Coldbackie Bay

[NC 605 604]–[NC 612 606]

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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* at, 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 hiller, 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 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 quartzofeldspathic 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, Wand SW-verging (Z-profile), minor- and medium-scale F2 folds. The S2 fabric is axial planar to F2 structures, and its orientation lies dose 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 preexisting 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 13 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 synforrn + 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 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 southeasterly 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 outcrops 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 down-throw 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).

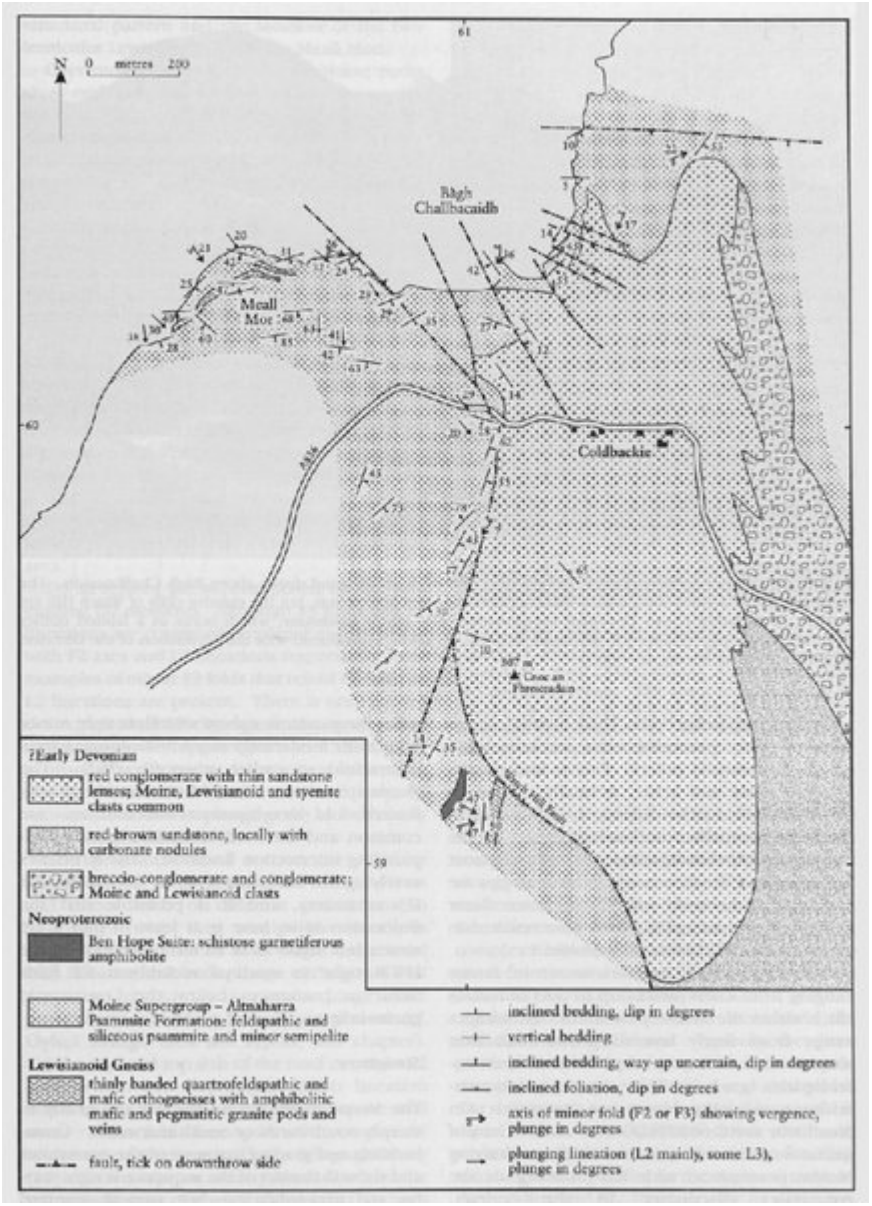
Conclusions

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

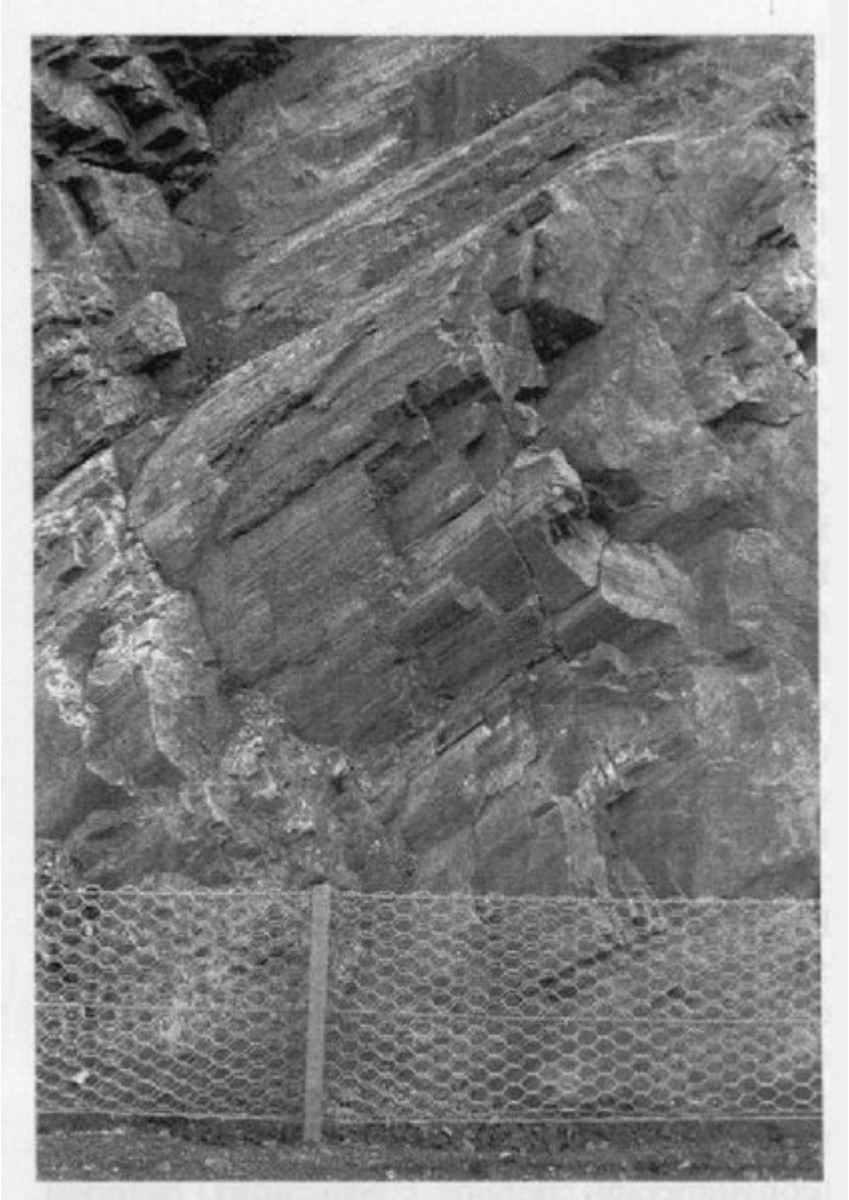
study.

References



(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 Bagh 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.)



(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.)