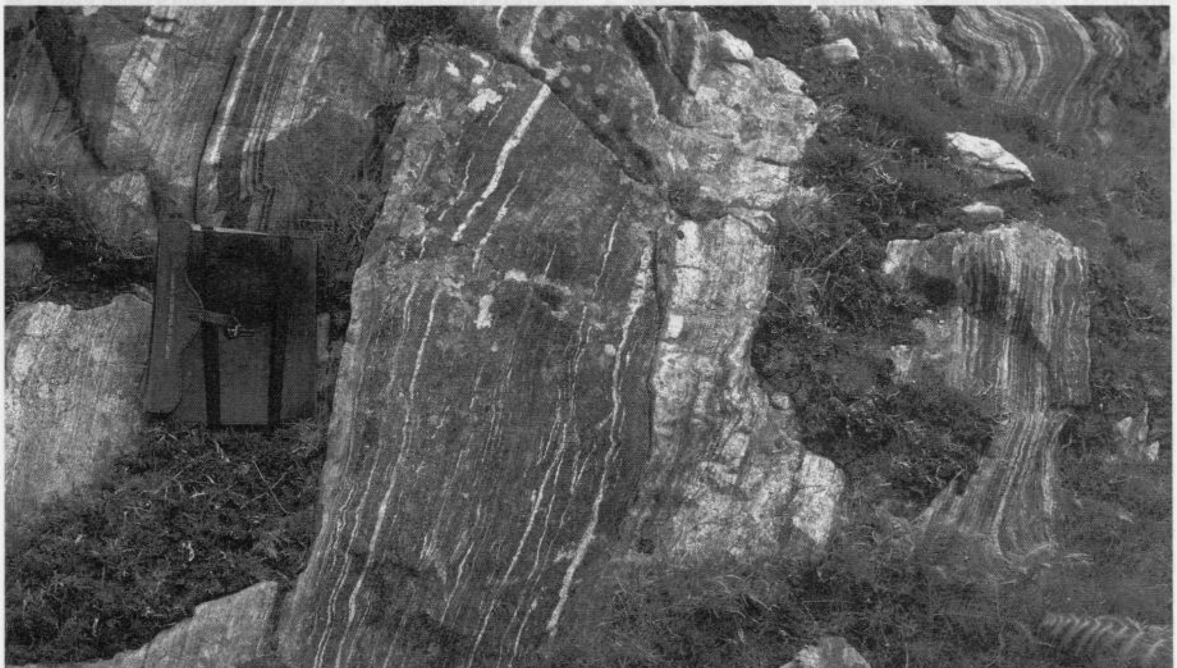

**Figure 6.35** Banded felsic and mafic Lewisianoid orthogneiss of the Naver Inlier at NC 584 325. The map case is 32 cm high. (Photo: R.A. Strachan, BGS No. P580516, reproduced with the permission of the Director, British Geological Survey, © NERC.)

Group (see Figure 6.2). They are mostly pale-grey to pink, medium-grained, flaggy to blocky, thinly bedded, feldspathic and micaceous psammites with subsidiary schistose garnet-biotite semipelite and pelite interbeds and some striped siliceous psammite units. The layering in the psammites is generally modified bedding, but sedimentary structures are rare. In places, the psammites contain 1–5 mm-thick layers of quartz, plagioclase and microcline clasts. Pods and ribs of pale-grey, hornblende-garnet-bearing calc-silicate are also present (e.g. at NC 560 307), indicating that the rocks have been subject to at least lower amphibolite-facies metamorphism. Lensoid masses of variably foliated amphibolite, up to 5 m thick, occur locally (e.g. NC 567 308) and probably represent deformed and metamorphosed basic intrusions. These mafic sheets are a southerly extension of the Ben Hope Suite. Contacts between the Moine and Lewisianoid units are sharp and normally concordant, but are not apparently marked by abnormally high tectonic strains.

Two phases of deformation, D1 and D2, have been identified in the Moine. The dominant structures are of D2 age and are represented by tight to open folds. Many of these have a reclined attitude and F2 fold axes lie parallel to a SE- to SSE-plunging L2 mineral and extension lineation. Shear bands and asymmetrical quartz-feldspar augen indicate a general top-to-the-NW direction of tectonic transport parallel to L2. F2 folds display large- and small-scale curvilinear hinge geometries characteristic of 'sheath folds' (Strachan and Holdsworth, 1988). A bedding-parallel S1 mica fabric passes around the hinge zones of the F2 folds, within which the axial-planar S2 fabric is seen as a tight crenulation cleavage in semipelitic and pelitic units. Minor F1 folds are rare. Prominent folds deform the western boundary of the Naver Inlier and these are designated F2 (Figure 6.34). The three smaller Lewisianoid inliers that lie west of Ben Klibreck occupy the cores of major F2 antiforms that have been modified locally by ductile thrusts developed during folding (Strachan and Holdsworth, 1988). In the Lewisianoid gneisses a pervasive hornblende lineation orientated sub-parallel to L2 in the Moine rocks is commonly seen.

A major D2 ductile thrust, the Naver Thrust, is located along the base of the steep western slope of Ben Klibreck (Figure 6.34). This was first identified here by Moorhouse (1977) and forms the type locality. In the north of the Ben Klibreck site, this thrust is marked by a sharp contact between Lewisianoid rocks (Naver Inlier) and the overlying, coarse-grained gneissose psammitic to semipelitic Klibreck Psammite Formation (Figure 6.2; Strachan and Holdsworth, 1988). Traced southwards, the easternmost 'arm' of the Lewisianoid outcrop diverges from the Naver Thrust so that a very narrow strip of Altnaharra Psammite intervenes (Figure 6.34). Here, a thin allochthonous slice of Lewisianoid gneisses lies along the thrust plane. F2 folds within the Altnaharra Psammite and the Naver Lewisianoid rocks progressively tighten towards the thrust, and for 20–30 m below the thrust the Moine and Lewisianoid rocks exhibit an intense blastomylonitic S2 schistosity sub-parallel to the thrust plane.

The Moine rocks of the Klibreck Psammite Formation are compositionally similar to the Altnaharra Psammite Formation. However, they are noticeably coarser-grained (*c.* 2 mm vs *c.* 1 mm grain diameter) and contain numerous concordant quartz-feldspar segregations, features absent in the Moine rocks west of the Naver Thrust. The precise metamorphic grade is uncertain but comparison with other Moine gneisses suggests they were deformed and metamorphosed under middle amphibolite-facies conditions (Barr, 1983). The gneissose fabric, termed 'S1', is deformed by attenuated, tight to isoclinal F2 folds whose axial plunge varies from gently to the ESE to gently to the SSW. D2 linear fabrics are rather weakly developed by comparison with those present west of the Naver Thrust; this probably results from continued grain-size coarsening and annealing within these higher-grade rocks during and following D2 deformation. Two sheets of Lewisianoid gneisses outcrop along strike from each other approximately halfway up the north-western slope of Ben Klibreck (Figure 6.34). Similar Moine lithologies occur on either side of these inliers, suggesting that they could be occupying fold cores. However, they occur at the same structural level as the ductile Klibreck Thrust (D2) identified some 3 km farther south (Strachan and Holdsworth, 1988). Hence, it seems more likely that they are allochthonous sheets marking the northward extension of this structure. The Klibreck Psammite Formation is confined to the

Naver Thrust Zone and hence is equivalent to the Druim Chuibhe Psammite Formation farther north (see **Aird Torrisdale** GCR site report, this chapter).

The Klibreck Psammite Formation is overlain tectonically on the western slopes of Ben Klibreck by the Bettyhill Banded Formation, which comprises migmatitic semipelitic, pelitic and striped psammitic gneisses with small calc-silicate pods, with lenticular garnetiferous amphibolite bodies (Figure 6.34). The lower contact of the Loch Coire Formation is a major D2 ductile thrust, the Torrisdale Thrust, which has been mapped southwards from the north coast (British Geological Survey, 2004c; see **Aird Torrisdale** GCR site report, this chapter). Barr *et al.* (1986) mistakenly correlated this structure with the Swordly Thrust. The Torrisdale Thrust is marked by a sharp contact between striped psammite and semipelite (Klibreck Psammite Formation) and gneissose psammite (Bettyhill Banded Formation) along which discontinuous slices of mafic and felsic Lewisianoid gneisses occur. The lower parts of the Bettyhill Banded Formation carry a strongly blastomylonitic layering and sparse SSE-plunging F2 tight to isoclinal folds. Sub-parallel L2 lineations are once again weak, owing to the strong syn- to post-D2 recrystallization and grain-size coarsening. The migmatitic layering and early isoclinal folds (F1?) are both deformed by the F2 folds. The local preservation of pyroxene and brown hornblende within amphibolite lenses and pyroxene-bytownite assemblages in calc-silicate lenses indicates that the rocks have undergone middle amphibolite-facies metamorphism (Barr *et al.*, 1986; Strachan and Holdsworth, 1988).

Above the Bettyhill Banded Formation lies the Swordly Thrust, whose trace just clips the summit of Ben Klibreck, Meall nan Con (961 m). Overlying the thrust are migmatitic pelites and semipelites of the Loch Coire Formation, containing biotite, muscovite and garnet. Only minor interbanded psammite units are seen in this lower part of the unit. Quartz and quartz-feldspar segregation veins and pods are abundant in these coarsely foliated gneissose rocks, and leucotonalitic and granitic veining and patches are also present.

The Moine rocks of the Ben Klibreck site area are intruded by discrete sheets of granite (*sensu lato*) and pegmatite. These intrusions are generally absent 1–2 km west of the Naver Thrust, but become progressively more-common eastwards until they are locally abundant within the Klibreck Psammite, Bettyhill Banded and Loch Coire formations. Barr (1985) divided these intrusions into three 'suites' on the basis of their structural relationships. The earliest is represented by a series of subconcordant, pink granitic 'sills'. These range from 10 cm to 30 m in thickness and are clearly intrusive, with disorientated xenoliths and pegmatitic apophyses that cross-cut the bedding in the adjacent country rocks. The most prominent is the Ben Klibreck Sill, a pink biotite granite and granodiorite with hornblendic dioritic patches, which crops out within the Klibreck Psammite Formation (Figure 6.34). Kinny *et al.* (2003b) obtained U-Pb SHRIMP ages from zircons and U-Pb TIMS ages from titanites from the Klibreck Sill. Inherited zircon cores gave ages ranging from *c.* 1200 Ma to 1800 Ma, but the rims gave a $^{206}Pb$-$^{238}U$ age of 420 ± 6 Ma, taken as the age of intrusion. Titanite ages of 416 ± 3 Ma overlap the zircon rim ages. These intrusions cut F2 folds of bedding but carry a penetrative L–S fabric defined by quartz ribbons and feldspar augen and which is parallel to S2. Emplacement is interpreted as syn- to late-D2. They are normally granites or granodiorites and comprise plagioclase ($An_{20}$–$An_{32}$), microcline, quartz and biotite with accessory hornblende, titanite, magnetite and zircon. The second 'suite' is represented by a series of slightly discordant granitic and pegmatitic granite veins, which range from a few centimetres to a few metres in thickness and have generally N-dipping contacts. They consist of approximately equal proportions of quartz, microcline and plagioclase. They contain a weak S2 fabric, defined by quartz ribbons that wrap perthite and antiperthite porphyroclasts; intrusion probably occurred during the late stages of D2. Finally, very coarsely pegmatitic (several centimetres grain size), graphic-textured, quartz-albite-microcline leucogranites showing little or no internal deformation, cross-cut all folds and foliations. They were evidently emplaced after D2 deformation had ceased. The first and second of these intrusive suites probably represent parts of one essentially continuous phase of syn-D2 magmatism. Some intrusions are peraluminous and may have formed from melting of Moine metasedimentary rocks or parts of the Lewisianoid basement, whereas the more-granodioritic members have normal I-type mineralogies.

## Interpretation

The site contains three features that make it particularly significant:

1 variable basement–cover relationships;
2 a major ductile thrust zone associated with the emplacement of high-grade, migmatitic Moine gneisses onto lower-grade, non-migmatitic Moine rocks;
3 syn- to post-tectonic Caledonian granitic rocks emplaced during and after ductile thrusting.

The Lewisianoid basement rocks occur in two distinct structural settings. The basement west of the Naver Thrust occurs in the cores of F2 antiforms as a series of para-autochthonous inliers. The absence of high-strain tectonic fabrics along the contacts with the Moine psammites suggests that these contacts are modified unconformities (Strachan and Holdsworth, 1988). The gneissic layering characteristic of the Lewisianoid inliers is a relic of the Archaean and/or Proterozoic high-grade metamorphic events that affected these basement rocks prior to deposition of the Moine sediments. The Lewisianoid inliers east of the Naver Thrust are allochthonous sheets that apparently rest on ductile thrusts, but their upper contacts may also represent modified Moine–Lewisianoid unconformities.

Read's (1931) conclusion that the Ben Klibreck section represents an eastward transition into migmatized rocks requires revision in the light of the recent research. There is a consensus that the junction between gneissose and non-gneissose Moine rocks is a sharp lithological boundary, the Naver Thrust, which is associated with a zone of blastomylonites typical of high tectonic strains. Structural analysis indicates that NW-directed D2 ductile thrusting of high-grade migmatitic Moine rocks onto lower-grade, unmigmatized Moine rocks was broadly synchronous with widespread F2 interfolding of Lewisianoid and Moine rocks in the footwall of the thrust (Strachan and Holdsworth, 1988). The Naver Thrust has been traced to the north coast of Sutherland (Moorhouse and Moorhouse, 1983) and extends south to near Golspie, where it is concealed beneath the Old Red Sandstone cover (Figure 6.2). It may represent the northern continuation of the Sgurr Beag Thrust, which can be traced north from Inverness-shire and Ross-shire to the Dornoch Firth (Barr *et al.*, 1986; Strachan and Holdsworth, 1988). However, correlations between the Moine rocks of the Naver Nappe and overlying Sutherland nappes with Morar Group and Glenfinnan Group sequences farther south remain problematical. Thus, the east Sutherland Moine rocks, structurally derived from some considerable distance to the east (at least tens of kilometres), are viewed here as discrete but separate parts of the Moine succession (see also Strachan *et al.*, 2002a).

The SE- to SSE-trending L2 mineral and extension lineation developed within the Moine and Lewisianoid rocks of the Ben Klibreck area is traceable westwards across central Sutherland to the Moine Thrust Belt (Figure 6.4; Soper and Brown, 1971). D2 ductile thrusting and folding at Ben Klibreck is hence mainly Caledonian (Ordovician–Silurian) in age. The age of earlier events within the Moine rocks is uncertain. Barr *et al.* (1986) suggested that migmatization of the Moine rocks above the Naver Thrust occurred during the Neoproterozoic partly on the basis of correlation with migmatitic Moine rocks of the Glenfinnan area (see **Fassfern to Lochailort Road Cuttings** GCR site report, Chapter 8). These authors were also influenced by an Rb-Sr isochron age of $649 \pm 30$ Ma for the post-tectonic Strath Halladale granite (M. Brook in Pankhurst, 1982), which intrudes migmatitic Moine rocks in east Sutherland and Caithness (McCourt, 1980). However, recent TIMS U-Pb zircon age dating has revised the age of intrusion to $426 \pm 2$ Ma (Kocks *et al.*, 2006). This is in accord with similar Late Silurian ages for the emplacement of the Strath Naver and Vagastie Bridge granites (Kinny *et al.*, 2003a), suggesting that sheeted granite bodies were intruded coeval with the later phases of the Scandian Event. It also fits with the Early Ordovician (Grampian) age inferred for Moine migmatites along strike from Ben Klibreck on the north Sutherland coast (Kinny *et al.*, 1999).

The spatial concentration of granites and pegmatites within the Naver Thrust Zone combined with the field evidence, which indicates a syn- to post-D2 (i.e. late Scandian) age of emplacement, imply that this structure exerted a strong control on granitic intrusion (Strachan and Holdsworth, 1988). Read (1931), Brown (1967, 1971) and Soper and Brown

(1971) considered that there was a close genetic relationship between migmatization of the Moine rocks and formation of the various granites and pegmatites. Brown (1967, 1971) interpreted the geochemistry of the migmatites to show that they formed *in situ* as a result of sodium metasomatism, with the granites and pegmatites providing channelways for infiltration of sodic fluids. Irrespective of the precise origin of the migmatites, a genetic relationship with the Late Silurian-age granites and pegmatites is clearly unlikely if the Sutherland migmatites are of Neoproterozoic or Early Ordovician (Grampian) age as suggested by Kinny *et al.* (1999). Only some of the earlier patchy granitic and leucotonalitic bodies that are prominent in the Badanloch and Strath Halladale areas appear to relate to the Early Ordovician event.

## Conclusions

The site is of national importance because it includes the type locality for the Naver Thrust, a regional-scale ductile thrust within the Caledonian belt of northern Scotland. NW-directed displacements along the Naver Thrust emplaced high-grade, migmatitic Moine semi-pelitic gneisses onto lower-grade, non-migmatitic, generally psammitic Moine rocks. Ductile thrusting was accompanied by widespread tight to isoclinal folding and formation of large-scale sheath-folds in the footwall. Inliers of Lewisianoid gneiss basement occur in two contrasting settings: as thin, discontinuous allochthonous sheets, which rest on ductile thrusts in the hangingwall of the Naver Thrust, and as para-autochthonous antiformal fold cores in the footwall. The Naver Thrust also exerted a strong structural control on the emplacement of a variety of Late Silurian-age granites and pegmatites, intruded during and immediately following thrusting. The limited geochemical data available is consistent with formation of the granites and pegmatites by melting or partial assimilation of Moine rocks and possibly also of some Lewisianoid basement. Zircon dating has shown that movement on the Naver Thrust occurred in the Late Silurian (Scandian) event of the Caledonian Orogeny. The migmatites seem to relate only to the Grampian (?D2) or possibly earlier Neoproterozoic events, whereas the main granite bodies were intruded towards the end of the subsequent Scandian Event at *c.* 425 Ma.

