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 9

Lewisian and Moine of Shetland

INTRODUCTION

D. Flinn

The Shetland Isles lie about 165 km north-east off the Scottish mainland, and are almost halfway between Scotland and Norway. Geologically, much of Shetland is an inlier of Caledonian and pre-Caledonian metamorphic rocks, surrounded by Devonian (Old Red Sandstone) and younger rocks. Correlation of the Precambrian metamorphosed units with the mainland has been based on lithological similarities, aided by radiometric dating and seismic reflection profiles. The rocks within the inlier have been correlated tentatively with those in Scotland, but it should be noted that the correlative work on Shetland has been carried out by geologists more conversant with Scottish geology than with that of Norway.

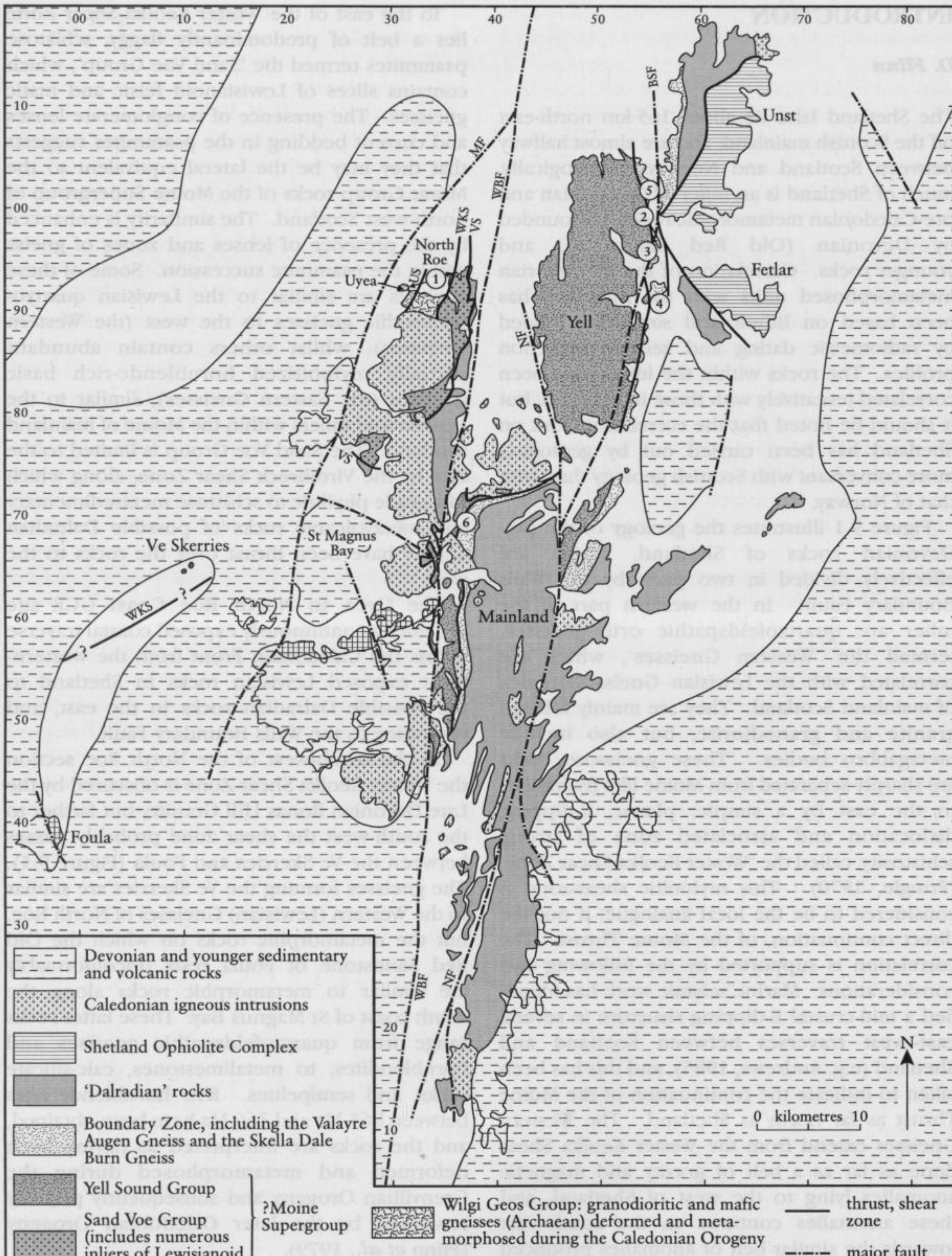
Figure 9.1 illustrates the geology of the pre-Devonian rocks of Shetland, which are effectively divided in two parts by the Walls Boundary Fault. In the western part of the inlier are quartzofeldspathic orthogneisses, termed the 'Western Gneisses', which are correlated with the Lewisian Gneiss Complex of mainland Scotland. They are mainly foliated granite and granodiorite, but also include metagabbro bodies. These gneissose rocks are sharply separated from Moine-like psammites to the east by a simple, planar, E-dipping dislocation and associated zone of strong schistosity, called the 'Wester Keolka Shear Zone' (Pringle, 1970). This mylonitic shear-zone is considered to be the local analogue, if not the direct continuation, of the Moine Thrust. The correlation is supported by the following two considerations. Marine seismic work has identified a mid-crustal E-dipping structure in several east–west traverses between Scotland and Shetland (e.g. Andrews, 1985), and this has been taken to indicate the continuation of the Moine Thrust as far north as Shetland. The Western Gneisses extend from the Wester Keolka Shear Zone as far as a belt of gravity and magnetic anomalies lying to the west of Shetland, and these anomalies continue to the south-west towards the similar belt of anomalies produced by the Lewisian of north-west Scotland. K-Ar hornblende ages ranging from 2873 Ma to 2661 Ma have been obtained from the basic gneisses (Uyea Group) in the Western Gneisses (Flinn *et al*., 1979).

