Port Vasgo–Strathan Bay

[NC 572 659]–[NC 588 646]

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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 meta-conglomerate 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 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 2–3km 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. Petite 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 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 chlorine rims are a product of the late retrogression. Garnetiferous seznipelitic 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 [NC 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 petite 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 petite 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 down-throw 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* ed., 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 volcanidastic 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 preexisting, 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 hiller. 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 Ll 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 Mean an t-Sithe and Creag Rainich GCR site report, Chapter 7).

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

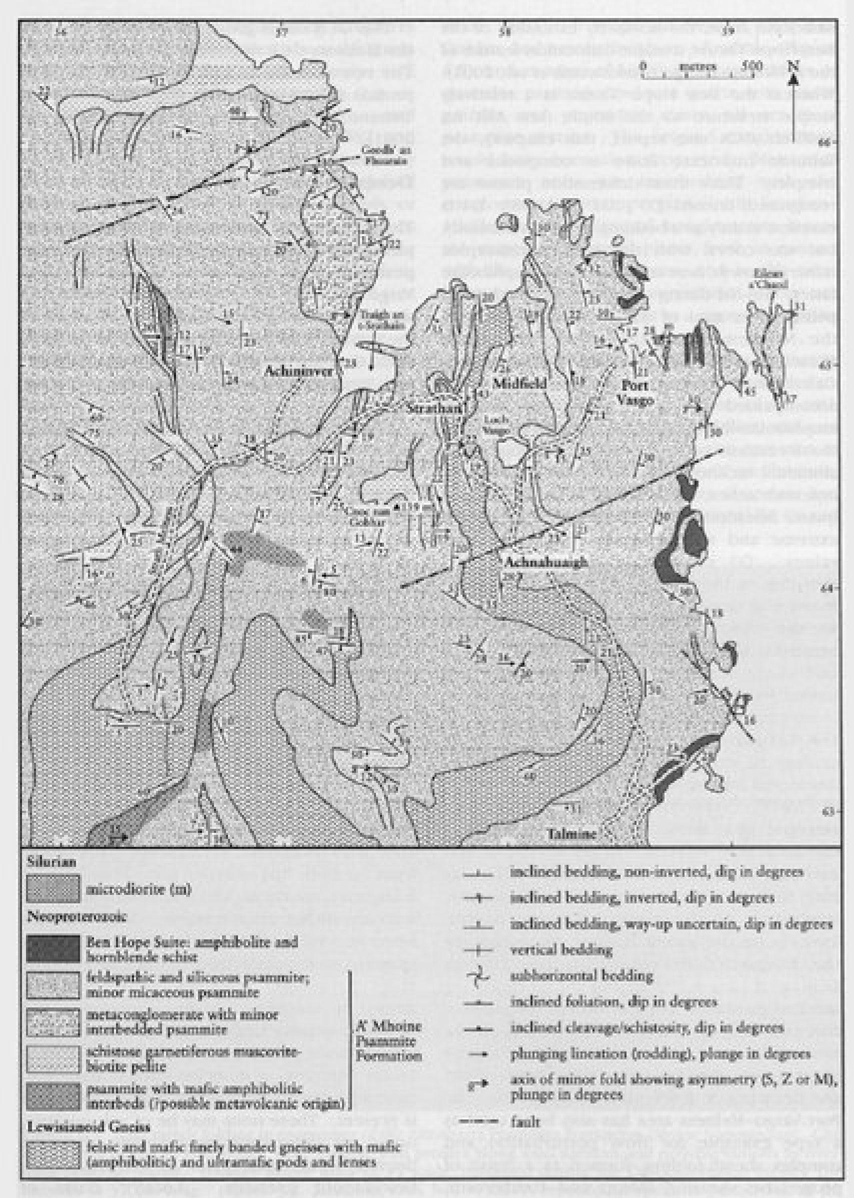
GCR site report, this chapter). The zone was formed by the overall WNW translation of the Moine and Lewisianoid rocks in the A' Mhoine Nappe towards the foreland during the Caledonian Orogeny. The structural complexities are well displayed at outcrop scale and have been used to illustrate differing models 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 volcanicla,stic 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.

References



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

(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.)