# OYKEL BRIDGE (NC 383 010)

*N.J. Soper*

## Introduction

The Oykel Bridge section exposes some of the finest examples of mullion structures to be seen in Britain. Wilson (1953) described mullions as 'clustered columns made of the local country rock', which here are Moine psammites belonging to the Altnaharra Psammite Formation (Morar Group). The geometrical relationship of the mullions to regionally developed minor structures was essentially established during the primary survey of this part of the Caledonides, but how these structures, and particularly the regional 'stretching lineation' that is parallel to the mullions, relate to the broad-scale evolution of the orogen became a major controversy. The site has played an important historical role in the development of ideas relating small-scale structures and microfabrics to regional tectonics.

In structural terms, mullions are a type of linear structure, commonly associated with, and parallel to, fold axes and mineral alignments. The terms 'mullion' and 'rodding structure' were initially used indiscriminately, but Wilson used examples from Oykel Bridge and Ben Hutig (see **Ben Hutig** GCR site report, this chapter) to distinguish mullions, columnar structures composed of the country rock, from rods, found in deformed quartz veins and pebbles enclosed within the rock. Wilson differentiated 'fold', 'cleavage' and 'irregular' mullions, as described below. It was recognized from the days of the primary survey that the Moine rocks of Sutherland are characterized by a SE-plunging mineral lineation, roughly normal to the Moine Thrust Belt, and referred to on the geological maps as a 'direction of stretching in schistose rocks'. The mullions, rods and early 'D2' fold axes lie parallel to this regional lineation (Figure 6.4). Read (in Read *et al.*, 1926) thought that the mullions resulted from two deformations, firstly north-east–south-west compression to produce the folding, then north-west–south-east stretching associated with movement on the Moine Thrust, to produce the mullions. This interpretation contains the essence of a major debate that ensued among structural geologists about the relationship of linear fabrics to regional displacement patterns, a fundamental problem that took half a century to resolve.

British structural geologists were at this time much influenced by the German 'symmetrological' school of Sander and others (e.g. Sander, 1930, 1934), which sought to deduce the kinematic (movement) pattern from the geometry and orientations of rock structures and microfabrics. Tectonic axes were defined in terms of a co-ordinate system related to the symmetry of a structure. For example in a fold pair with monoclinic symmetry, '**b**' would be the principal fabric axis (the fold axis or hinge line), '**ab**' the axial surface, and '**ac**' the plane of symmetry (or profile plane) normal to '**b**' (e.g. Wilson, 1961). It was assumed that folds form by displacement parallel to the axial surface and at a right angle to the fold axis, so '**a**' defined the movement direction and '**b**' an axis of rotation. With hindsight this is only one end member of a whole range of geometrical relationships between folding and displacement. It is now known that fold axes form in directions determined by the orientation of bedding in relation to incremental strain at the time of their initiation. Once formed the fold axes can rotate towards the principal extension direction, so there is no simple relationship between fold symmetry and finite strain, or to 'movement'.

Wilson (1953) in his classic description of the Oykel Bridge mullions interpreted them as the products of 'rolling or shearing movements acting at right angles to their lengths', as had Phillips (1937) in his regional microfabric study of quartz c-axis orientations in Moine psammites: they were '**b**'-lineations. Wilson did not accept that the mullions had formed by stretching parallel to their length. Phillips on the other hand appears to have accepted the view of Clough (in Peach *et al.*, 1912) that rodding and similar structures had been subjected to 'pressures from four sides in opposite pairs, leaving constituents to squeeze out...'. Expressed in modern terms of strain, Clough was describing a constriction–extension or cigar-shaped prolate strain ellipsoid, whose principal extension direction was marked by the regional SE-plunging lineation. Both Wilson and Phillips denied that the SE-plunging structures had any relationship to movements on the Moine Thrust, regarding the main tectonic and metamorphic evolution of the Moines (that produced the mullions) as earlier than the Caledonian thrusting, and thus of Proterozoic age.

In contrast, workers in the Moine Thrust Belt such as Read (1931) and Bailey (1935) regarded the SE-plunging linear fabric in the mylonites as marking a north-westerly direction of thrusting, normal to the thrust front: they were '**a**'-lineations. The '**a**'- vs '**b**'-lineation argument reached its ultimate absurdity when Christie (1963) used symmetry alone to infer, quite counter-intuitively, that displacement on the Moine Thrust had been to the south-west, parallel to the thrust front and at right angles to the dominant fold axes and linear structures (including the mullions).

## Description

The mullions are displayed in the gorge of the River Oykel between the new road bridge (NC 3855 0090) and Oykel Falls (NC 3825 0115), about 400 m upstream (Figure 6.36). They are composed of psammites belonging to the Altnaharra Psammite Formation (Morar Group), and form striking columnar structures that plunge downstream to the ESE at about 20° (Figure 6.37a). In the gorge section, the Moine psammites strike ESE and are generally inclined steeply to the SSW; cross-bedding indicates that the beds also young in that direction. The rocks show abundant small- and meso-scale folding and lie on the northerly long limb of a kilometre-scale, tight, asymmetrical, ESE-plunging antiformal F2 fold. The opposing SSE-dipping overturned limb is exposed along the River Einig with the major hinge coincident with the confluence of the rivers Oykel and Einig (Figure 6.36). Note that in the vicinity of Oykel Bridge the beds are inverted and face downwards and the antiform is informally termed the 'Einig Syncline'. The mullions are developed on the steep limb of this fold a short distance from the hinge zone, but are absent from the SE-dipping short limb.

ENE-striking joints provide cross-sections of the mullions. The best developed are 'fold mullions' as defined by Wilson (1953) and are commonly concavo-convex in section (Figure 6.37b). The convex part is a fold closure, the surface often corresponding to a thin pelitic bed that forms a micaceous sheath to the mullion. The internal bedding is sometimes concordant to the outer surface, but often discordant, with the appearance of deformed cross-bedding. The concave segments, of which there may be several, are discordant to internal bedding and are counterparts to the convex closures of

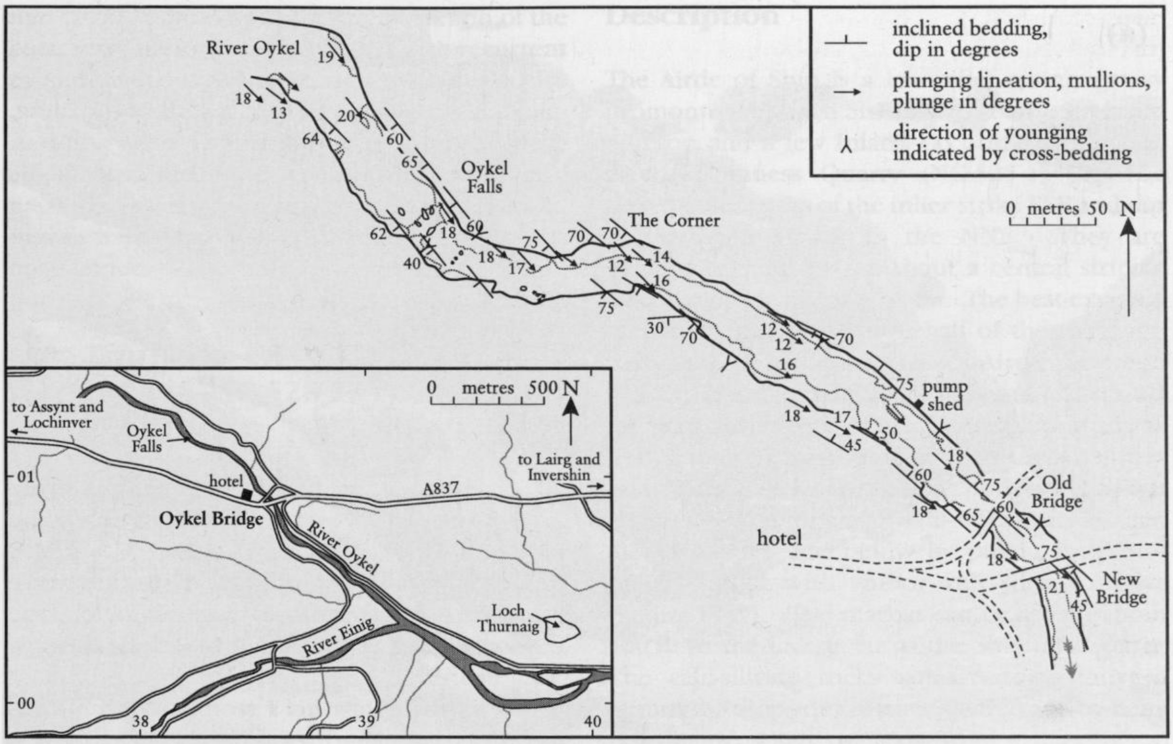


**Figure 6.36** Simplified geological map of the Oykel Bridge area. After Wilson (1953).

adjacent mullions. There are also 'cleavage mullions' in which one or more bounding surface corresponds to a NE-inclined foliation that is presumably associated with the synclinal fold mentioned above. 'Irregular mullions', as described by Wilson (1953) have a very irregular cross-section, possibly constrained by the shapes of adjacent mullions.

There is a well-developed mineral elongation alignment parallel to the axes of the mullions; this is the regional lineation, designated L2 (e.g. Strachan and Holdsworth, 1988). Where a micaceous sheath is developed, commonly it also carries a weak crenulation fabric, oblique to the mullion axis.

## Interpretation

It is now apparent that the early surveyors such as Clough (in Peach *et al.*, 1912) were correct to interpret the regional SE-plunging mineral lineation as marking the principal extension direction of the main deformation to which the Moine rocks had been subjected. The lineation does indeed also correspond with the direction of displacement in the Moine Thrust Belt, with kinematic indicators indicating top-to-the-NW (Holdsworth and Grant, 1990). The regional F2 folds, and the locally developed mullions, were formed within this regional D2 strain/displacement field. Statistical parallelism of the fold axes and the lineation is thought to be due to passive rotation of the axes towards the extension direction, locally giving a sheath-like fold geometry. Rodded pebbles in the A' Mhoine Psammite Formation at Ben Hutig were the subject of a strain study by Wood (1973), who interpreted them as having extremely prolate shapes (but see **Ben Hutig** GCR site report, this chapter).

While this would account for the coincidence of fold-mullion axes with the lineation, and their near-perfect columnar form, the mechanism by which they developed into discrete but interlocking bodies has not been established. It is here suggested that inner-arc space problems associated with the antiformal 'Einig Syncline' at Oykel Bridge, combined with flexural slip on non-parallel surfaces (bedding and cross-bedding) that were deforming within a constrictional strain field, led to the initiation of many small roughly coaxial folds. These folds developed with variably oriented axial surfaces, and eventually 'detached' to form the nested

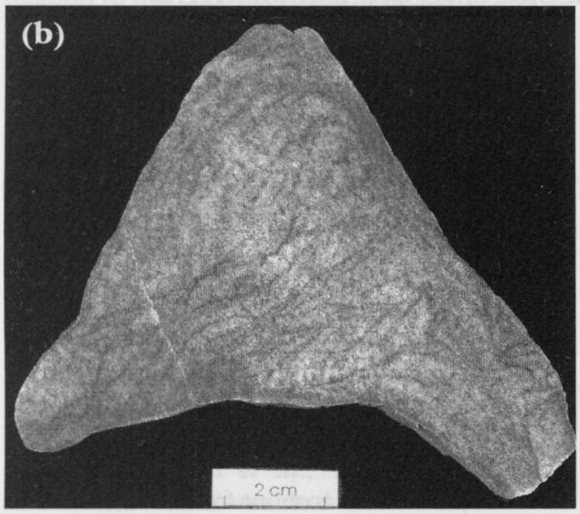


**Figure 6.37** ▲(a) Down-plunge view of mullions composed of psammites of the Altnaharra Psammite Formation in the gorge of the River Oykel, immediately downstream from the new road bridge (NC 386 009). The mullions show internal cuspate structures interpreted as deformed cross-bedding. (Photo: N.J. Soper.). ◄(b) Psammite mullion with traces of cross-bedding showing oversteepened foreset angles. Polished face on specimen collected by N.J. Soper. (Photo: British Geological Survey, No. P580524, reproduced with the permission of the Director, British Geological Survey, © NERC.)

columns. Note that mullions also occur in the **Coldbackie Bay** GCR site where they are attributed to coaxial F2 and F3 folding. However, in both sites the psammites occur in a similar structural situation in areas of high prolate strain close to D2 fold hinges. At Oykel Bridge the constrictional strain also appears to result from superimposed deformations that relate regionally to stacking of thrust sheets in the Moine sequence and to the mylonites of the Moine Thrust Belt.

## Conclusions

The spectacular mullions in Moine psammites displayed at Oykel Bridge are columnar structures whose long axes plunge 10°–20° to the ESE, parallel to a regional elongation lineation and to the axes of the dominant set of folds (F2) that affect the Moine rocks. Their origin and significance has long been the subject of debate. Were they produced by compression normal to their length, or extension parallel to it? Were they associated with major Precambrian orogenic movements at right angles to their length, or with Caledonian transport to the north-west on the Moine Thrust, parallel to it? The current view is that mullions developed parallel to the principal stretching direction during the main, Caledonian deformation of the Moine rocks, probably associated with recurrent movements along the Moine Thrust Belt. The deformation was of constriction–extension type, resulting in a prolate (flattened cigar-shaped) strain ellipsoid. The Oykel Bridge section exposes some of the finest examples of mullions in Britain and the site is of national importance.

## THE AIRDE OF SHIN (NC 519 146–NC 528 134)

*N.J. Soper*

### Introduction

The peninsula on the north-east shore of Loch Shin, known as 'The Airde', exposes a strip of felsic and amphibolitic mafic gneisses, metalimestones (marble) and schistose calc-silicate rocks, almost 1 km wide, flanked to the north-east and south-west by Moine psammites of the Altnaharra Psammite Formation (Morar Group). The gneissose rocks form part of the arcuate outcrop of mainly Lewisianoid rocks that can be traced southwards from Loch Shin and westwards through the Allt Doir' a' Chatha section to Glen Cassley (Figure 6.38a). This regional swing in strike forms part of what is known as the Assynt 'bulge'; the regional doming of the Moine rocks that overlie the Assynt Culmination that lies to the west (see Chapter 5). The finely layered nature of the gneissose lithologies, their association with calcareous rocks of clear sedimentary origin and structural concordance with the enclosing Moine psammites, led H.H. Read (in Read *et al.*, 1926) to interpret these rocks as part of the Moine sequence. He suggested a volcanic origin for the amphibolitic rocks, regarding them as 'Durcha-type Moines', the type locality for which lies along strike to the south (see **Allt Doir' a' Chatha** GCR site report, this chapter). Subsequently, a geochemical study by Winchester and Lambert (1970) showed the amphibolitic and calcareous rocks at The Airde of Shin (Shinness) to be compositionally akin to similar lithologies in the Lewisian Gneiss Complex, but unlike Moine calc-silicates. They interpreted the whole strip from Loch Shin to Glen Cassley as a highly attenuated Lewisianoid inlier.

### Description

The Airde of Shin is a low-relief mainly grassy promontory in Loch Shin with sporadic lochside outcrop and a few inland occurrences, notably at the Shinness Quarry (NC 525 137). The Lewisianoid rocks of the inlier strike ESE and dip at moderate angles to the NNE. They are disposed symmetrically about a central strip of marble and calc-silicate schist. The best-exposed section is in the northern half of the inlier, on the western shore of The Airde between NC 521 139 and NC 519 146 (Figure 6.38b). At the southern end of the section is a small peninsula composed of white, coarsely crystalline calcite marble in pods up to 1 m thick, interlayered with calc-silicate schist and flanked above and below by pelitic and semi-pelitic schist with minor calc-silicate layers (Figure 6.39). The marble can be traced about 500 m to the ESE as far as the Shinness Quarry. The calc-silicate rocks consist dominantly of tremolite, diopside, calcite, quartz and sphene (Read *et al.*, 1926, pp. 138–40).

To the north amphibolitic mafic gneisses are interleaved with pale biotitic quartzofeldspathic gneisses. Locally recumbent minor folds deform the gneissose layering, generally showing 'Z' symmetry. Fold axes plunge moderately northwards, congruent with a penetrative mineral lineation. There are several slightly discordant dyke-like bodies of amphibolite, strongly veined by aplitic material, that probably represent pre-Caledonian dolerite intrusions within the Lewisianoid gneisses. There are also a few actinolite-rich pods, which are interpreted as boudinaged ultramafic intrusions.

At NC 520 144 a narrow belt of very platy quartz-muscovite schist marks the boundary between the Lewisianoid gneisses and the Moine psammites to the north. The schist appears to be derived from the psammitic lithologies by shearing, recrystallization and hydration of feldspar. The overlying psammites are coarse grained, arkosic and locally pebbly with feldspar clasts up to 1 cm across. They are probably right-way-up; although no sedimentary structures have been recorded close to the gneiss contact, upward-younging cross-bedding is seen 1 km to the north at NC 521 154.