To the east of the Wester Keolka Shear Zone lies a belt of predominantly flaggy, schistose psammites termed the 'Sand Voe Group', which contains slices of Lewisianoid felsic and mafic gneisses. The presence of conglomerate lenses and current bedding in the psammites suggests that they may be the lateral equivalent to the Morar Group rocks of the Moine Supergroup of north-west Scotland. The similarity is enhanced by the presence of lenses and zones of gneiss within the psammite succession. Some of these gneisses are similar to the Lewisian quartzo-feldspathic gneisses to the west (the Western Gneisses), whilst others contain abundant partially mylonitized hornblende-rich basic gneisses (the Eastern Gneisses), similar to the Lewisianoid inliers within the Moine of mainland Scotland. The Sand Voe Group is limited to the east by the Virdibreck Shear Zone, along which low-grade phyllitic to schistose metasedimentary and metavolcanic rocks of possible Dalradian affinity have been thrust over the rocks to the west.

The **Uyea to North Roe Coast** GCR site provides a continuously exposed coastal traverse across the Caledonian Front from the western-most exposed Lewisian rocks in Shetland to the possible Dalradian rocks in the east, and extending to the Walls Boundary Fault.

To the south-west of the North Roe section the Wester Keolka Shear Zone is obscured by the Late Devonian Ronas Hill Granite, but farther to the south-west the shear zone probably passes between the Ve Skerries and Foula (Figure 9.1). The gneisses forming the Ve Skerries are similar to the Western (Lewisian) Gneisses of North Roe, but the metamorphic rocks on which the Old Red Sandstone of Foula rests unconformably are similar to metamorphic rocks along the south coast of St Magnus Bay. These latter rocks range from quartzofeldspathic gneisses and hornblendites, to metalimestones, calc-silicate rocks, and semipelites. K-Ar hornblende ages between 863 Ma and 366 Ma have been obtained, and the rocks are interpreted as having been deformed and metamorphosed during the Grenvillian Orogeny and subsequently partially reworked by the later Caledonian Orogeny (Flinn *et al*., 1979).

The metamorphic rocks to the east of the Walls Boundary Fault have been termed the 'East Mainland Succession' (Flinn *et al*., 1972), and have been divided into four 'divisions' which have been correlated with different parts of the


Unst
Fetlar
Yell
North Roe
Uyea
St Magnus Bay
Ve Skerries
WKS
Mainland
Foula
0 kilometres 10
N
Devonian and younger sedimentary and volcanic rocks
Caledonian igneous intrusions
Shetland Ophiolite Complex
'Dalradian' rocks
Boundary Zone, including the Valayre Augen Gneiss and the Skella Dale Burn Gneiss
Yell Sound Group
Sand Voe Group (includes numerous inliers of Lewisianoid gneisses)
?Moine Supergroup
metasedimentary rocks affected by Grenvillian orogenesis
Wilgi Geos Group: granodioritic and mafic gneisses (Archaean) deformed and metamorphosed during the Caledonian Orogeny
Uyea Group: granodioritic and mafic gneisses (Archaean)
thrust, shear zone
major fault

◄**Figure 9.1** Simplified geological map of Shetland, showing the major rock units and structures. US – Uyea Shear Zone; VS – Virdibreck Shear Zone; WKS – Wester Keolka Shear Zone; MF – Melby Fault; WBF – Walls Boundary Fault; NF – Nesting Fault; BSF – Bluemull Sound Fault. GCR sites: 1 – **Uyea to North Roe Coast**; 2 – **Gutcher**; 3 – **North Sandwick**; 4 – **Cullivoe**; 5 – **Hascosay**; 6 – **Voxter Voe and Valayre Quarry**.

Moine and Dalradian successions of the Scottish mainland (Flinn, 1988). In the north-west, the rocks of the Yell Sound Group resemble the Loch Eil and Glenfinnan groups of the Moine Supergroup. The other three divisions, which are exposed in the south and east of Mainland Shetland, and also on the islands of Unst and Fetlar, have been correlated with the Dalradian Supergroup. They are described in the GCR Volume *Dalradian Rocks of Scotland* (Stephenson *et al.*, in prep). On Unst and Fetlar the 'Dalradian' rocks are overlain tectonically by the Shetland Ophiolite Complex, which has been described in the GCR Volume *Caledonian Igneous Rocks of Great Britain* (Stephenson *et al.*, 1999).

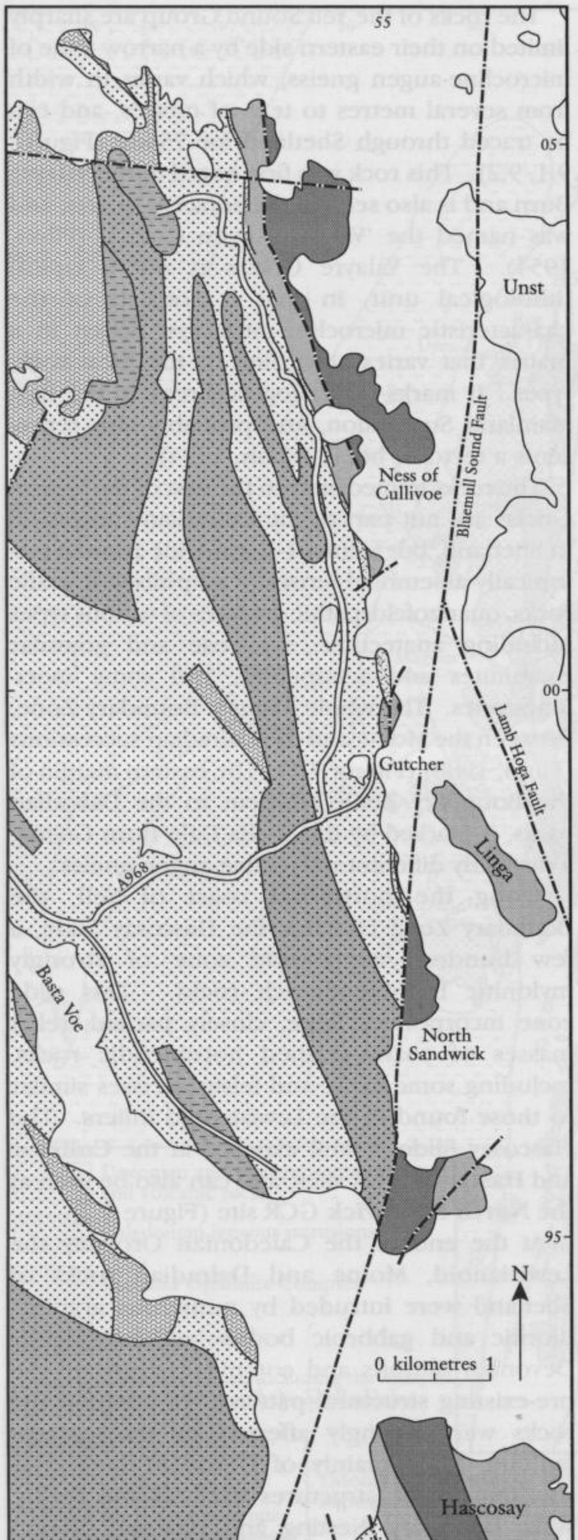
The Yell Sound Group rocks are best exposed in the cliffs of Yell, but can be traced to the south-west onto Mainland, first as a series of thermally metamorphosed xenoliths or roof pendants in the intrusive igneous rocks of the Graven Complex, and then in coastal sections adjacent to and east of the Walls Boundary Fault. They are correlated with the Moine of Scotland because they are composed dominantly of granofelsic psammite (formerly termed 'Moine granulite'), with irregularly distributed garnet-studded, hornblende schist bands and inliers of Lewisianoid hornblendic gneiss (Flinn, 1994). The psammitic succession is interrupted at three levels by large lenticular masses or lenses of quartzite, pelite and semipelite (Flinn, 1994). The **North Sandwick** GCR site provides good exposures of one of these lenses, the Cullivoe 'Lens', together with the adjacent psammites of the Yell Sound Group. Recrystallization has transformed the psammites in some areas of Yell into paragneisses. These and other gneisses may be seen in the **Gutcher** GCR site, and on Mainland Shetland rocks of the Yell Sound Group can be seen in the **Voxter Voe and Valayre Quarry** GCR site.

The rocks of the Yell Sound Group are sharply limited on their eastern side by a narrow zone of microcline-augen gneiss, which varies in width from several metres to tens of metres, and can be traced through Shetland for 75 km (Figures 9.1, 9.2). This rock was first noted in the Valayre Burn and is also seen in the adjacent quarry, and was named the 'Valayre Augen Gneiss' (Flinn, 1954). The Valayre Gneiss is not a typical lithological unit, in that it consists of the characteristic microcline-megacryst augen in a matrix that varies according to the local rock-types. It marks a lithological break in the East Mainland Succession, and probably also represents a tectonic break (Flinn, 1994).

The rocks immediately to the east of the Valayre Gneiss are not part of the Dalradian succession in Shetland, but form a 1–2 km-wide zone of tectonically assembled lenses of amphibolitic mafic rocks, quartzofeldspathic gneisses of various types including anatectites, schistose and granular psammites and semipelites, and some meta-limestones. The whole forms a Boundary Zone, between the Moine and the Dalradian successions (Flinn, 1988) (Figure 9.1). The eastern margin of the Boundary Zone, adjacent to the Dalradian rocks, is marked by the Skella Dale Burn Gneiss, a distinctly different microcline-augen gneiss.