The southern part of the inlier is effectively a mirror image of the northern part; the marble and calc-silicate lithologies are succeeded to the south by amphibolitic mafic and felsic gneisses,

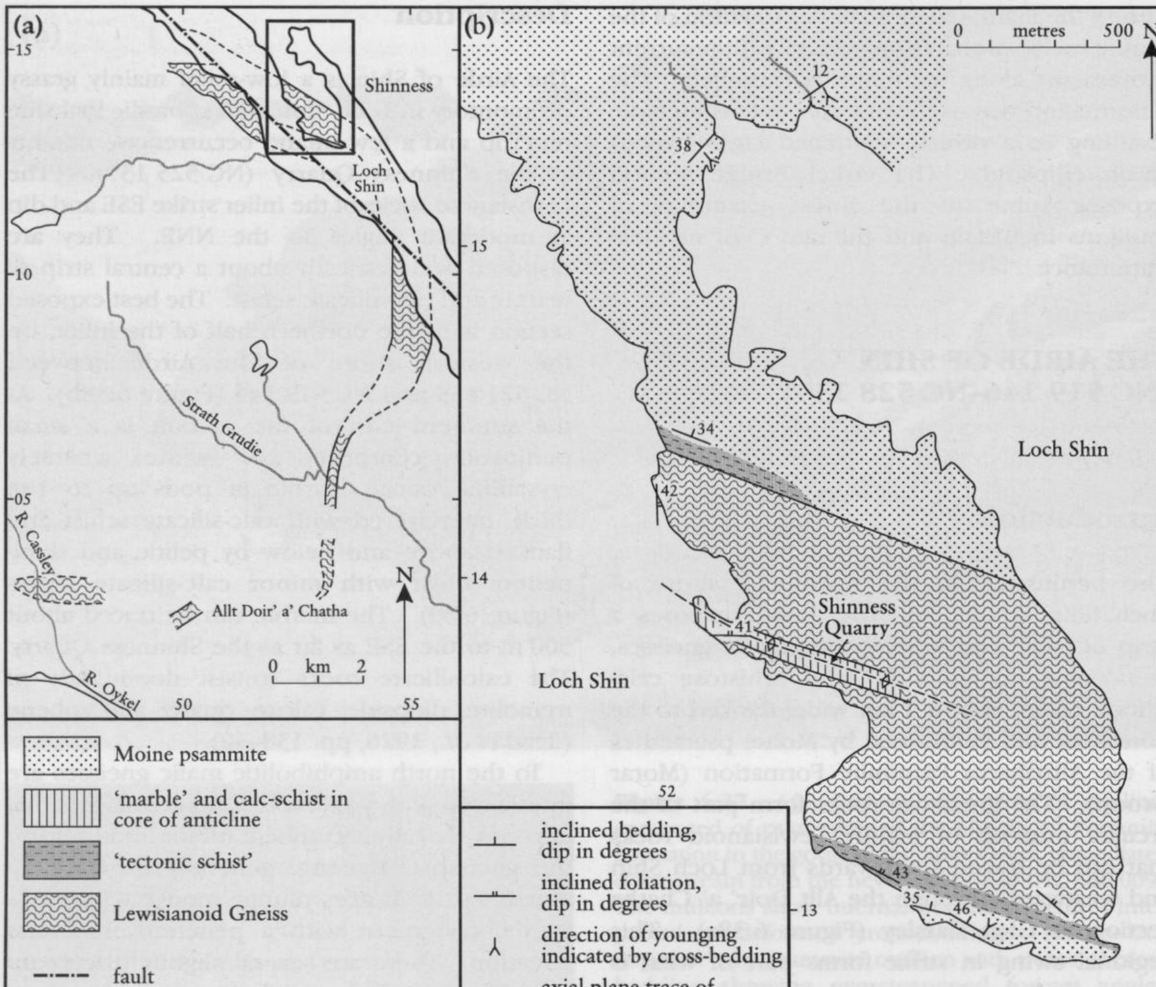


**Figure 6.38** (a) Location map of the Loch Shin area showing the strip of Lewisianoid rocks that extends from Loch Shin to the River Cassley. (b) The Airde of Shin Lewisianoid Inlier. Based on Winchester and Lambert (1970) and Strachan and Holdsworth (1988).

platy quartz-muscovite schist and Moine psammites with minor folds of 'S'-profile. Psammites crop out on the south coast of The Airde where they exhibit highly strained but recognizably inverted cross-beds.

## Interpretation

The contrast in fabric between the gneissose rocks and bedded Moine psammites, and the presence of two types of intrusion within the gneisses that are not seen in the adjacent Moines, leave little doubt that a basement–cover relationship is preserved at The Airde. The Lewisianoid affinity of the gneisses and associated calcareous rocks has been confirmed by the geochemical studies of Winchester and Lambert (1970).

At the time of Winchester and Lambert's re-instatement of the Shinness Lewisianoid Inlier, the concept of 'Lewisian slices' in the Moines was prevalent. Peacock (1975) interpreted the platy muscovite schists that he had recognized at the margins of the inlier as 'slide rocks' formed during interleaving of the Moine and Lewisian strata. He was not alone at the time in failing to address the general problem posed by the need to infer a thrust-sense displacement below the inlier and one of lag-sense (younger on older) above.

This problem was resolved through a structural study made by Strachan and

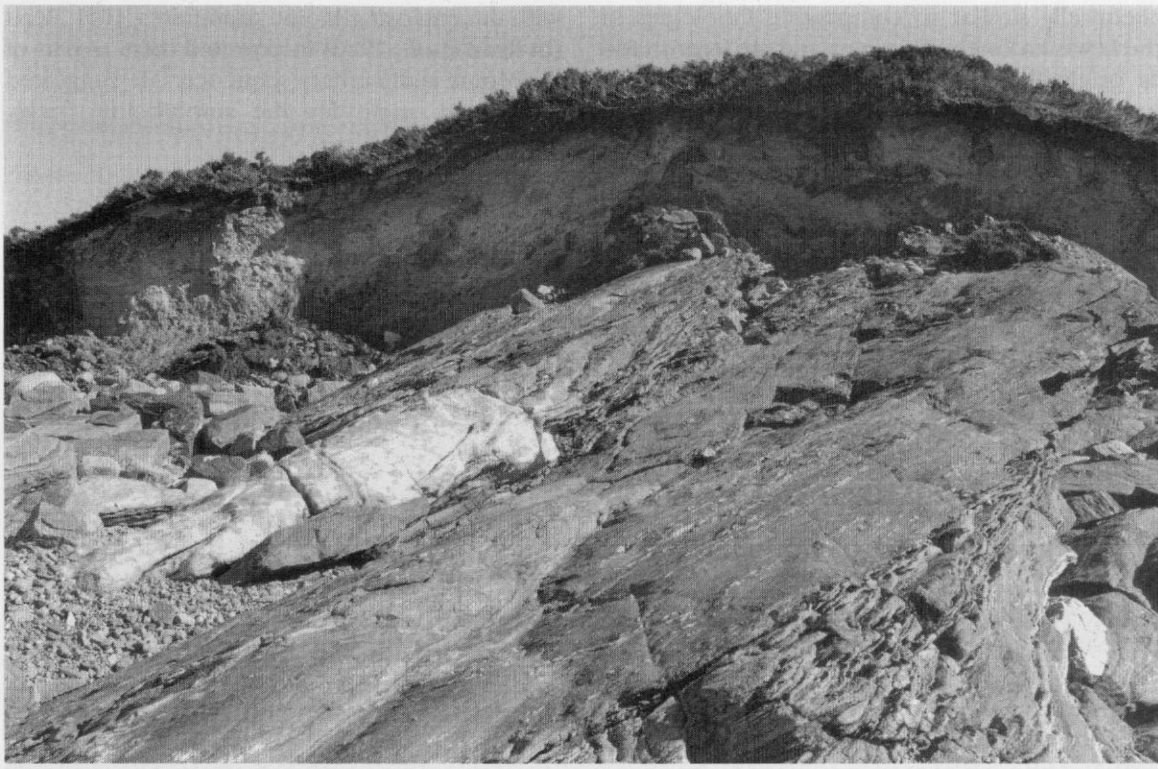

**Figure 6.39** Boudins of white-weathering calcite marble in calc-silicate schist in Lewisianoid gneisses in the hinge zone of a D2 anticline. Western shore of The Airde of Shin at NC 521 139. (Photo: Susan Hall.)

Holdsworth (1988) in the context of an investigation of regional basement–cover relationships in the Sutherland Moines. On the basis of the reversal in minor fold geometry on either side of the marble outcrop and the reversal in younging direction in the adjacent Moine rocks noted above, they inferred the presence of an isoclinal D2 (Caledonian) anticline closing sideways to the south-east, whose axial surface coincides with the marble outcrop. However, this interpretation does not entirely explain the zone of intense shear strain of presumed D1 age at the Moine–Lewisianoid contact.

A further unresolved problem is the age of the basement rocks. Eclogitic pods within grey gneisses from the eastern Glenelg Lewisian Inlier have yielded Grenville Sm-Nd garnet–cpx–whole-rock ages (Sanders *et al.*, 1984). Hence other Lewisianoid inliers within the Moines may have undergone Grenville reworking prior to Moine deposition, and the location of a putative Grenville front within the Northern Highlands is still an outstanding problem in Scottish geology. However, the presence of recognizable dyke-like intrusions within the Shinness gneisses, even after Caledonian deformation, militates against Grenville reworking and suggests that the Lewisianoid gneisses were formed during the Scourian event (*c.* 2.5–2.9 Ga) and not substantially modified until the Caledonian Orogeny.

## Conclusions

Excellent, though limited, outcrops on the western shore of The Airde of Shin reveal a Lewisianoid basement inlier sandwiched by Moine psammites of the Morar Group. The basement lithologies consist of mafic and felsic gneisses, and metasedimentary rocks, including marble and calc-silicate rocks. Exposure is sufficient to enable the tectonic relationship between basement and cover to be determined: the older rocks occupy the core of a recumbent anticline that is assigned to the second phase (D2) of regional deformation and is thought to be of Caledonian age. Intense shearing, resulting in the production of a platy muscovite-rich psammite ('tectonic schist'), has obliterated any features along the putative basement–cover unconformity. The basement rocks are chemically similar to comparable lithologies in the Lewisian Gneiss Complex and are interpreted as originally Scourian in age. The site is of national importance in encapsulating the problems associated with Lewisianoid inliers in the Moine succession and contains the largest occurrence of metacarbonate rocks in the Sutherland and Ross-shire Lewisianoid gneisses.

## ALLT DOIR' A' CHATHA (NC 500 023)

*N.J. Soper*

### Introduction

The Allt Doir' a' Chatha GCR site provides a stream section through a 200 m-thick sequence of interbanded amphibolitic and quartzofeldspathic gneisses, flanked by Moine psammites of the Morar Group (Figure 6.40). The gneisses form part of a strip that extends from Loch Shin through this locality to Glen Cassley (Figure 6.38a). Although exposure is limited, the site is of historical interest in Highland geology, particularly when related to the better-exposed and more lithologically diverse **The Airde of Shin** GCR site. Because of the finely layered nature of the gneisses, their association with calcareous rocks of clear sedimentary origin at The Airde of Shin and structural concordance with the enclosing Moine psammites, H.H. Read (in Read *et al.*, 1926) interpreted them as part of the Moine sedimentary sequence. He suggested a volcanic origin for the amphibolitic rocks, coining the term 'Durcha-type Moines'. Consequently, he disputed a basement origin for all the stripes of layered amphibolite that occur within the Moines of Sutherland and Ross-shire, arguing that 'You cannot have a Lewisian inlier one hornblende crystal thick!'.

This view had considerable influence on post-war research in the Highlands, and several previously identified Lewisianoid inliers were re-interpreted as Moine (e.g. Sutton and Watson, 1953). However, subsequent structural studies re-affirmed the presence of basement 'slices' at a high level in the Moine sequence, and geochemical investigation of the Durcha mafic and felsic gneisses by Winchester and Lambert (1970) suggested that they were more probably of Lewisian affinity.

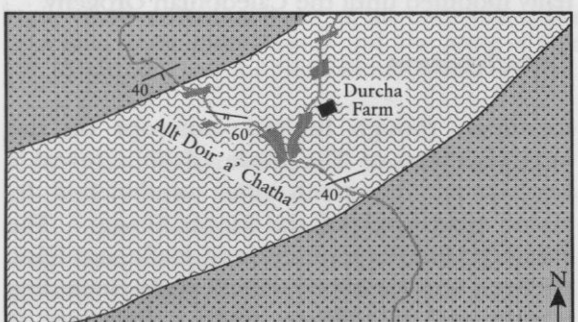


**Figure 6.40** Sketch map of the Allt Doir' a' Chatha Lewisianoid Inlier; amphibolitic mafic gneiss outcrops shown in darker grey.

### Description

The Lewisianoid rocks are exposed sporadically in the Allt Doir' a' Chatha from NC 5015 0224 upstream to the deer fence at NC 4980 0248, an outcrop length of about 300 m (Figures 6.40, 6.41). They consist of an interlayered sequence of striped amphibolite, epidote-amphibolite, biotite-rich felsic gneiss and quartzofeldspathic gneiss, all dipping moderately to the south-east. The gneisses are concordant with the psammitic Moine rocks of the Altnaharra Psammite Formation above and below. Petrographical descriptions of the main rock-types can be found in Read *et al.* (1926, pp. 144–5).

The upstream contact with the Moine psammites is located about 45 m below the deer fence, marked by a layer of platy quartz-muscovite schist, interpreted by Peacock (1975) as tectonic in origin (see **The Airde of Shin** GCR site report, this chapter). The psammites are very platy, with no younging evidence preserved.

### Interpretation

Field and geochemical evidence (Winchester and Lambert, 1970) have shown that the strip of dominantly amphibolitic rocks to which the 'Durcha Moines' belong have Lewisianoid affinities. Poor exposure precludes a structural interpretation of basement–cover relationships

**Figure 6.41** View downstream from the upper Moine contact in the Allt Doir' a' Chatha. (Photo: N.J. Soper.)

at the Durcha site. By analogy with **The Airde of Shin** GCR site, the basement rocks may lie in the core of the same recumbent anticline, but owing to the swing in strike between the two localities (Figure 6.38a) caused by the Asssynt 'bulge', the inverted limb would now lie to the north. Extreme attenuation of the Lewisianoid gneisses during Caledonian deformation induced the fine striping, which misled H.H. Read into advocating an original sedimentary and volcanic origin for these rocks.

## Conclusions

The Allt Doir' a' Chatha exposes a strip of highly attenuated amphibolitic and quartzofeldspathic gneisses that are interpreted as part of a Lewisianoid basement inlier within Moine psammites of the Altnaharra Psammite Formation (Morar Group). As the type locality of Read's 'Durcha-type Moines', the site is important in the history of geological research in the Highlands. It stands as an example of how the 'authority view' had great influence but in time was ultimately abandoned. Some 3 km along strike to the west, at NC 47 03, a more-complete section in the River Cassley shows similarly attenuated, striped mafic and felsic Lewisianoid gneisses.

# THE ROGART PLUTON AND MIGMATITE COMPLEX

*N.J. Soper*

The Rogart Pluton and related migmatite complex extend over about 115 km$^2$ in south-east Sutherland (see Figure 6.42). The pluton is a zoned quartz-monzodiorite–granodiorite–granite body, emplaced into metasedimentary rocks of the Moine Supergroup, which are migmatized to the east and north of the intrusion. The main interest lies in the relationship between the 'central granodiorite' and its fringing 'migmatite complex', a relationship not seen on this scale elsewhere in the British Caledonides. There are four GCR sites that illustrate the various features of the pluton and its migmatized envelope. The Loch Airighe Bheg GCR site illustrates mainly features of the pluton itself and is described in Stephenson *et al.* (1999). The three other GCR sites, described below, deal with various aspects of the migmatized envelope. As the conclusions relate to the whole pluton and its envelope, they are presented following the descriptions and interpretations specific to the three individual sites.

The Rogart Pluton belongs to the Argyll and Northern Highlands Suite and its intrusion has been dated by the TIMS zircon U-Pb method as 425 ± 1 Ma, i.e. Late Silurian (R.A. Strachan, pers. comm., 2003). Brown *et al.* (1968) obtained K-Ar biotite ages of *c.* 420 Ma from the pluton suggesting that the pluton cooled relatively rapidly. Emplacement was coincident with a period of pronounced uplift and erosion of the Scottish Highlands at the end of the Caledonian Orogeny. The pluton and migmatite complex are overlain unconformably at their south-east extremities by conglomerate and sandstones of the Langwell Conglomerate Member, the basal unit of the Devonian Lower Old Red Sandstone succession. The concordant and gradational contact of the central granodiorite against its migmatized envelope contrasts with the abrupt and discordant contacts shown by many of the Late Silurian 'Newer' Granites, for example the Helmsdale Granite of eastern Sutherland (Figure 6.4), suggesting a deeper and more-ductile environment of emplacement of the Rogart Pluton.