Along the north-east coast of Yell, the Boundary Zone contains the Hascosay Slide, a few hundred metre-wide zone of strongly mylonitic hornblende-rich rocks. This slide zone incorporates large, closely packed, relict masses of coarse-grained hornblendic rocks, including some mafic and felsic gneisses similar to those found in the Lewisianoid inliers. The Hascosay Slide is well exposed at the **Cullivoe** and **Hascosay** GCR sites, and can also be seen at the **North Sandwick** GCR site (Figure 9.2).

At the end of the Caledonian Orogeny the Lewisianoid, Moine and Dalradian rocks of Shetland were intruded by numerous granitic, dioritic and gabbroic bodies. These mainly Devonian plutons and complexes truncate the pre-existing structural pattern. In addition the rocks were strongly affected by transcurrent faulting, again mainly of Devonian age. The resulting major structures such as the Melby, Walls Boundary, Nesting and Bluemull Sound faults control both the distribution of lithological units and strongly influence the topography of Shetland (Figure 9.1).



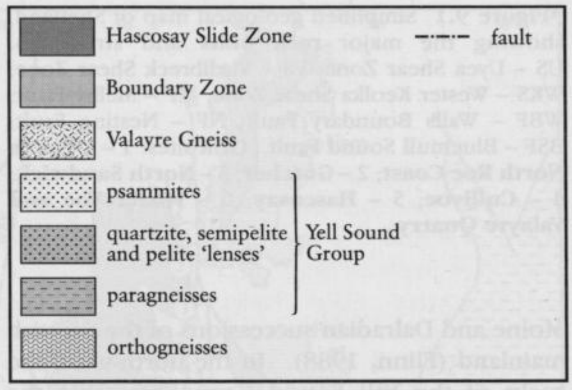


Figure 9.2 Map of the north-east coast of Yell showing the main rock units and the locations of the **Gutcher**, **North Sandwick**, **Hascosay** and **Cullivoe** GCR sites. After 1:50 000 Sheet 130, Yell (British Geological Survey, 1994).

UYEA TO NORTH ROE COAST (HU 310 930–HU 380 950)

D. Flinn

Introduction

The N-facing cliffs of North Roe in the north-west part of Mainland Shetland present a continuously exposed and mostly accessible section through the Caledonian Front (Figure 9.3). From west to east, the section consists of: Lewisian gneisses (the Western Gneisses), overthrust from the east by Moinian psammites containing tectonically emplaced Lewisianoid inliers, which are in turn overthrust from the east by metasedimentary rocks and greenschists of probable Dalradian affinity. These Shetland exposures extend the basic tectonic features and lithologies of the Caledonian Front seen in mainland Scotland some 230 km to the north, about halfway to Norway. The thrusts in Shetland dip more steeply and are associated with higher-grade metamorphism than in mainland Scotland, so that the area is of national and international importance in studies of the Caledonides.

The area was mapped by J Phemister for the Geological Survey between 1930 and 1932 (see Wilson, 1932 for brief description) and in more detail by Pringle (1964, 1970). Subsequent work has refined the understanding of the structure and wider stratigraphical correlation of the units