The Rogart Complex lies immediately to the south of the major regional migmatite complex of central Sutherland, termed the 'Loch Coire Complex' by several authors (Read, 1931; Brown, 1967; Barr, 1985). These regional migmatites are developed in dominantly semi-pelitic Moine rocks, whereas the Rogart Migmatite Complex formed in psammitic and

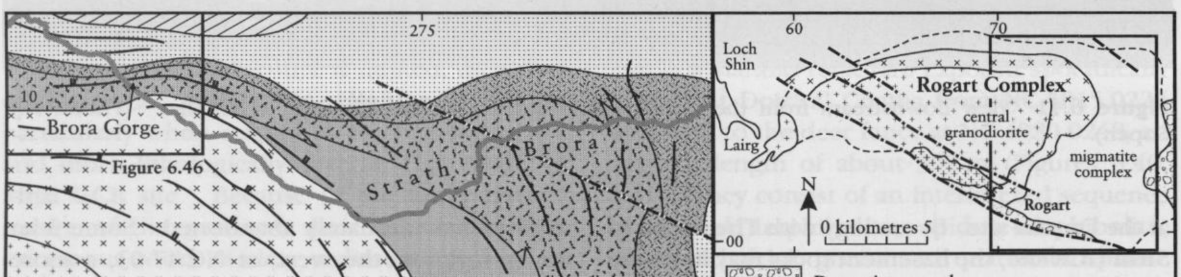


**Figure 6.42** Geological map of the eastern part of the Rogart Complex.

semipelitic rocks of the Morar Group. A narrow strip of unmigmatized rocks separates the two areas of migmatitic rocks (Figure 6.42). The spatial association of the Rogart migmatites with the central granodiorite and the inwardly increasing degree of migmatization towards the pluton imply that the migmatites are related to the intrusion of the pluton, rather than part of the regional migmatite complex that happened to be intruded by the Rogart Pluton. A narrow fringe of migmatitic rocks on the eastern margin of the Migdale granite, a few kilometres south of Rogart (Figure 6.4), is also interpreted as a 'contact migmatite'.

The complex was originally surveyed by Hugh Miller, part of whose report of 1893 (quoted in Read *et al*., 1925) described the process of conversion of Eastern (Moine) Schists into granitic gneiss. It was re-examined by H.H. Read, who divided the fringing migmatite complex into an inner 'zone of inclusions' and an outer 'zone of veins' (Read *et al*., 1925, 1926). H.H. Read accepted Miller's view that the granitic portion of the migmatites originated by transformation of Moine country rock. He envisaged assimilation of parts of the 'granulite' (psammite) roof of the intrusion by 'pegmatite magma' expelled from the consolidating central granodiorite, to produce streaky biotite granite (now recognized as the neosome portion of the migmatite complex). Today, this is seen as the 'magmatic' end-member of a range of migmatization processes, the other end being entirely subsolvus (non-magmatic) metasomatism (Ashworth, 1985).

Structural mapping by Soper (1963) revealed a funnel-shaped foliation pattern in the central granodiorite and a subhorizontal amphibole alignment in the marginal quartz-monzodiorite. A small component granite intrusion cross-cuts the two main rock-types in Strath Fleet. Soper envisaged a ballooning emplacement mechanism, whereby the central granodiorite deformed its own migmatitic envelope, eventually punching through it on the north-western side. He divided the migmatite complex into three zones (Figure 6.42): an outer zone of weakly migmatized Moine rocks with regional structures preserved and with numerous aplite, granite and pegmatite veins; an intermediate zone with granodioritic neosome and Moine palaeosome in roughly equal proportions; and an inner zone with streaky migmatitic granodiorite (neosome) dominant, in which regional structures have been obliterated and new structures developed parallel to the contact with the central granodiorite intrusion.

## CREAG NA CROICHE (NC 721 040)

***N.J. Soper***

### Introduction

The migmatitic envelope of the Rogart Complex is widest to the east of the central granodioritic intrusion to the north of Strath Fleet, where glaciated crags provide excellent exposure. The Creag na Croiche site includes the contact of the outer quartz-monzodiorite component of the central intrusion with migmatitic granodiorite, and displays a selection of migmatite types and structural features of the inner migmatite zone (Figures 6.42, 6.43).

### Description

Crags at the western end of the site (NC 716 040) consist of the outer quartz-monzodiorite, whose modal composition is: plagioclase $An_{22-24}$ (48–53%), quartz (14–19%), perthitic K-feldspar (7–13%), biotite (9–13%), hornblende (7–14%), sphene and other accessory minerals (1–2%). The quartz-monzodiorite carries a weak NE-trending planar fabric defined by hornblende and biotite with a subhorizontal alignment of amphibole. There are numerous elongate appinitic xenoliths whose long axes generally lie within the quartz-monzodiorite foliation. The interdigitated sinuous contact with migmatitic biotite granodiorite is gradational over a few tens of metres and is marked by a loss of hornblende and the incoming of a streaky or nebulitic appearance. The migmatitic granodiorite carries small, partly assimilated appinitic xenoliths, and larger more-angular fragments of psammite, many of which are only weakly migmatitic. Eastwards, the nebulitic granodiorite contains an increasing proportion of interleaved psammitic palaeosome, forming typical stromatic (formerly 'lit-par-lit') migmatite. The foliation strikes NNE and is folded around an antiform–synform pair. Towards the eastern end of the site area around Little Rogart, a sheeted intrusion of quartz-monzodiorite is present within the nebulitic and stromatic migmatites.

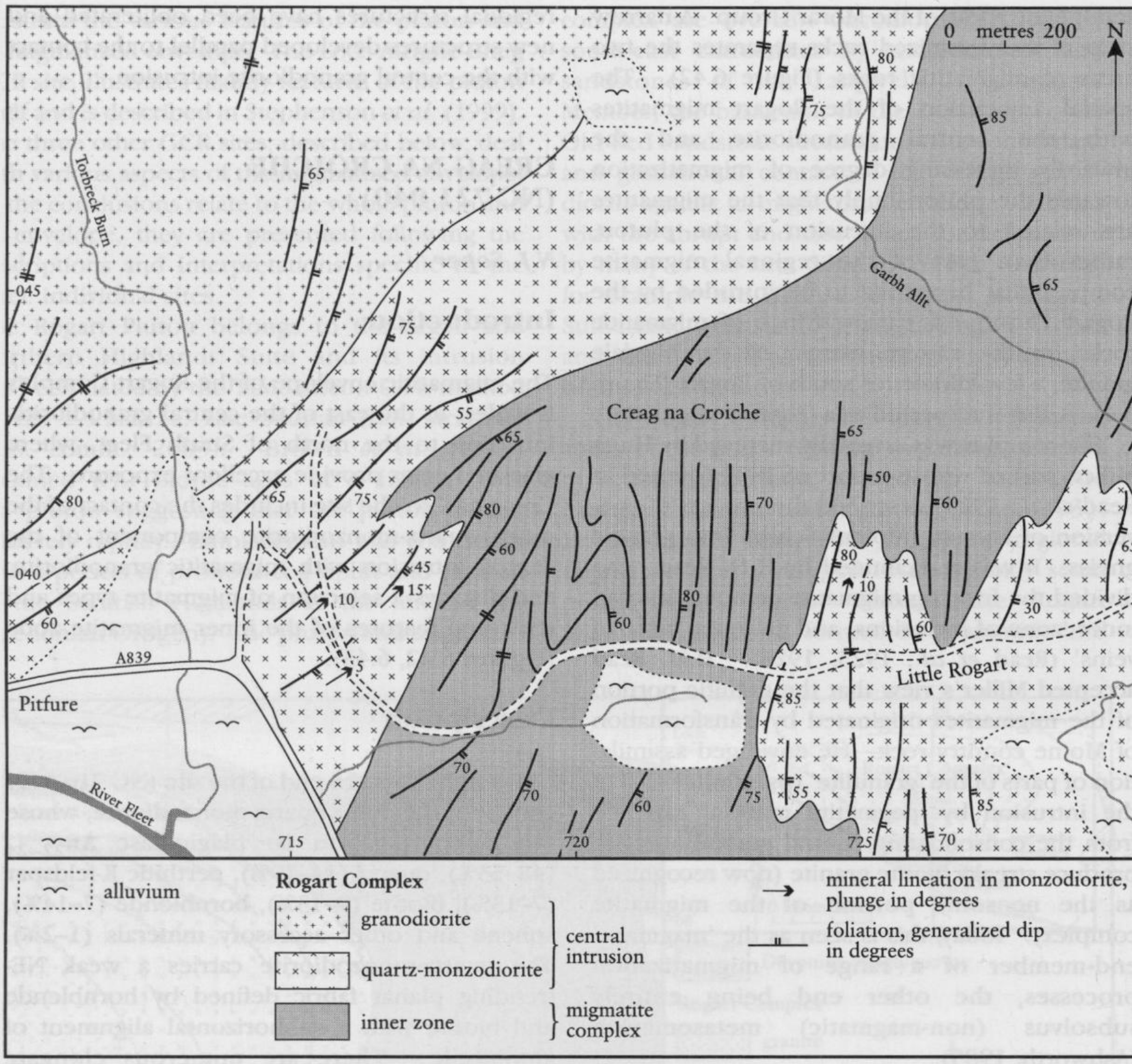


**Figure 6.43** Geological map of the Creag na Croiche area.

## Interpretation

It is inferred that the migmatites formed an envelope around the central granodiorite–quartz-monzodiorite intrusion during its ascent and were deformed as the pluton distended its envelope during final emplacement. The parallelism of fabrics in the outer quartz-monzodiorite and in the migmatites, and the folds in the migmatites that trend parallel to the contact, both support this interpretation. An intrusive origin for the central granodiorite is supported by the sheets of quartz-monzodiorite within the migmatites, to the east of and separate from the main body. The granodiorite does not represent metasomatized Lewisianoid basement, as was suggested by D.L. Reynolds (see discussion of Soper, 1963). No petrogenetic investigation of the migmatites has been undertaken since the advent of rapid analytical methods. Hence the geochemical and mineralogical processes involved in the formation of the migmatitic granodiorite remain unclear. Possibilities include Read's suggestion of reaction between residual liquid and psammite; partial melting (anatexis); subsolvus metasomatism; or some combination of these processes. The site, together with the others designated in the Rogart Complex, would provide an excellent basis for future textural and geochemical studies that could throw light on this problem.

## ABERSCROSS BURN–KINNAULD (NC 748 013, NC 763 001)

*N.J. Soper*

## Introduction

This site is complementary to **Creag na Croiche** in that it is located in the outer part of the migmatite complex surrounding the Rogart Pluton and shows the transition from unmigmatized Moine metasedimentary rocks into thoroughgoing migmatites. Descriptions of the outer part of the migmatite complex were provided by Read *et al.* (1925), who designated it a 'zone of veins', in contrast to the inner 'zone of inclusions', and by Soper (1963) who emphasized the structural relationships.

## Description

The site comprises two separate areas, Aberscross Burn to Morvich and Morvich to Kinnauld (Figure 6.44); these are described

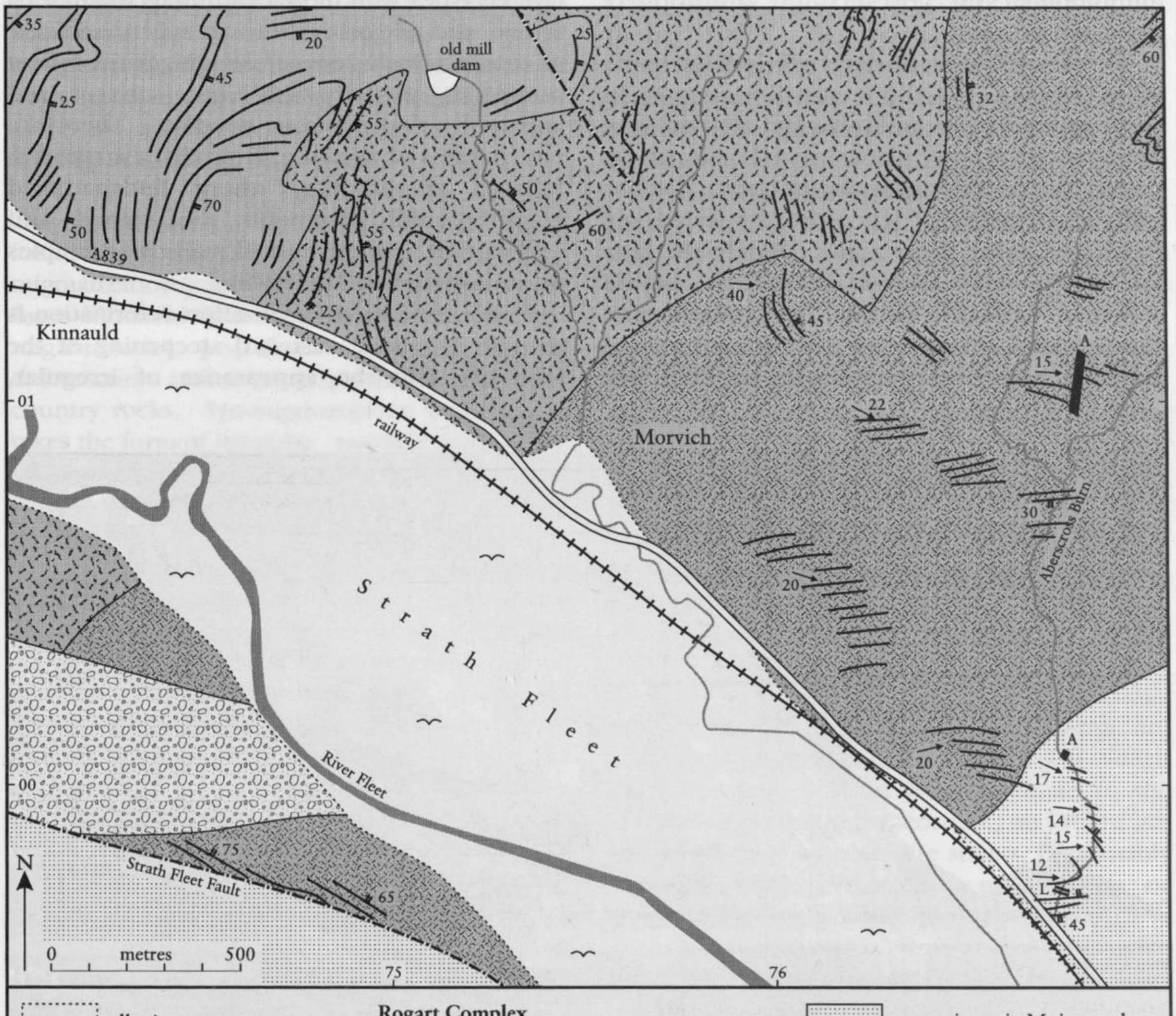


**Figure 6.44** Geological map of the Aberscross Burn to Kinnauld area.

together, starting in the east at Aberscross Burn (NC 765 996).

The burn exposes flaggy psammites and subordinate semipelites of the Altnaharra Psammite Formation (Morar Group), folded into an open, E-plunging antiform, apparently a late structure. The pervasive regional L2 linear fabric (*sensu* Strachan and Holdsworth, 1988) plunges gently east and consists of a mineral alignment, defined by quartz and biotite, together with 'grooving' of the foliation planes, a weak expression of mullion-like structure (see **Oykel Bridge** GCR site report, this chapter). Pre-tectonic amphibolite and post-tectonic lamprophyre dykes are present.

To the north-west, on crags overlooking Strath Fleet (Figure 6.45), the metasedimentary rocks show an increase in grain size and a progressive obliteration of the planar and linear fabric, mainly due to recrystallization of quartz. Diffuse veins and patches of leucosome appear, some developed along shear zones. Where the host metasedimentary rock is semipelitic, biotite selvages typically fringe the leucosomes. Parallel-sided, dilational veins of pegmatite and aplite are present throughout the complex, but there is a concentration in the outer migmatite zone, the 'zone of veins' of Read *et al.* (1926).

North-west of Morvich, the proportion of leucosome increases to between one- and two-thirds and a variety of migmatite types are developed. The commonest type are stromatic ('lit-par-lit') migmatites, developed from interlayered psammite + semipelite, the leucosome being preferentially developed in the more-micaceous lithologies, interbanded with discrete layers of unmigmatized psammite. Semipelites and pelites produce various types of migmatite: streaky migmatites with biotite schlieren; layered types with more-continuous biotite-rich layers; and oligoclase-bearing augen gneisses. All contain inclusions of less-migmatized host semipelite, normally with biotite selvages, and apparently derived from boudins. There are rare patches of agmatite, typically developed in foliated amphibolite, where feldspathized amphibole-rich fragments are veined and enclosed by aplitic granitoid material; examples were described by Ma (1948).

Evidence of syn-migmatization deformation is seen in a general eastward steepening of the foliation, and the appearance of irregular,

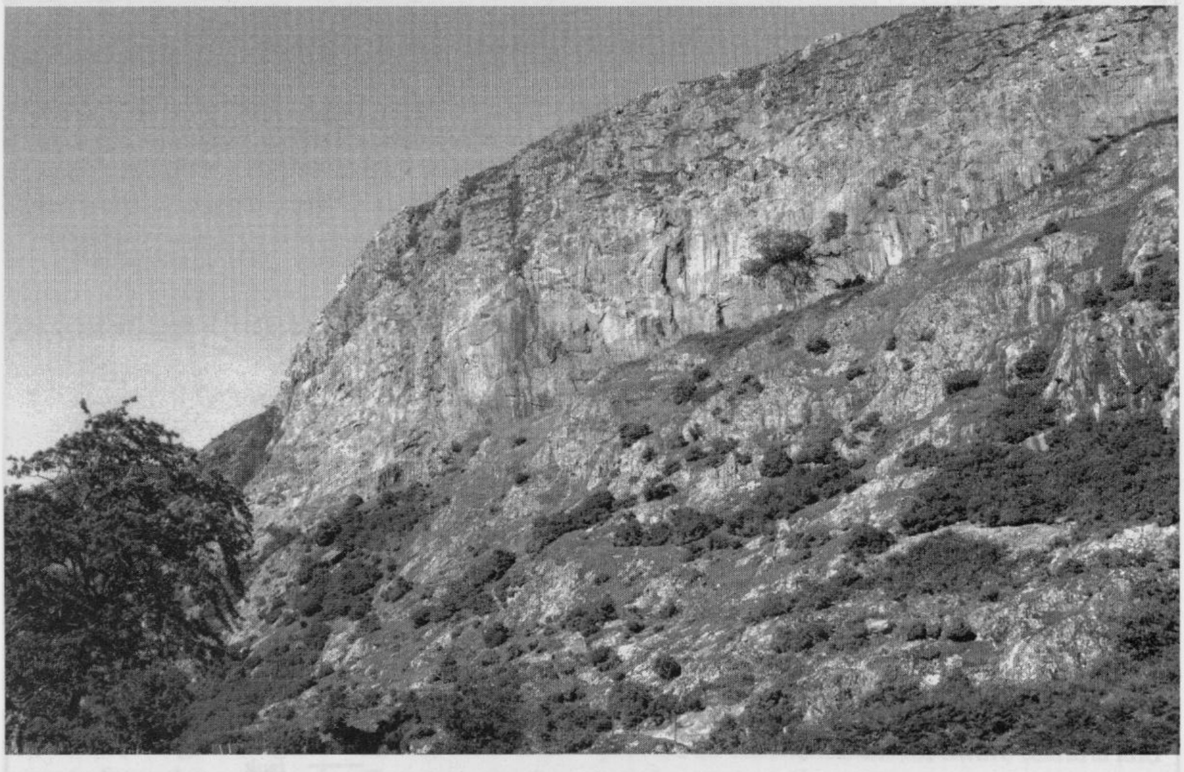

**Figure 6.45** Marian's Rock, cliffs formed of gneisses of the migmatite complex above Morvich at NC 750 010. (Photo: N.J. Soper.)

'swirling' folds on all scales. Towards the western end of the GCR site, north of Kinnauld, the foliation has a more-regular north-easterly strike, reflecting the trend of the quartz-monzodiorite–migmatite contact that lies 3 km to the west. However, the foliation dips steeply south-east, away from the contact. Original features of the Moine rocks, such as the regional D2 linear fabric, are largely obliterated. In addition to the normally parallel-sided, narrow aplitic microgranite and quartz-feldspar pegmatite veins, there are larger sheets and diffuse masses of foliated granodiorite and pink, unfoliated aplitic granite. There are numerous transitions between the various 'igneous' components of the complex, and evidence of both intrusive and replacive relationships.

## Interpretation

The progressive obliteration of the flaggy foliation and the L2 linear fabric with increasing migmatization is well displayed at the Aberscross Burn–Kinnauld GCR site and establishes that the migmatization post-dates the main regional deformation and metamorphism of the Moine country rocks. Syn-migmatization deformation takes the form of irregular, 'swirling' folds of the migmatitic layering. The more-regular strike and steep 'outward' dip seen towards the western end of the site as the central granodiorite contact is approached, passes westwards into a zone of contact-parallel folding, seen at the **Creag na Croiche** GCR site. These structures support the view that the ballooning central granodiorite distended its own migmatite envelope (Soper, 1963).

# BRORA GORGE (NC 706 107–NC 717 099)

***N.J. Soper***

## Introduction

On the north-east margin of the Rogart Pluton the migmatitic envelope is much narrower and is expressed as a ridge of higher ground. The Brora Gorge GCR site is located where the River Brora has cut through this ridge. Here the migmatite envelope is little more than 300 m wide and the inner migmatite zone is absent (Figure 6.46). The site provides an almost continuous river gorge section from the outer quartz-monzodiorite of the central Rogart intrusion through the narrow migmatitic envelope into unmigmatized Moine psammites.

## Description

The section extends upstream from Braegrudie croft (NC 717 099) and commences in the outer quartz-monzodiorite. A typical sample from this locality has a modal composition of plagioclase $An_{24}$ (53%), quartz (19%), biotite (13%), hornblende (7%), perthitic K-feldspar (7%), sphene and other accessory minerals (1%) (Soper, 1963). The quartz-monzodiorite has a steep, S-dipping foliation and gently ESE-plunging lineation defined mainly by hornblende. The quartz-monzodiorite carries non-migmatitic psammite xenoliths and is cut by a large aplitic microgranite dyke that trends parallel to the river and crosses the contact described below.

The contact of the quartz-monzodiorite with stromatic migmatites dips steeply to the south, concordant with the foliation in both rock-types, and is transitional over a few metres. For the next 100 m of section, sheets of quartz-monzodiorite are interleaved with a variety of migmatite lithologies, hosted by psammite, semipelite and pelite with a leucosome of rather variable biotite granodiorite (quartz, potash feldspar, oligoclase, biotite). Agmatite occurs in the sparse amphibolitic metabasic bodies in the Moine rocks. Farther upstream, for about 100 m, similar steeply inclined migmatites without quartz-monzodiorite intercalations strike ENE. The final 100 m of the gorge are composed of stromatic migmatites in which the leucosome portion is subordinate to the generally psammitic palaeosome, and there are several discrete amphibolite sheets, presumably originally early, pre-tectonic mafic dykes or sheets. Upstream from the gorge there is a gradational passage into flaggy Moine psammites that comprise the strip of non-migmatitic country rocks, about 0.5 km wide, that separates the Rogart Complex from the regional migmatite complex of central Sutherland.

## Interpretation

The foliation and lineation within the outer quartz-monzodiorite of the Rogart Pluton at the

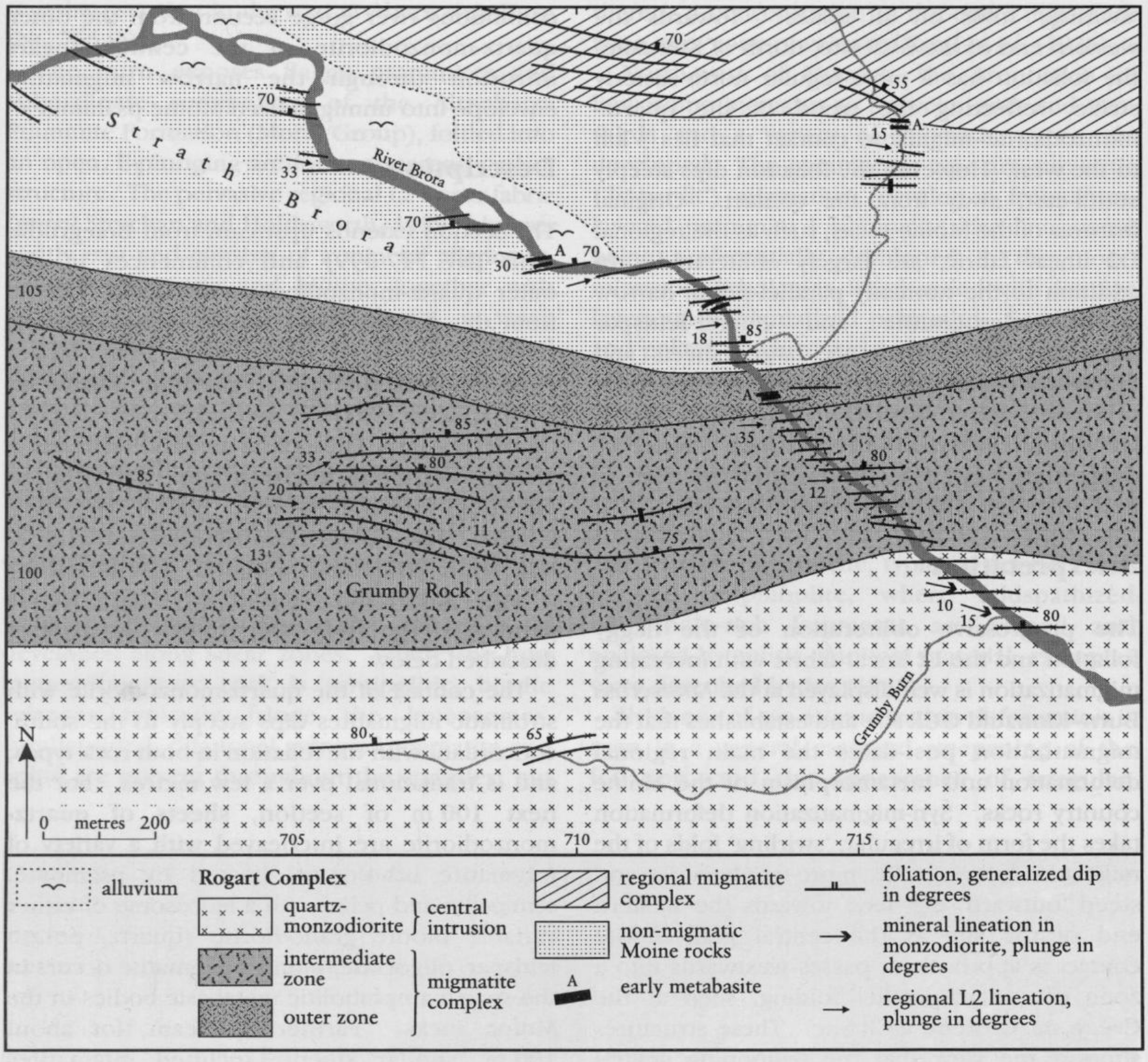


**Figure 6.46** Geological map of the Brora Gorge area.

Brora Gorge GCR site and elsewhere along unfaulted eastern and northern contacts, has been interpreted by Soper (1963) to be caused by the ballooning effect of the distending pluton prior to its final consolidation. At Brora Gorge the quartz-monzodiorite–migmatite contact is intrusive and sheeted and the following features are seen: the inner migmatite zone is missing, presumably having been breached; the quartz-monzodiorite carries psammite xenoliths, showing that during intrusion it 'sampled' non-migmatitic Moine country rocks; and the migmatite envelope is narrow, subvertical and attenuated. These features tend to support the view that the distending intrusion invaded, distorted and in places punched through its own migmatite envelope. In the extreme north-west of the Rogart Complex the quartz-monzodiorite is in direct contact with unmigmatized Moine country rocks (Figure 6.42).

## Rogart Pluton and Migmatite Complex – general conclusions

The Rogart Complex is the best example in Britain of a granitoid intrusion with an envelope of country rocks that have been transformed to migmatite – an apparent mixture of granite and more-refractory residual metasedimentary rocks. While the phenomenon of regional-scale migmatization has been studied for a century, 'contact migmatization' has received little attention. It is clear that the central intrusion at Rogart is somehow responsible for the production of its migmatitic envelope, which it subsequently intruded and deformed. However, the geochemical changes of the migmatization process have not been investigated. The three designated GCR sites provide excellent exposures on which such a study could be based.

At **Creag na Croiche** the central granodiorite/quartz-monzodiorite intrusion is in gradational contact with the migmatite envelope comprising nebulitic migmatitic granodiorite and stromatic migmatites developed from a range of meta-sedimentary lithologies. In contrast, at **Aberscross Burn–Kinnauld** the outer part of the migmatite complex is seen, flaggy Moine psammites becoming progressively migmatized westwards, with a concomitant obliteration of regional tectonic structures and the incoming of both cross-cutting veins and concordant sheets of granitic material. At the **Brora Gorge** a complete section is exposed through the migmatite complex, whose outcrop here is only some 300 m wide. A variety of relationships are preserved that support the view that the central granodiorite invaded and deformed its own migmatite envelope during the final 'ballooning' phase of its emplacement.

## CARN GORM (NH 442 629)

*E.K. Hyslop*

### Introduction

The Carn Gorm pegmatite is the largest of the Neoproterozoic ('Knoydartian' or 'Morarian') pegmatites discovered to date in the Moine rocks of the North-west Highlands. The pegmatite contains large muscovite books, which have been the subject of much geochronological work, with appropriate repercussions for the tectonic and metamorphic history of the Moine succession. The pegmatitic granite body lies within the Ben Wyvis Pelite Formation in the Glenfinnan Group. It is particularly well exposed around the summit of Carn Gorm (Figure 6.47) due to the relatively flat-lying orientation of the adjacent gneissose pelites and semipelites.

Although L.W. Hinxman mapped the Carn Gorm area in 1903 for the Geological Survey, no particular mention was made of the pegmatite and it is not described in the related memoir for Sheet 93 (Peach *et al.*, 1912). However, during the wartime search for strategic minerals Kennedy *et al.* (1943) described several pegmatites from the Ben Wyvis area, including two localities on Carn Gorm, as a potential source of commercial mica. Long and Lambert (1963) carried out pioneering Rb-Sr isotopic studies on the large muscovites present in the Carn Gorm pegmatite, and van Breemen *et al.* (1974) followed this up with further detailed isotopic dating. Both studies showed that the muscovites had Neoproterozoic ages of 700–800 Ma, thus pre-dating the Caledonian Orogeny. As a result of the dating of the Carn Gorm pegmatite and other pegmatite bodies in the Morar and Glenfinnan areas, a 'Morarian' or 'Knoydartian' orogenic event was proposed.

### Description

Carn Gorm is a rocky and heathery summit 556 m above sea level on the southern flank of Ben Wyvis. The Carn Gorm pegmatite lies within a belt of pelitic rocks approximately 5 km wide that stretches north-east from Strathconon (NH 392 570) through Tarvie (NH 423 585) and Loch Garve, to Carn Gorm and Ben Wyvis (NH 463 684). The pelitic rocks, termed the 'Sgurr Marcasaidh Formation' in Strathconon and the 'Ben Wyvis Pelite Formation' farther north, are attributed to the Glenfinnan Group. The psammite unit that borders the pelites to the south-east, the Tarvie Psammite Formation, has been assigned to the Loch Eil Group (Holdsworth *et al.*, 1994) reducing the Glenfinnan Group rocks to a narrow outcrop. Rathbone and Harris (1979) studied grain-size reduction in Morar Group psammites along the western edge of the pelitic belt. They demonstrated an increase in strain towards inliers of Lewisianoid material, which occur along the boundary, and concluded that this junction represents a northerly extension of the Sgurr Beag Thrust (see **Kinloch Hourn** GCR site report, Chapter 8). The rocks in the Ben Wyvis area are generally flat-lying, which is thought to represent the pre-Caledonian disposition of the Moine assemblage (Harris, 1991). Open, upright F3 folds, considered to be of Caledonian age (e.g. Holdsworth and Roberts, 1984) clearly deform the main schistosity and the pegmatites in the Carn Gorm area.

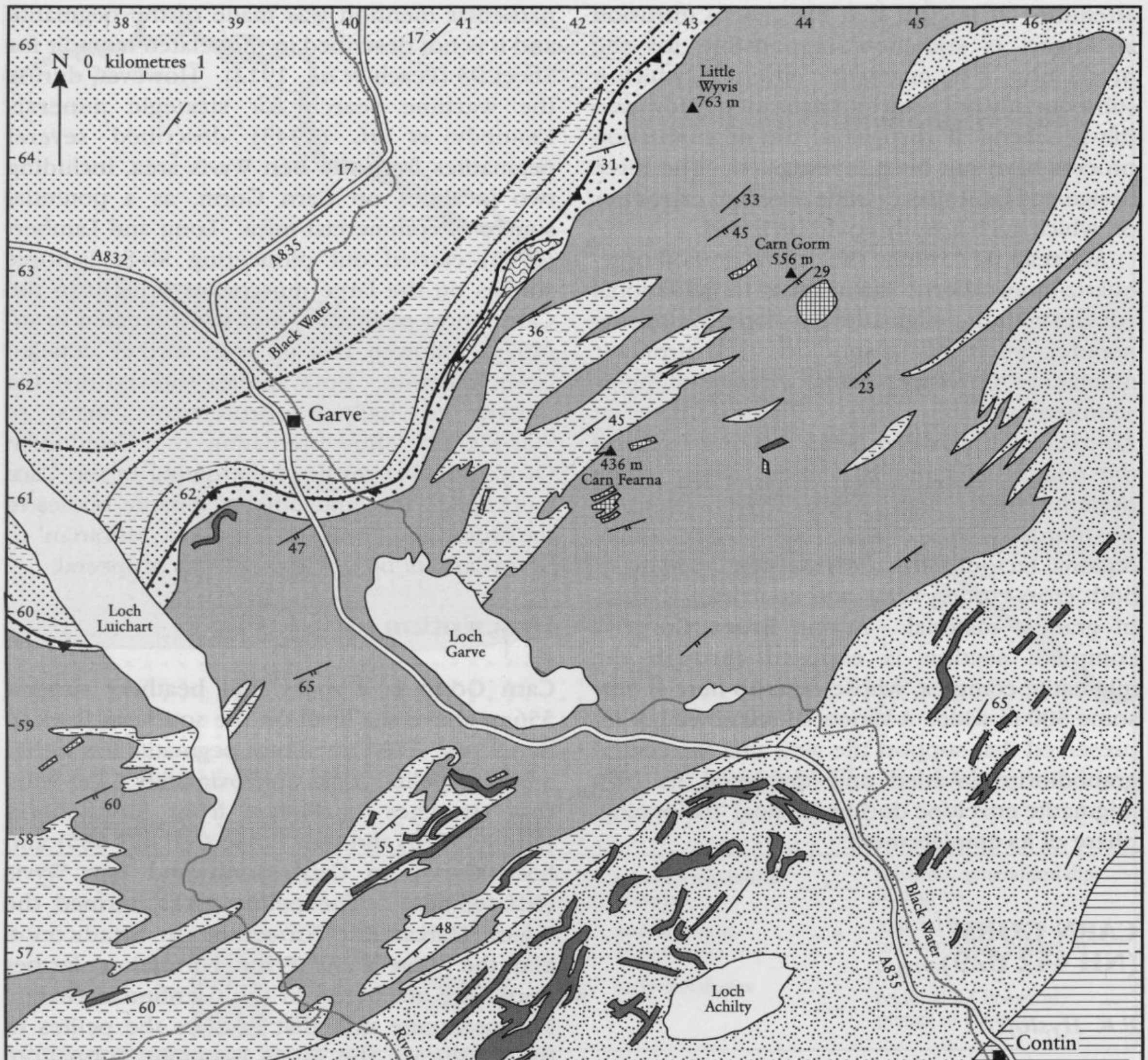


**Figure 6.47** Geological map of the Garve area showing the location of Carn Gorm. Compiled from BGS 1:50 000 sheets 83W, Strathconon (British Geological Survey, 2001) and 93W, Ben Wyvis (British Geological Survey, 2004a).