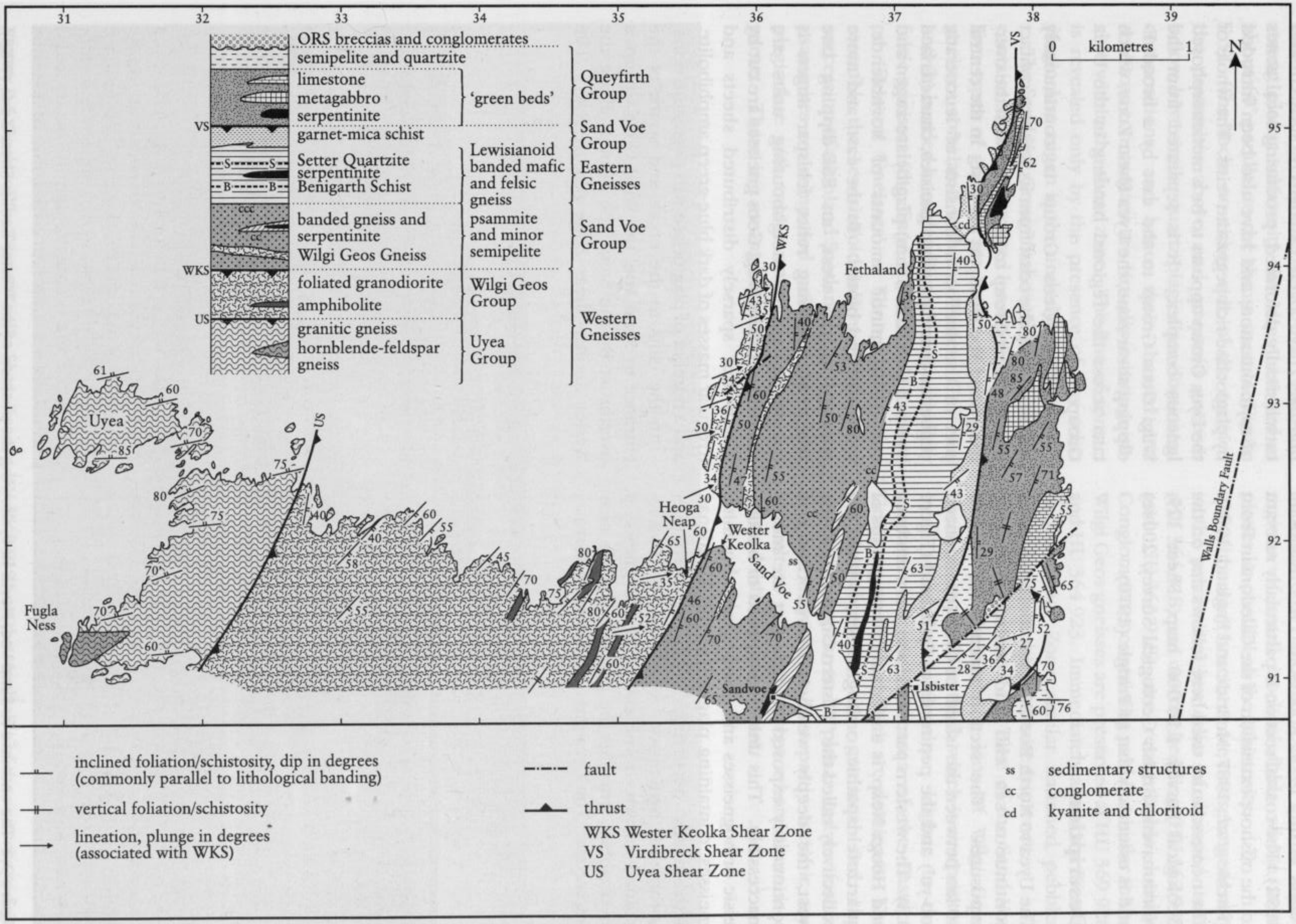


Figure 9.3 Map of the Uyea to North Roe Coast GCR site, North Maven, Mainland, Shetland.

(Flinn *et al.*, 1979; Robinson, 1983; Roddom, 1992). The coastal section is particularly relevant to the offshore extension of the Caledonian Front (Ritchie *et al.*, 1987; McBride and England, 1994). The nomenclature used here follows that on the Geological Survey 1:50 000 map, Sheet 129, Northmaven (British Geological Survey, 2004e) and is essentially that of Pringle (1970).

Description

The Uyea to North Roe GCR site comprises near-continuous sea cliff and limited foreshore exposures. The section extends for roughly 10 km between the island of Uyea (pronounced 'oo-ye') and the peninsula of Fethaland (Figure 9.3). The western part of the site, between Uyea and Heoga Neap, is underlain by two groups of quartzofeldspathic orthogneisses, which are collectively called the 'Western Gneisses'. In the west, the deeply weathered Uyea Group is continuously exposed in cliffs that are mostly inaccessible. This unit is composed of banded felsic orthogneisses and coarse-grained granitic gneisses, containing plagioclase and K-feldspar, with locally occurring bands of pyroxene-hornblende mafic rock. A large body of coarse-grained brown hornblende-feldspar gneiss, a metagabbro, intrudes the granitic gneisses near Fugla Ness. The Uyea gneisses are not schistose, but they have been extensively sheared and cataclastically deformed, producing local zones of mylonitization, and have also been intruded by plagioclase-rich pegmatite veins. The whole of the Uyea Group appears to be a metamorphosed igneous complex. It is separated from the Wilgi Geos Group to the east by a broad E-dipping shear-zone, the Uyea Shear Zone, which cuts across the regional banding in the Uyea Group.

The Wilgi Geos Group is continuously exposed along the coast from its western contact with the Uyea Group to its contact with the overlying Sand Voe Group in the east. In the central part of the section it consists of leucocratic oligoclase-quartz granitoid gneisses, characterized by small (less than 5 mm) plagioclase augen and containing minor amounts of hornblende, muscovite and biotite. To the east, and more strongly to the west, an ESE-dipping late schistosity enclosing relict feldspar augen is developed as the neighbouring units are approached. The Wilgi Geos gneisses are cut by widely but sparsely distributed sheets and irregular masses of dark blue-green amphibolite, and a number of plagioclase-rich pegmatite veins.

In the cliffs to the north and south of the entrance to Sand Voe, the Wilgi Geos Group is overthrust by the Sand Voe Group, along the Wester Keolka Shear Zone (Figure 9.4). The