The Carn Gorm pegmatite is exposed over an area of approximately 200 $m^2$, and although its upper contact has been largely removed by erosion, it is at least several metres thick. It is generally concordant with the foliation in the host rocks and its lower contact is clearly exposed in several places. The pegmatite body is composed of quartz, muscovite, potash feldspar and plagioclase feldspar, biotite and garnet (Figure 6.48). Beryl and tourmaline also occur and the muscovite books are commonly up to 20 cm across and 3 cm thick. Strictly, it is a pegmatitic leucogranite. It has a primary, coarse, mineralogical layering that trends north-east, parallel to the regional strike of the country rocks, and most of the mica within the pegmatite is also aligned in this orientation. This internal layering has been enhanced by subsequent deformation and recrystallization, which becomes stronger towards the pegmatite margins. Other pegmatites in the Carn Gorm area, including the nearby body at Carn Fearna, have similar mineralogies and internal structures.

The Carn Gorm pegmatite contains inclusions of pelitic and psammitic country rock, which occur as enclaves commonly several metres long by about 1 m wide, and which maintain the regional strike of the country rocks. The pelitic inclusions consist of biotite-rich gneissose pelite or more commonly muscovite-rich schistose semipelite, that contains concordant quartz veins, small lenticular pegmatites and abundant tourmaline. Adjacent to the pegmatite the pelitic country rocks are particularly muscovite-rich with abundant quartz veins and lensoid quartz-feldspar segregations. Muscovite is common as small flakes throughout the pelitic matrix, as well as forming individual porphyro-blasts typically *c*. 1 cm in size. Kennedy *et al*. (1943) noted the increasing amount of muscovite in the pelite as the main pegmatite body is approached, and described the immedi-

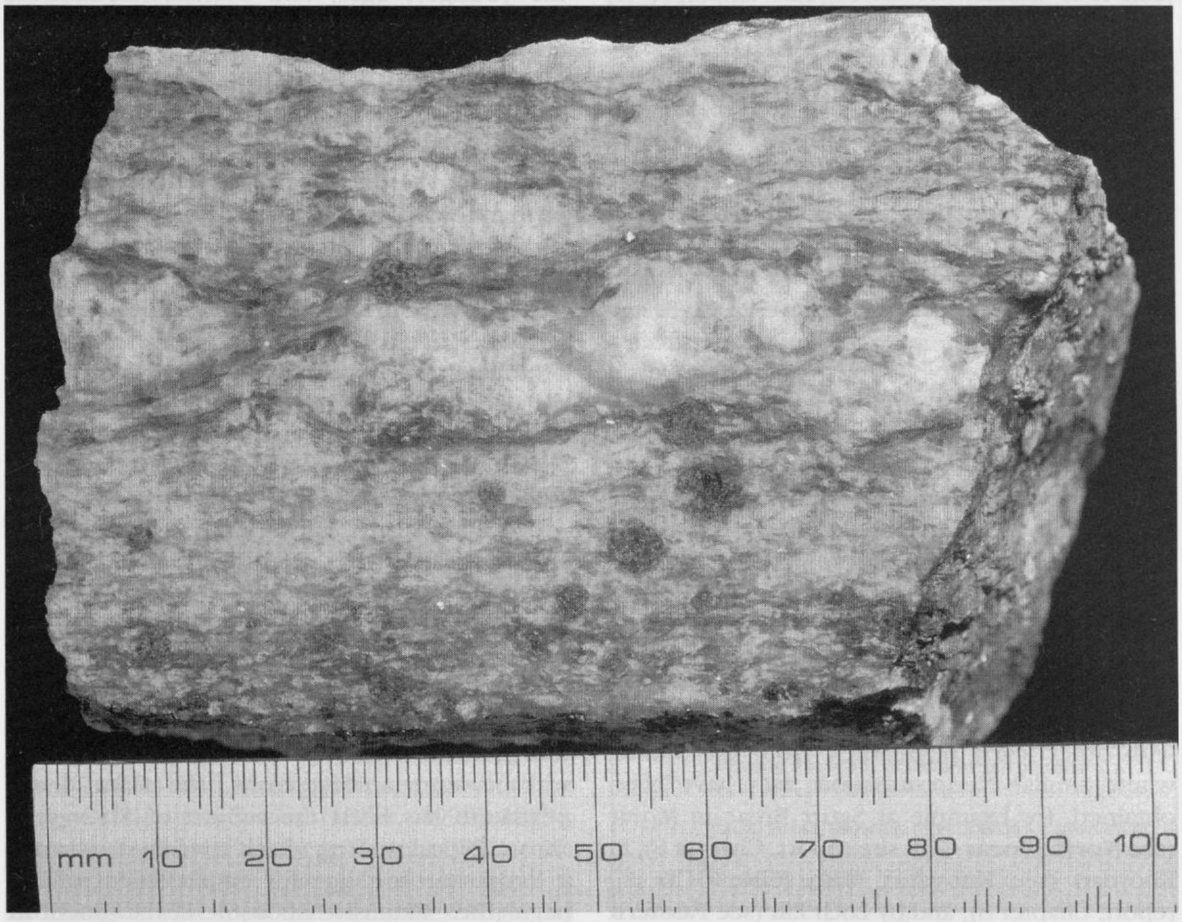


**Figure 6.48** Specimen of pegmatitic leucogranite from Carn Gorm. The crude foliation, defined by quartz and muscovite, encloses lenticular aggregates of white feldspar and subsidiary pale-grey quartz. Dark-red garnets up to 5 mm across are prominent. (Photo: E.K. Hyslop.)

ate host rock as 'highly injected', becoming saturated with pegmatite material giving a transitional pelite–pegmatite boundary. Within the pegmatitic body itself muscovite is best developed near its margins and adjacent to the country rock inclusions, suggesting reaction between the pegmatite and host rocks during pegmatite crystallization.

## Interpretation

The Carn Gorm pegmatite is one of a suite of pegmatite bodies in the Ben Wyvis area, several of which have produced Neoproterozoic isotopic ages. These pegmatites are similar to other Neoproterozoic pegmatites identified from across the Moine outcrop, and their origin has been the subject of much debate. The intimate relationship between the Carn Gorm pegmatite and its country rocks, in particular the gradational margins and the presence of pegmatite material in the host rocks, indicate that it is unlikely to have been emplaced by discrete injection of an igneous melt from depth. Rather the evidence suggests that the pegmatite formed as a result of recrystallization and locally segregated neosome development from the surrounding country rocks.

In an early Rb-Sr isotopic survey of the Moine assemblage, Long and Lambert (1963) examined several pegmatite bodies from the Carn Gorm area. A sample of muscovite from a concordant pegmatite 6 m by 4 m in size gave an Rb-Sr age of 705 ± 25 Ma, and a second muscovite from a 'small feldspar-muscovite segregation' gave an age of 625 ± 20 Ma. An Rb-Sr muscovite age of 680 ± 10 Ma was also obtained from a larger pegmatite at nearby Carn Fearna (NH 426 614). These ages were interpreted to show that the muscovites formed initially at around 700–800 Ma, but their Rb-Sr isotopic systems were reset to younger ages by the later Caledonian deformation and metamorphism. Initial Sr ratios from this study imply that the pegmatites were derived from the local Moine country rock. The pegmatite suite at Carn Gorm was correlated with other 'early pegmatites' from the Moine, where similar Neoproterozoic ages have been obtained, for example at Sgurr Breac in Morar (see **North Morar** GCR site report, Chapter 8), in Knoydart (see **Knoydart Mica Mine** GCR site report, Chapter 8), and by Loch Eilt (see **Fassfern to Lochailort Road Cuttings** GCR site report, Chapter 8) (van Breemen *et al.*, 1974).

Van Breemen *et al.* (1974) carried out a more-detailed geochronological investigation of the Carn Gorm pegmatite. They obtained nine Rb-Sr ages ranging from 700–800 Ma from four muscovite books from a single pegmatite. The detailed pattern of Rb-Sr ages within individual muscovite books was also examined, showing that the oldest ages were obtained from the centres of books, with younger ages towards the margins. These age variations were attributed to minor movement of radiogenic Sr and Rb within some mica books and the loss of radiogenic Sr from others, both caused by post-crystallization Caledonian deformation and metamorphism of the pegmatite. These authors followed Long and Lambert (1963) in correlating the Carn Gorm pegmatite with a suite of pegmatites of similar age from throughout the Moine assemblage, and concluded that they had formed as a result of a period of tectono-metamorphism at this time.

The fact that the smallest pegmatites record the youngest ages, and that the centres of muscovite books retain the oldest ages, supports this proposal of pegmatite formation during the Neoproterozoic (*c.* 800 Ma) followed by later disruptive isotopic disturbance. This interpretation is supported by more-precise U-Pb zircon and monazite ages of *c.* 800 Ma for pegmatites from the western Moine succession (Rogers *et al.*, 1998), and evidence documenting isotopic disturbance of Neoproterozoic pegmatites during Caledonian deformation (Powell *et al.*, 1983). The presence of upright D3 folds throughout the Carn Gorm area, which disrupt the pegmatites, indicates that later deformation and recrystallization of probable Caledonian age occurred widely in these Glenfinnan Group rocks.

## Conclusions

The Carn Gorm pegmatite is the largest and possibly the best exposed of the Neoproterozoic ('Knoydartian' or 'Morarian') pegmatites, the older suite of pegmatites in the Moine succession that pre-date Caledonian deformation. Together with its surrounding rocks, the Carn Gorm pegmatite has been the subject of Rb-Sr geochronological studies, which have demonstrated a Neoproterozoic age for emplacement of the pegmatite. Extensive neosome development in the country rocks, and the gradational nature of the pegmatite boundaries, suggest that the Carn

Gorm pegmatites formed as a result of in-situ recrystallization and segregation during a Knoydartian or Morarian (*c.* 800 Ma) tectono-metamorphic event.

The Carn Gorm pegmatite is particularly valuable because of its well-exposed state, and the low intensity of D3 Caledonian deformation, preserving much of its original character. The site is of national importance as it demonstrates how isotopic dating has been used to elucidate the tectonic history of the Moine succession. It also shows that Neoproterozoic metamorphic events affected the Moine rocks several hundred million years before Caledonian orogenic activity in Ordovician and Silurian times.

## COMRIE (STRATHCONON) (NH 413 560)

***J.R. Mendum***

### Introduction

Metabasic rocks, now mainly amphibolite sheets or pods, are particularly abundant in parts of the Moine Supergroup. Near Comrie, in Strathconon, lenticular amphibolitic mafic bodies are notably abundant in folded psammites and minor semipelites that lie in the lower part of the Loch Eil Group, here called the 'Tarvie Psammite Formation' (see Holdsworth *et al.*, 1994). The regional geology is shown in Figure 6.47. The mafic bodies are pervasively foliated except in the central parts of thick lenses, where relict igneous textures are preserved. Original discordant relationships between the intrusive mafic bodies and the bedded Moine psammites can still be seen, although the amphibolite bodies are now strongly deformed.

Early mafic sheets that pre-date the structural fabrics and folds are locally common in the Moine metasedimentary succession, particularly around the Glenfinnan Group–Loch Eil Group boundary. Farther south in Glen Moriston (see **Glen Doe** GCR site report, Chapter 8) folded and boudinaged mafic dykes and sheets, now amphibolites and metagabbros, cross-cut the Ardgour Granite Gneiss (Millar, 1990, 1999). These metagabbros have been dated at 873 ± 6 Ma (Millar, 1999) and this age of intrusion is indistinguishable from that of the West Highland Granite Gneiss Suite at 873 ± 7 Ma (Friend *et al.*, 1997). The ages were obtained from zircons using U-Pb TIMS and SHRIMP methods respectively.

L.W. Hinxman first mapped the amphibolites around Comrie for the Geological Survey in 1900 and 1901. He noted their folded nature and commented on their particular density and thickness in the Scatwell–Comrie–Cnoc Dubh area, north-west of Loch Achilty (Horne and Hinxman, 1914).

### Description

At the Comrie GCR site the amphibolitic mafic bodies and adjacent psammites are exposed on two smooth glaciated rocky knolls, 15–20 m high. They lie adjacent to the minor road between Contin and the dam at Loch Luichart (Figures 6.49, 6.50). Unfortunately, the two knolls that constitute the GCR site show considerable growth of lichen and moss that obscure some of

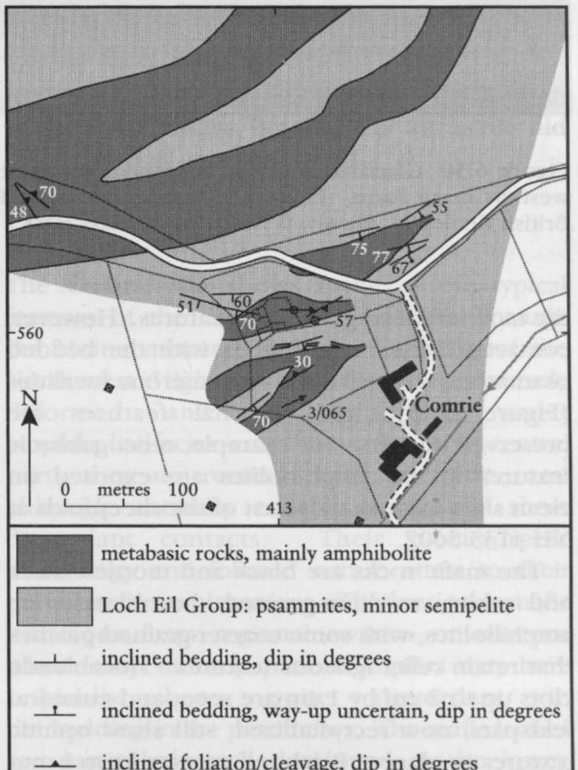


**Figure 6.49** Geology of the area around Comrie Farm, Strathconon.

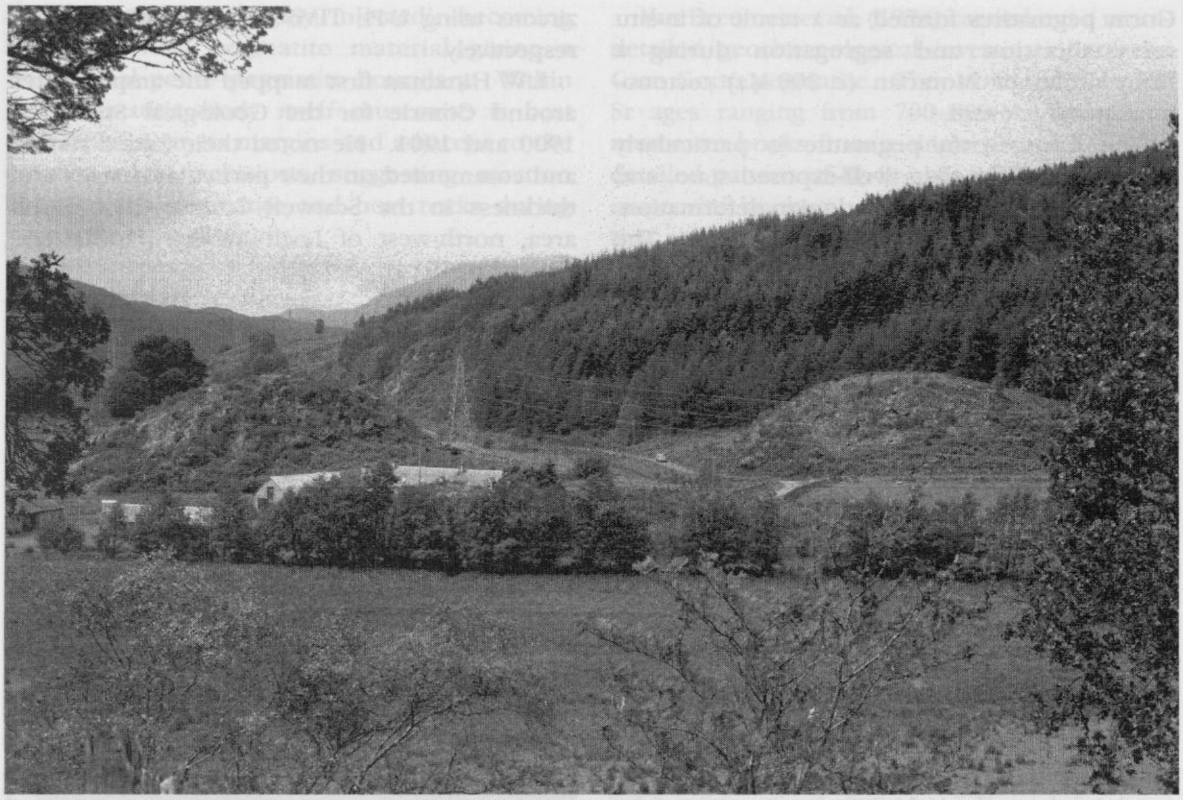

**Figure 6.50** Glaciated rock knolls formed of amphibolitic mafic sheets and lenticular pods. Looking north-west to Comrie Farm. (Photo: J.R. Mendum, BGS No. P552291, reproduced with the permission of the Director, British Geological Survey, © NERC.)

the more-detailed geological features. However, contacts of the mafic bodies with the bedded psammites are well seen at numerous localities (Figure 6.49), and internal features are preserved in parts. For example, relict gabbroic textures in the amphibolites are exposed on clean slabs immediately east of the sheepfolds at NH 4133 5602.