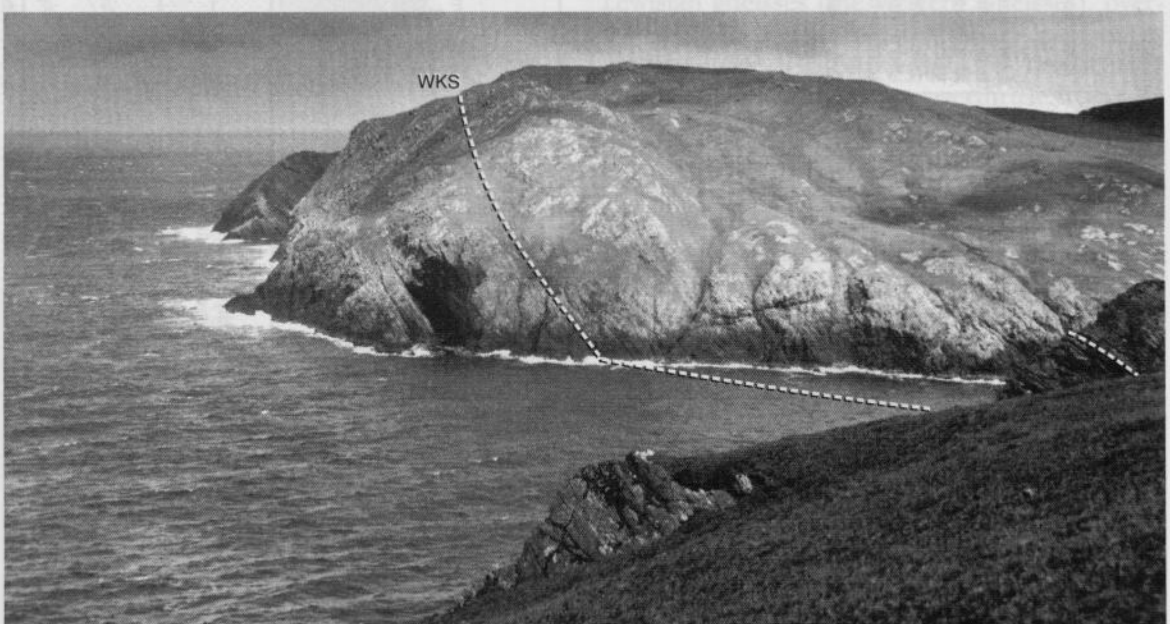


Figure 9.4 The entrance to Sand Voe, North Roe, showing the position of the Wester Keolka Shear Zone (WKS). View northwards from HU 3560 9191. (Photo: D. Flinn.)

shear zone is characterized by a consistent strong planar schistosity that dips eastward at about 60° parallel to the thrust contact (Figure 9.5). The rocks on either side of the contact, the psammites above, and granitoid gneisses below, have similar quartz-plagioclase-dominated compositions, and hence their sheared and schistose counterparts are virtually indistinguishable within the shear zone. The line of contact is revealed only by the presence of tiny relict plagioclase augen in the underlying gneisses.

The Sand Voe Group is about 830 m thick and contains several intercalated lenses of orthogneiss. Two types of gneisses are found: (a) granitoid gneisses correlated with the Western Gneisses; and (b) banded hornblendic mafic and subsidiary felsic gneisses (the 'Sand Voe Banded Gneisses' or 'Eastern Gneisses' – Flinn, 1988) that resemble the Lewisianoid inliers in the Moine succession of mainland Scotland. The dominant psammites are composed mainly of quartz and plagioclase with minor amounts of micas and garnet. There is a strong schistosity parallel to compositional layering, except in the hinge regions of small isoclinal folds whose axial planes lie parallel to the schistosity.

Sedimentary structures are not seen generally in the psammites, but relics of slumped units (HU 364 918) and current bedding (HU 362 915 and HU 363 918) are recognizable locally. Conglomerates containing pebbles similar to the Wilgi Geos gneisses are preserved at HU 369 926 and HU 364 923. Immediately above the Wester Keolka Shear Zone similar flattened pebbles occur locally in the psammite sequence.

Some 50 m above the base of the Sand Voe Group is a cross-cutting lens of Wilgi Geos gneisses, up to 100 m thick, which is overprinted by a secondary schistosity. Higher in the psammite succession lenses of the Eastern Gneisses, up to 50 m thick are dominant. The contacts between the gneisses and the psammites appear to be planar and conformable, but they are at least partly tectonic and difficult to pinpoint except where there is a marked lithological contrast.

Figure 9.5 Rocks of the Wester Keolka Shear Zone at HU 3560 9191 on the south side of the entrance to Sand Voe, North Roe. The coin lies over the shear plane and is 2.5 cm in diameter. (Photo: D. Flinn.)

The psammites of the Sand Voe Group become very platy and fissile at the junction with the overlying Eastern Gneisses. These mainly Lewisianoid gneisses are about 230 m thick, and similar lithologies occur in the Hascosay Slide Zone on Yell (see **Cullivoe** GCR site report, this chapter). They are of striking appearance, being mainly whitish and quartzofeldspathic, but with very sharply defined dark-grey to greenish-black mafic laminations, and thin bands. The dark layers represent concentrations of hornblende with garnet, biotite and epidote. They are typically continuous, parallel and generally rectilinear, with locally up to 25 laminations per centimetre. Within these banded gneisses, and wrapped by the laminations, are mainly unfoliated lenses of other rock-types varying in size from tens of centimetres to tens of metres. They include garnet amphibolite, hornblende-plagioclase gneiss (with augite and garnet), serpentinite, steatite, zoned balls of talc-actinolite-biotite rock (metasomatized serpentinite), and garnet-hornblende-clinopyroxene-quartz granofels. The hornblende in the laminated rocks is blue-green, but locally the unfoliated lenses contain relict brown hornblende and pyroxene.