The mafic rocks are black and mottled black and white, medium-grained, hornblende-rich amphibolites, with some coarser-grained patches that retain relict igneous textures. Hornblende clots up to 2 cm by 1 cm are seen, and euhedral feldspars, now recrystallized, still show ophitic textures in places. Brick-red garnets from 1 mm to 2.5 mm across are very abundant close to the margins of the metabasic body but sparse or absent elsewhere. The amphibolites contain a foliation defined by the hornblende alignment, but the marginal 10–35 cm-wide zone is strongly foliated. Locally, shear zones marked by finely foliated amphibolite also occur within the metabasic bodies. Horne and Hinxman (1914) gave petrographical descriptions of the Comrie mafic rocks. The typical amphibolite consists of green hornblende and plagioclase feldspar (upper andesine) laths with development of irregular sphenes containing ilmenite or rutile cores in places. Anhedral quartz and sieved epidote-clinozoisite grains are developed, probably as a result of the breakdown of labradoritic plagioclase feldspar to a more-albitic (Na-rich) variety during metamorphism. Other thin sections contain up to 80% green hornblende with subsidiary plagioclase feldspar, quartz and irregular garnets and sphene. Ilmenite, magnetite and rutile are common accessory minerals.

The Tarvie Psammite Formation in this area consists of feldspathic psammites with siliceous and micaceous beds and minor semipelitic units. Cross-beds are seen at NH 4126 5602 and hematite-stained seams are present, probably representing magnetite-rich heavy-mineral laminae in the original sands.

Some 130 m SSE of Comrie farm buildings, small rocky psammite exposures by the track show excellent tight small-scale folds with a penetrative axial-planar cleavage that dips steeply south-east. Minor thin lenticular amphibolite sheets up to 60 cm thick are present in the psammites. The folds and related penetrative cleavage are clearly refolded by secondary open folds with an accompanying NNW-trending steeply dipping cleavage.

Contacts of the mafic sheets are normally parallel or sub-parallel to bedding in the adjacent psammite, but locally can be markedly discordant, for example at NH 4141 5608. The pervasive foliation in the amphibolite bodies is orientated close to bedding in the psammites, and passes through discordant contacts with virtually no deflection. Within the amphibolite are lenticular and irregularly shaped enclaves of pervasively recrystallized coarse-grained gneissose psammite. The psammite adjacent to the contact is typically pinkened, recrystallized and coarsened, and thin quartz and quartz-feldspar pegmatite veins are present. Horne and Hinxman (1914) record a 'calcareous biotite schist' at the margin of a thick metabasic sheet about 200 m north of Comrie Farm, but this appears to correspond to a sheared and faulted contact between the mafic sheet and the psammites.

## Interpretation

The mafic rocks were originally dolerite (and rarely gabbro) sheets that intruded the dominantly psammitic Moine sequence prior to the first major penetrative deformation. Generally they were concordant with bedding in the adjacent Loch Eil Group metasedimentary rocks, but at least locally they cut across the bedding at moderate to high angles. U-Pb TIMS dating of zircons from the metagabbros at Glen Doe, farther south, show that similar mafic bodies were intruded at around 873 Ma at considerable crustal depth (Millar, 1999) (see **Glen Doe** GCR site report, Chapter 8). Only relatively minor contact effects are seen at Comrie and the main mineralogical changes and development of thin quartz and quartz-feldspar pegmatite veins can be attributed to subsequent deformation and metamorphism. The overall outcrop pattern in the Comrie area appears to reflect large-scale tight folding and boudinage of the more-competent metabasic sheets.

The mafic rocks have been metamorphosed to amphibolites, and normally contain a pervasive foliation that is contiguous with the penetrative S2 cleavage in the adjacent psammites. The presence of almandine garnet, generally close to the margins of the basic bodies, relates to either the original composition of the mafic intrusion (e.g. locally more iron-rich) or more probably to metamorphic fluid diffusion effects involving the adjacent psammites and subsidiary semi-pelites.

The intrusive mafic rocks in the Strathconon district form a distinct swarm, part of a larger suite within the Moine succession that extends from the north coast of Sutherland southwards to the Strontian Pluton (Smith, 1979). Winchester (1976) distinguished two separate swarms farther west in Ross-shire, one with a tholeiitic basalt geochemistry, and the other showing more-alkaline basalt affinities. Moorhouse and Moorhouse (1979) showed that geochemically distinct swarms ('suites') were also present in Sutherland. Millar (1990) found that the meta-dolerites and metagabbros in Glen Moriston are all tholeiitic with affinities to present-day Mid-Ocean Ridge Basalts, but different intrusions did show different geochemistries.

## Conclusions

The Comrie site shows many of the typical features of the early mafic rocks that intrude the Moine metasedimentary succession of the North-west Highlands. Although pervasively deformed and metamorphosed under amphibolite-facies conditions, in their central parts they do retain igneous textures, and although normally concordant, locally show discordant contacts. Their metamorphic mineralogy and foliated nature attest to their pre-tectonic emplacement. The lenticular mafic intrusions form regional swarms or clusters, whose map outcrop pattern implies may have originally been quite discordant to the bedding in the psammites. The mafic bodies are particularly well developed in the lower, dominantly psammitic part of the Loch Eil Group. Their lenticular nature is largely a product of the Neoproterozoic and Caledonian deformation that affects the overall sequence. However, it may also reflect the original geometry of the mafic intrusions at depth and the ductile nature of the host metasedimentary rocks.

The Comrie site is important as a representative of the typical metabasic bodies in the Moine succession. The generally low strain in the Comrie area has preserved some of the original intrusive features of the intrusions.

## CROMARTY AND ROSEMARKIE INLIERS (NH 808 688–NH 831 699, NH 759 611–NH 768 621)

***A.J. Highton***

## Introduction

The Cromarty and Rosemarkie inliers comprise two contrasting 'windows' into Precambrian 'basement' rocks surrounded by Devonian Old Red Sandstone sedimentary rocks. These structural inliers occur north of Rosemarkie, and around the Sutors of Cromarty (Figure 6.51). They expose distinctive rocks with apparently complex tectonothermal histories that show affinities with both the Moine psammites and semipelites and the Lewisianoid gneisses to the north-west. The inliers lie adjacent to the Great Glen Fault, and are among the few localities that illustrate the ductile movement history of this fault system. The overall movement history of this fault system is increasingly well understood (see Smith and Watson, 1983; Harris, 1995; Stewart *et al.*, 1997, 1999). Sinistral movements dominate the Silurian and Devonian history of the fault, but a post-Devonian dextral offset of some 25–29 km largely accounts for the contrasting nature of the Devonian successions on either side of the Moray Firth and Great Glen (D.A. Rogers *et al.*, 1989).

The brief description of the inliers that followed the original survey by Hugh Miller in 1889 (in Horne, 1923) made little comment on the affinities of the metamorphic rocks, although Flett (in Horne, 1923) entertained the possibility that the amphibole-bearing rocks were part of a fault-bounded slice of Lewisian basement. Detailed work by Harris (1978), Rathbone (1980) and Rathbone and Harris (1980) showed that the inliers are lithologically dissimilar and have experienced different tectonometamorphic histories. The dominantly psammitic and semipelitic rocks of the Cromarty Inlier were tentatively attributed to the Glenfinnan Group. In contrast, in the Rosemarkie Inlier, Rathbone (1980) described the intercalation of Moine-like psammites and semipelites with amphibolites and finely striped hornblende-bearing felsic and mafic gneisses. Rathbone and Harris (1980) suggested that the striped hornblendic felsic and mafic gneisses were of Lewisianoid affinity. Most other Lewisianoid inliers in the Northern Highlands occur either as cores of major antiformal structures or as allochthonous sheets bounded by ductile shear-zones (Lambert and Poole, 1964; Rathbone and Harris, 1979; Barr *et al.*, 1986; Strachan and Holdsworth, 1988; Strachan *et al.*, 2002a). The Rosemarkie outcrop differs in that it lies well to the east and structurally above the nearest proven occurrence of allochthonous Lewisianoid rocks. There is no evidence for either an unconformable relationship or a discrete tectonic discontinuity between the Moine and probable Lewisianoid rocks within the inlier, although the rocks are highly strained (Rathbone and Harris, 1980).

Concordant and discordant leucogranite veins are common in the Rosemarkie Inlier and as they are tightly folded and strongly lineated, their intrusion appears to have occurred relatively early in the tectonometamorphic history of the inlier. A swarm of weakly deformed granite and pegmatite intrusions, probably of late Caledonian age, occurs within the Cromarty Inlier (Rathbone and Harris, 1980). Post-tectonic calc-alkaline appinitic microdiorite dykes are also present in the Cromarty Inlier.

The Mid-Devonian Kilmuir Conglomerate and Raddery Sandstone formations unconformably overlie the basement rocks on their north-western side (Fletcher *et al.*, 1996). In Rosemarkie Glen a small fault-bounded wedge of purple-brown siltstones, sandstones and locally breccia, interpreted to be of Early Devonian age, is exposed at the south-west end of the Rosemarkie Inlier (Figure 6.51).

## Description

The GCR site covers two restricted areas of coastal outcrop along the cliffed north-western side of the Inner Moray Firth. The metamorphic rocks are best exposed on raised rock platforms around the high-water mark.

### *Cromarty Inlier*

This site comprises a coastal section along part of the North Sutors on the north side of the

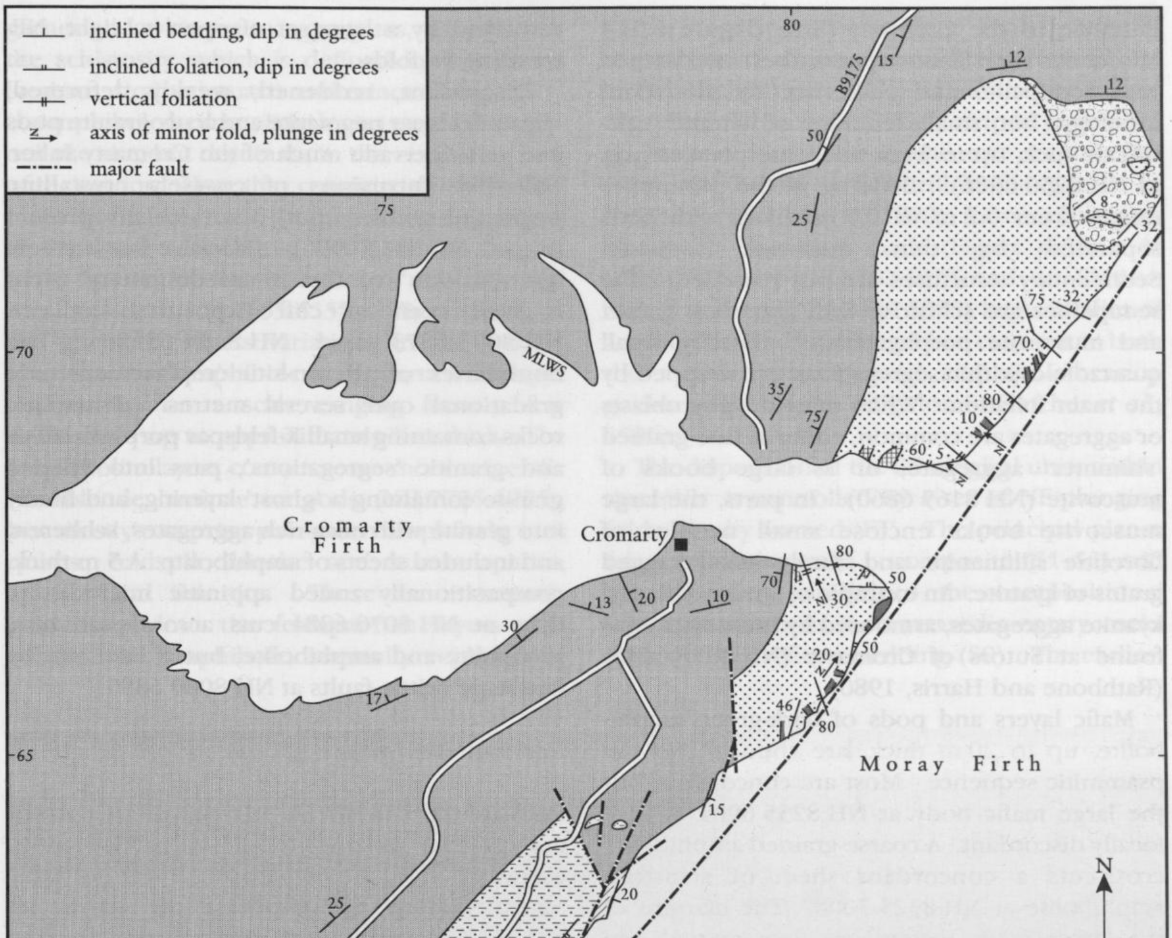


**Figure 6.51** Geology of the Rosemarkie and Cromarty area. Compiled from British Geological Survey one-inch Sheet 94, Cromarty (Institute of Geological Sciences, 1973), 1:50 000 Sheet 84W, Fortrose (British Geological Survey, 1997c), and Rathbone and Harris (1980).

entrance to the Cromarty Firth (Figure 6.51). Micaceous and siliceous psammites, interlayered with semipelite and pelite are the dominant lithology, but small lenticles of altered calc-silicate rock, up to 3 cm thick, are present (e.g. at NH 8250 6906). Bedding in the psammites ranges from 0.2 m to 0.7 m thick, with beds separated by thin mica-rich laminae. Sedimentary structures are not recorded. The semipelites are schistose with abundant garnet and muscovite porphyroblasts. Locally, small quartzofeldspathic segregations are wrapped by the main foliation. White mica porphyroblasts or aggregates are common, either as fine-grained 'shimmer' aggregate, or as large books of muscovite (NH 8169 6860). In parts, the large muscovite books enclose small needles of fibrolitic sillimanite and rarely small ragged grains of kyanite. An example of strained bladed kyanite aggregates, armoured by muscovite, was found at Sutors of Cromarty (NH 8078 6630) (Rathbone and Harris, 1980).

Mafic layers and pods of dark-green amphibolite, up to 20 m thick, are abundant in the psammitic sequence. Most are concordant, but the large mafic body at NH 8255 6904 is least locally discordant. A coarse-grained amphibolite cross-cuts a concordant sheet of schistose amphibolite at NH 8325 7008. The margins of the larger mafic masses are fine grained and schistose, but pass rapidly inwards into coarse-grained amphibolite. Metamorphic assemblages and textures predominate, although relict sub-ophitic textures are locally preserved (NH 8198 6869). Thinner mafic bodies are generally schistose throughout. The amphibolites pre-date all but a possible primary deformational phase affecting the inlier.

The succession is folded by 'F3', minor- and intermediate-scale tight folds. In the southern part of the inlier F3 axial traces trend north-east, but swing east–west and north-west at the South Suitor Stacks (NH 812 670). They remain NW-trending in the northern part of the inlier (Harris, 1978). The folds are strongly curvilinear with gently to moderately plunging axes, and do not show a consistent plunge direction or sense of asymmetry. A penetrative S3 axial-planar mica foliation is developed in most lithologies. Evidence for earlier deformations is confined to rare F1 isoclines, which are cut by the mafic intrusions and overprinted by the regional S2 foliation and a pervasive S2 foliation and related lineation, L2. Both the F2 and F3 structures are reworked by a later set of open to tight, NE-trending F4 folds.

Discordant, reddened, weakly deformed, quartz-feldspar pegmatite and leucogranite pods and veins pervade much of the Cromarty Inlier. Dyke-like intrusions of coarsely crystalline pegmatitic granite up to 3 m thick, are present (e.g. at NH 8316 6996). Pervasive late-tectonic 'granitization' of the metasedimentary rocks is well seen in cliff exposures between NH 8093 6873 and NH 8194 6868. The boundaries of the in-situ 'replacement' are gradational over several metres. Psammitic rocks containing small K-feldspar porphyroblasts and granitic 'segregations', pass into foliated granite containing a 'ghost' layering, and finally into granite with mica-rich aggregates, schlieren, and included sheets of amphibolite. A 5 m-thick, compositionally zoned appinitic microdiorite dyke at NH 8070 6884 cuts across psammite, semipelite and amphibolite, but is itself cut by late-stage brittle faults at NH 8080 6885.

### *Rosemarkie Inlier*

Rocks of the Rosemarkie Metamorphic Complex are well exposed along the coastal section north-eastwards from below Learnie Farm to Ethie Shore (Figure 6.51). East of Learnie at NH 755 610 thinly interlayered psammites and semipelites are intercalated with gneissose feldspathic psammites and other felsic gneisses. These generally Moine-like lithologies are interleaved with schistose amphibolite and layered hornblendic felsic gneisses. The overall strike of the lithological units trends north-east, slightly oblique to the coast throughout much of the site but complex fold patterns are present.

The 'Moine' lithologies are well seen close to the low-water mark between NH 761 612 and NH 767 619 and consist predominantly of psammites with subsidiary semipelites. The psammites are grey to pink-grey, flaggy, medium- to coarse-grained with partings picked out by pelitic laminae. Thin quartzofeldspathic lenticles impart a weakly gneissose appearance to the rocks. Small lenses of calc-silicate rock are locally present (NH 7517 6018). Lenses of hornblendic felsic gneiss occur in a 20–45 m-wide zone in psammites in the south-west corner of the site. A schistose semipelite unit, up to 30 m thick, lies on the seaward side of the psammite-hornblendic felsic gneiss unit (NH 7618 6120). The semipelite contains porphyroblasts of garnet and white mica aggregates, wrapped by the schistosity, which is defined by micaceous laminae, strained quartz and minor feldspar.

Amphibole-bearing lithologies occur throughout the site, but dominate in the north-east part of the section. Here they comprise thinly banded mafic and felsic gneiss (homblende-rich gneisses of Rathbone and Harris, 1980), whose contact with the metasedimentary rocks is sharp and locally folded (NH 7655 6155). The layering in the gneisses reflects variations in the relative abundance of amphibole and quartz + feldspar and occurs on a scale ranging from a few millimetres up to approximately 1 m thick. The amphibolite layers contain some monomineralic hornblende laminae or pods (NH 7725 6275), but mostly comprise pale-green amphibole with quartz, feldspar, biotite and minor apatite, sphene and ilmenite. These are commonly gradational into the feldspar-rich layers with subordinate amphibole, normally replaced by biotite. Also present are small pods of serpentinized ultramafic rock (NH 7690 6211). In the southern part of the site and to the east of the semipelite, a unit of finely striped pink felsic gneiss and intercalated schistose amphibolite (the mixed acid and hornblendic gneiss of Rathbone and Harris, 1980) forms exposures along the low-water mark (Figure 6.52). At Learnie Quarry (NH 752 613) and on Flowerburn foreshore (NH 7443 5895) larger bodies of amphibolite and/or metagabbro crop out in both the metasedimentary and amphibole-bearing gneissose lithologies (Highton in Fletcher *et al*., 1996).

The disposition of the lithological units within the inlier is controlled by a set of NE-plunging folds, locally termed 'F3'. The principal planar fabric in all the rocks is composite (S1–S2) and normally lies parallel to the compositional layering, which in the metasedimentary rocks undoubtedly reflects bedding (S0). The earliest

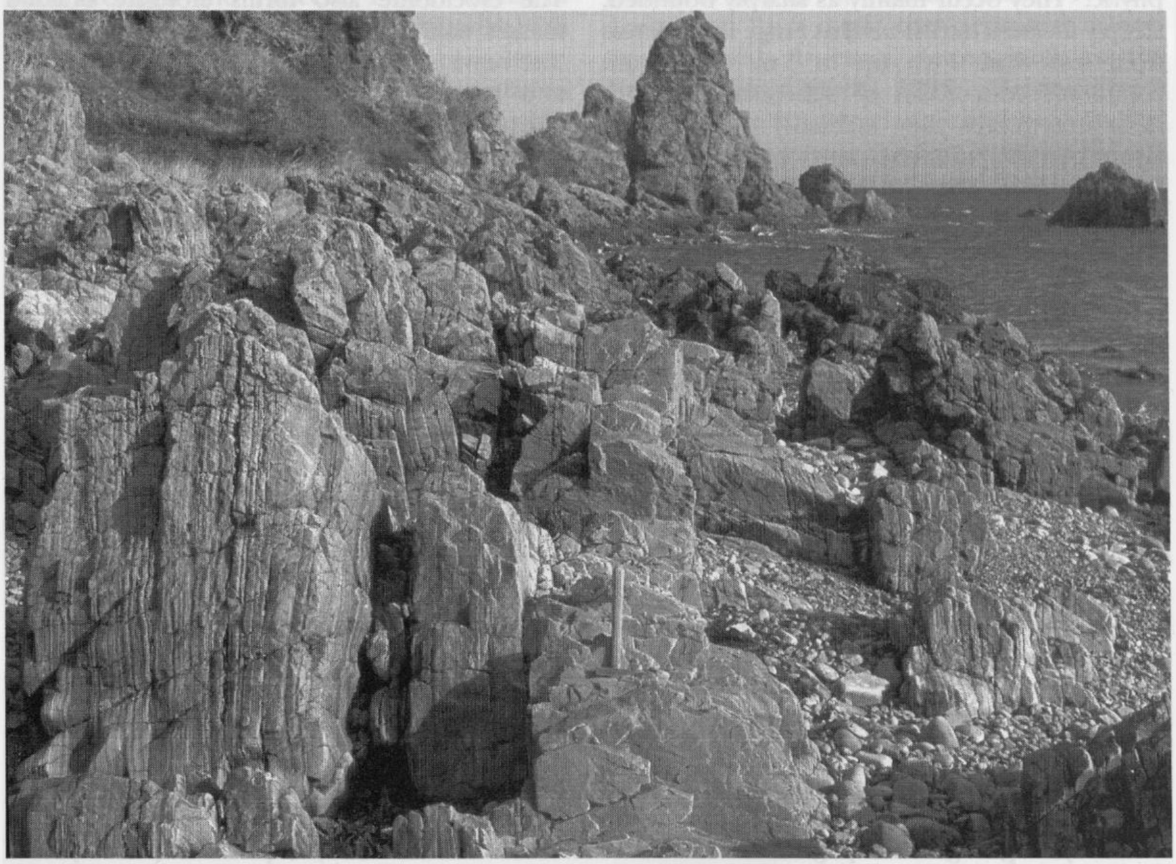

**Figure 6.52** Salmon-pink lineated and foliated leucocratic microgranite vein cutting subvertical, thinly banded amphibolitic felsic Lewisianoid gneisses. The hammer is 37 cm long. Learnie shore (NH 7620 6124). (Photo: J.R. Mendum, BGS No. P581260, reproduced with the permission of the Director, British Geological Survey, © NERC.)

folds seen are tight to isoclinal, minor F2 folds of the layering and S1 schistosity, and commonly show curvilinear axes. A related intense mineral rodding lineation (L2) normally plunges moderately to gently to the north-east. F2 folds and fabrics are commonly refolded by the F3 fold structures (e.g. at NH 7689 6111). Minor F3 folds are close to tight, upright asymmetrical structures, whose axes also plunge gently to moderately to the north-east. A good example is seen at NH 7673 6186. In the semipelitic lithologies an axial-planar crenulation cleavage (S3) is developed in the F3 fold hinges. In the north-east part of the site, the D3 and earlier structures and associated fabrics show some minor re-orientation and are locally refolded by a later set of NE-trending F4 open folds, for example at NH 767 617.

Numerous veins and sheets of red to salmon-pink microgranite and granitic pegmatite cut the metamorphic rocks in the inlier. The microgranites are leucocratic and variably K-feldspar-phyric. They occur mainly as sharply bounded, steeply inclined intrusions that range in thickness from less than 1 cm up to 5 m. They are commonly concordant or subconcordant, but in several places they markedly cross-cut the layering in the psammites and striped mafic and felsic gneisses. They are folded by the F2 and F3 structures and even show excellent interference structures. Examples of folded veins and original or tectonically enhanced cross-cutting relationships are seen at NH 767 617. In places the veins show necking and locally they are boudinaged. In some instances the microgranite veins appear to post-date F2 folds but they carry a variably developed foliation and a strong quartz rodding lineation, both of apparent D2 age. On the long limbs of the upright F3 folds (NH 771 626) the intrusions are attenuated, and characterized by an L–S fabric, defined by orientated muscovite and biotite laths and quartz-feldspar ribbons. In the porphyritic microgranite the microcline phenocrysts form augen, which locally show asymmetrical quartz-feldspar tails. On the short limbs of these structures, the intrusions dip more gently and show a concomitant increase in thickness. These intrusions are themselves cross-cut by several younger granitic pegmatite intrusions that largely post-date the folding events, for example at NH 767 617.

Minor cataclasite and pseudotachylite veining are present along the coastal outcrop of the Rosemarkie Metamorphic Complex, but the main late-stage brittle deformation features are steep to vertical brittle fractures and zones of brecciation that disrupt much of the outcrop (e.g. at NH 7576 6088). Most of the observed fault planes trend between north and NNW; only a few trend parallel to the nearby NE-trending Great Glen Fault. Mineralization is commonly associated with these fractures, which contain abundant pyrite, disseminated hematite and manganese. The Rosemarkie rocks are also cut by SE-dipping, low-angle faults, which exhibit both normal and reverse movements. A fine example of this is found at the nearby Cairds Cave (NH 7455 5954). The age of movement on these structures is uncertain. An important phenomenon in the history of the Great Glen fracture system is found adjacent to the south-east corner of the site at NH 7502 5992. Here, irregular veins of breccia full of blue crocidolite ('blue asbestos'), accompanied by abundant carbonate and prehnite-rich veins, are present. The crocidolite also forms elongate braided masses at the margins of the carbonate veins. The veins both cut across, and are cut by, major and minor brittle deformational structures. These fenite occurrences are the products of late Caledonian alkali metasomatism and probably link to the other occurrences farther south-west (Deans *et al.*, 1971; Garson *et al.*, 1984). They may link to the appinitic bodies and Ach'uaine hybrids that formed small but widely occurring intrusions coeval with the intrusion of many of the granodiorite plutons in the Grampian and Northern Highlands at around 425 Ma.

## Interpretation

The metamorphic rocks of the Rosemarkie and Cromarty inliers reveal a complex history of tectonometamorphic and igneous events. The status of the two inliers has yet to be fully established; published interpretations to date have focused mainly on their lithological and structural differences (Rathbone and Harris, 1980). The metasedimentary rocks of both inliers have lithological affinities with the Moine succession to the west and south-west of the Devonian cover sequence, and may correlate with the Loch Eil Group rocks (cf. May and Highton, 1997).

The Cromarty and Rosemarkie inliers have very different manifestations of granitic magmatism. The strong deformation of the abundant leucogranite intrusions at Rosemarkie shows that they were intruded early in the tectonic history of the inlier. Rathbone and Harris (1980) interpreted them as syn-D2, which accords with their overall structural relationships. Pink to red leucogranite veins are also found farther south-west along the Great Glen around Fort Augustus and in Ardgour (Stoker, 1983). In other parts of the world they are characteristic of large transpressional shear-zones, and leucogranite emplacement can be shown to be coeval with ductile lateral movements. Documented examples are the Red River Fault Zone that separates South China from Indochina (Leloup *et al.*, 1995), and the Karakoram fault zone in northern Ladakh (Searle *et al.*, 1998).

In contrast, the granitic rocks of the Cromarty Inlier are little deformed and are similar to other syn- to late-Caledonian granitic vein-complexes in the Highlands, such as those at Glenmoriston (May and Highton, 1997) and Glen Kyllachy (van Breemen and Piasecki, 1983). Areas of 'granitized' host rocks that pass into granite with restite fabrics are typical of such complexes. This feature is indicative of local assimilation during late-tectonic granite magmatism, rather than partial melting at high metamorphic grade (Rathbone and Harris, 1980). The cross-cutting form of most granite and pegmatite intrusions within the outcrop shows that the granitic melts were divorced from their source area.

The status of the amphibole-bearing lithologies within the Rosemarkie Inlier is also significant. Unequivocal metagabbro, amphibolite and schistose amphibolite of similar structural age are common to both the Rosemarkie (Highton in Fletcher *et al.*, 1996) and Cromarty inliers (Rathbone and Harris, 1980), and occur extensively in the Moine succession farther west (see **Comrie** GCR site report, this chapter). However, in the Rosemarkie GCR site, Rathbone and Harris (1980) noted the absence of garnet-bearing amphibolites, normally common in the early metabasic intrusions in the Moine succession. This led them to suggest that all amphibolite-bearing rocks here should be assigned to the Lewisianoid gneisses, even though in several instances the amphibolites intrude the dominantly psammitic host rock. The status of other amphibolite-bearing lithologies, such as the quartzofeldspathic gneisses with sparse hornblendic layers, is also questionable given the significant high strain in this part of the outcrop and the possible Neoproterozoic age for many of the basic meta-igneous rocks (Highton in Fletcher *et al.*, 1996). However, recent zircon U-Pb LA-MC-ICP-MS dating has shown that the striped mafic and felsic gneisses have a protolith age of between 2720 Ma and 2930 Ma, confirming their Lewisianoid identity (Mendum and Noble, in press).

The presence of the Lewisianoid rocks adjacent to the Great Glen Fault is critical to any interpretation of the tectonic history of the inliers, but its explanation is unclear. Harris (1995) interpreted the earliest ductile fold structures (F2) in the Rosemarkie Inlier as possibly formed during ductile transpression within the Great Glen Fault Zone, coeval with the main crustal shortening across the orogen. This implies significant early ductile displacement to juxtapose the Moine and Lewisianoid assemblages prior to regional tectono-metamorphism. In view of recent age dating from both the Northern and Central Highlands (Noble *et al.*, 1996; Friend *et al.*, 1997), the Great Glen Fault might then represent a long-lived crustal structure dating back to the Neoproterozoic (Harris, 1995). However, work on the mylonites, cataclasites and breccias that mark the fault zone in the Fort Augustus to Loch Linnhe section to the south-west has shown that such features can be explained as a product of both sinistral ductile and later brittle displacements of late Caledonian age (Stewart *et al.*, 1997, 1999).

Recent dating of zircons and monazites from the microgranite veins and the adjacent striped hornblendic and felsic gneisses of the Rosemarkie Inlier has thrown some light on its tectonometamorphic history (Mendum and Noble, 2003, in press). U-Pb TIMS isotopic dating has shown that the leucocratic microgranites were intruded at *c.* 400 Ma, coeval with the mid-Devonian Acadian event. Microgranite intrusion and subsequent deformation ('D2', 'D3') and the rapid differential uplift of the Rosemarkie Inlier, are all interpreted as a product of sinistral transpressional movements along the Great Glen Fault. Lateral movements totalling 25–30 km and uplift of some 15 km are implied. Such movements must have been completed prior to deposition of the mid-Devonian succession in the Eifelian giving a maximum timespan of only some 6–7 million years for the deformation and exhumation of the inlier. However, questions still remain as to the role of the D1 deformation, nature of the Moine–Lewisianoid relationships, age of the mafic intrusions, and pressure and temperature conditions accompanying the short-lived Acadian event.

The late history of the fault zone is entirely brittle, with lateral and vertical movements during the mid- to late Devonian. Fluid infiltration at this time is manifest in substantial carbonate veining, fluidized breccia dykes with carbonate matrices, fenitization and mineralization (Garson *et al.*, 1984). The fault system underwent dextral reactivation, firstly as a consequence of compression in late-Carboniferous–Permian times, and as an extensional structure during Permo–Triassic and late Jurassic rifting (Underhill and Brodie, 1993). It was also the site of Mid-Cretaceous to Neogene regional uplift.

Although the Rosemarkie Inlier coincides, in part, with a prominent aeromagnetic anomaly along the Great Glen Fault Zone, neither the Lewisianoid gneisses nor the metabasic rocks are thought to be the source of this anomaly. The source may reflect the presence of Early Proterozoic-age basement at shallow to mid-crustal levels adjacent to the fault zone (Rollin in Fletcher *et al.*, 1996).

## Conclusions

The Rosemarkie and Cromarty Inliers GCR site presents a unique perspective of one of the most important fault structures within the Caledonian orogenic belt, the Great Glen Fault Zone. The site covers two separate 'basement' inliers situated immediately adjacent to the fault zone and surrounded by Mid-Devonian sandstones and conglomerates, which unconformably overlie the 'basement' rocks.

The two inliers are lithologically and tectonically different. In the Rosemarkie Inlier rocks of Lewisianoid affinity occur within the partially gneissose sequence of Moine psammites and semipelites. The Lewisianoid and Moine rocks show little evidence of either an original unconformable relationship, tight interfolding, or of obvious tectonic discontinuities. The rocks are highly deformed and show fine-scale interlayering of the amphibolitic mafic and quartzofeldspathic rock-types. Amphibolitic mafic pods and sheets intrude both the Lewisanoid and Moine rocks. Abundant pink to red leucogranite veins intrude the interleaved Lewisianoid and Moine rocks; they post-date the first deformation episode, yet are tightly folded, lineated and strained during the main ductile deformation episodes (termed 'D2' and 'D3'). The leucogranite veins, whose emplacement has been dated by U-Pb methods on zircon and monazite at *c.* 400 Ma, appear to have been emplaced at a very early stage of this deformation.

The Cromarty Inlier consists of psammites and semipelites with amphibolitic mafic pods and lenses. It exposes a fine example of a granitic vein-complex and its localized interaction with the host rocks. The emplacement age of the granitic material remains unknown but may be Late Silurian or Mid-Devonian. The aspects of the late brittle faulting and metasomatism along the Great Glen Fault Zone are also uniquely preserved here.

The formation of the inliers is attributed to deformation and exhumation resulting primarily from sinistral transpressional movements along the Great Glen Fault Zone during the Acadian event between *c.* 400 Ma and 393 Ma. The two inliers are interpreted as fault-bounded lenticular 'basement' pods that have been uplifted relative to the surrounding areas during this short-lived mid-Devonian compressional event. Interleaving of Lewisianoid and Moine rocks and the generation of an early bedding-parallel schistosity pre-date this deformation and uplift. These early events may be Neoproterozoic, Ordovician or Silurian in age. Subsequent to Devonian uplift both inliers have experienced fracturing, brecciation and some metasomatic activity.

The Cromarty and Rosemarkie Inliers GCR site is of international importance in that it provides crucial evidence of the tectonic development of Scotland during the Acadian event, which is lacking elsewhere. The site also presents an excellent opportunity to study the structural dynamics within a major zone of crustal shear and transcurrent faulting. The site remains suitable for further studies of the geological relationships and the relative timing of the intrusive, structural and metamorphic events.