Certain distinctive layers can be traced within the Eastern Gneisses. At the base of the unit is a persistent layer of schistose garnet-rich psammite some 3 m thick. Some 60 m above the base is the Benigarth Garnet-Mica Schist, a pelitic unit several metres thick that can be traced for many kilometres. Sixty metres higher is the Setter Quartzite, a feldspathic quartzite up to 10 m thick that contains distinctive small pink microcline augen. Again, although only a thin unit, the quartzite can be followed for many kilometres. Neither the quartzite nor the schistose pelite bands are of undoubted sedimentary origin. Lenses of garnet amphibolite and hornblende-plagioclase mafic gneiss occur mainly above the Setter Quartzite in the upper part of the Eastern Gneisses, and are also found in the schistose pelite above.

The schistose garnetiferous pelites and semi-pelites lying to the east of the banded gneisses constitute the upper part of the Sand Voe Group. They are medium-grained garnetiferous, quartz + muscovite-rich schistose pelites with minor amounts of biotite. In places they contain sharply defined bands of muscovite-rich schist with centimetre-sized chloritoid porphyroblasts enclosing kyanite and garnet (HU 375 943). These lithologies can be followed intermittently for some 25 km to the south, as far as Hillswick Ness on the north shore of St Magnus Bay.

The garnetiferous schistose pelites of the Sand Voe Group have been overthrust from the east by the Queyfirth Group along the Virdibreck Shear Zone. Much of the Queyfirth Group in North Roe consists of a thick unit of calcareous, hornblendic and chloritic 'green beds', originally mafic volcanic and volcaniclastic rocks, locally interbanded with thin metalimestone and quartzite beds. Coarse-grained metagabbros also occur in places. The 'green beds' pass up into banded quartzites and psammites with serpentinite bands, interbedded with graphitic phyllite and schistose conglomerate units. Rocks of similar type in south-east Shetland (Flinn, 1967) are considered to belong to the upper parts of the Dalradian Supergroup; hence, the Queyfirth unit is considered to be of similar affinity.

The Virdibreck Shear Zone lies in a zone of strongly developed, fissile schistosity, which is apparently continuous with that found in the garnetiferous pelites of the Sand Voe Group to the west. Unlike the Wester Keolka Shear Zone, the Virdibreck Shear Zone is disturbed by crenulation cleavages, microfolding and larger-scale distortions. These are also common within the Queyfirth Group, together with much late, tight to isoclinal folding accompanied by coarsely lenticular shearing, cataclasis, open folding and faulting. They have been imposed on the early, bedding-parallel penetrative schistosity, which is present in both the Queyfirth and Sand Voe groups.

Interpretation

From their appearance and situation the Western Gneisses have long been considered to be equivalent to the Lewisian Gneiss Complex. This has since been confirmed by K-Ar dating of hornblendes from an early hornblendite intrusion in the Uyea Group, which yielded a spread of ages ranging from 2873 Ma to 2661 Ma (Flinn *et al.*, 1979). Provided there is no excess argon present, this spread is considered to be due to varying amounts of argon loss during a subsequent heating event, and the oldest date is taken to be nearest to the true age of emplacement. Robinson (1983) also obtained an ^{40}Ar-^{39}Ar total fusion age of 2440 Ma for a brown hornblende from the Uyea Group.

An ^{40}Ar-^{39}Ar step-heating age of 439 ± 3 Ma was obtained for blue-green hornblende from a recrystallized relict gneiss lens in the Eastern Gneisses (Robinson, 1983), and Roddom (1992) obtained an ^{40}Ar-^{39}Ar step-heating age of 466 ± 6 Ma from muscovite separated from schistose Wilgi Geos Group rocks immediately beneath the Wester Keolka Shear Zone. He interpreted this as a cooling age for the schistosity, indicating that the Wester Keolka Shear Zone was active at or before this date. He also obtained a date 20 million years younger than this for the Moine Thrust in the Eriboll area of Scotland, throwing some doubt on the direct correlation of the Wester Keolka Shear Zone and the Moine Thrust.

The Sand Voe Group has been broadly correlated with the Moine succession because of its psammitic nature and its structural position in contact with and to the east of the Archaean-age Western Gneisses. The dominantly psammitic lithologies are similar to those of the lower part of the Morar Group in that they contain conglomeratic and pebbly beds and current bedding, and the garnet-studded hornblende schists and calc-silicate bands characteristic of higher levels in the Moine are absent. However, Robinson (1983) pointed out that in detail the psammites of the Sand Voe Group are less feldspathic than those of the Morar Group, exhibit less current bedding and fewer clastic grains, and that heavy-mineral bands are absent. It is possible that the facies is laterally variable, and also that the stronger deformation of the Shetland rocks may have effectively destroyed some of the sedimentary features.

The schistosity superimposed on the Wilgi Geos Group gneisses and dated by Roddom (1992) lies parallel to the Wester Keolka Shear Zone and continues eastwards into the psammites and interbanded pelitic units of the Sand Voe Group and into the Eastern Gneisses with a consistent dip, parallel to the bedding and gneissic layering. It appears to be contiguous with a strongly developed schistosity adjacent and parallel to the Virdibreck Shear Zone, and with the main bedding-parallel schistosity and cleavage in the rocks of the Queyfirth Group. Adjacent to the Wester Keolka Shear Zone, at the base of the Eastern Gneisses, and in the Virdibreck Shear Zone, the schistosity is more strongly developed, such that the rocks are typically fissile, possibly as a result of later deformation.

To interpret this fabric as a single schistosity resulting from a single deformation would be naive in view of the different ages and very different lithologies involved. It is probable that the Eastern Gneisses, with features analogous to those in the Hascosay Slide Zone, formed by extreme heterogeneous deformation of older hornblendic gneisses. This unit is now interlayered with schistose pelitic units of lower competence, which would have preferentially taken up the deformation provided that the two lithologies were deformed at the same time. It seems likely that the schistosities formed at different times in the different lithologies, but have been reactivated during their later assembly.

The late folding, cataclasis, secondary cleavage and faulting distributed throughout the Queyfirth Group were probably related to movements on the Walls Boundary Fault (Flinn, 1977), which lies little more than 1 km to the east of the Virdibreck Shear Zone. Distortions caused by movement on the Walls Boundary Fault would have focused on the shear zone, which acted as a pre-existing surface of weakness, resulting in the fissile enhancement of the schistosity in the adjacent rocks.

The link between the Moine Thrust and the Wester Keolka Shear Zone is still uncertain, and McBride and England (1995) observed that it is not possible to justify the interpretation of the Moine Thrust as a single continuous structure between Scotland and Shetland on geophysical grounds. However, even if the Wester Keolka Shear Zone is not physically connected to the Moine Thrust, it plays a sufficiently similar role to be taken as the Caledonian Front in Shetland. The Western Gneisses link to the west with a belt of gravity and magnetic anomalies that extends south-west from Uyea towards north-west Scotland, defining the Caledonian Foreland (Flinn, 1969; Ritchie *et al.*, 1987).

The course of the Caledonian Front to the north of Shetland has been the subject of recent debate. Ritchie *et al.* (1987) suggested that the Moine Thrust (i.e. the Wester Keolka Shear Zone) trends approximately northwards, across the continuation of the gravity and magnetic anomaly that appears to characterize the foreland. This trend is based on their conclusion that the Caledonian Front must run to the west of a series of boreholes that were drilled in the area of significant gravity and magnetic anomalies, and which yielded granitoid rocks with

Caledonian K-Ar biotite ages (430–360 Ma). However, the Ronas Hill Granite, with a K-Ar age of 358 Ma (Miller and Flinn, 1966), intrudes the Western Gneisses to the west of the Caledonian Front in North Roe, indicating that the borehole evidence alone does not necessarily pin down the position of the Caledonian Front.

Flinn (1992, 1993) suggested that the Caledonian Front intersects, and is offset by, the Walls Boundary Fault north of Shetland and then continues to the north-east along the south side of the belt of gravity and magnetic anomalies, and passing to the south of the boreholes described by Ritchie *et al.* (1987). Ritchie and Hitchen (1993) challenged this conclusion, noting that Flinn's (1992) model failed to take into account the accepted location of the Caledonian Front in east Greenland. Work using more up-to-date palaeogeographical reconstructions (e.g. Higgins *et al.*, 2001), has shown that there is little doubt about the presence of the *c.* 430 Ma Caledonian Front in east Greenland. However, the exact position of the Moine Thrust has not been identified, but it is difficult to see that it would cross the gravity and magnetic anomalies that are believed to mark the Caledonian Front.

McBride and England (1994) could not recognize the Moine Thrust in a seismic line to the north of Shetland, but they did identify a reflective wedge, which they considered might represent a thrust zone below the Moine Thrust itself. They suggested that the Moine Thrust had been truncated by strike-slip movements along the Walls Boundary Fault.

Conclusions

The Uyea to North Roe Coast GCR site is an excellently exposed, roughly 10 km-long coastal section that is representative of the pre-Caledonian and Caledonian metamorphic rocks to the west of the Walls Boundary Fault. It includes rocks of probable Lewisian, Moine and Dalradian affinities, and lies at the most north-easterly extent of these units. The section is undoubtedly of international importance for correlation purposes along the Caledonides orogenic belt.

In the west of the GCR site, between Uyea and Heoga Neap, are exposures of Archaean granitic gneisses and subsidiary mafic rocks (the Western Gneisses) correlated with the Lewisian Gneiss Complex. These have been overthrust from the east, along the Wester Keolka Shear Zone, by psammites and schistose semipelites and pelites, which are interlayered with banded Lewisianoid felsic and mafic gneisses. The over-thrust metasedimentary rocks, the Sand Voe Group, have been correlated with rocks of the Moine Supergroup on the Scottish mainland. The Wester Keolka Shear Zone therefore fulfils a similar role to the Moine Thrust on the Scottish mainland, and it has been suggested that it may be a northern continuation of that structure, marking the position of the Caledonian Front in Shetland. The eastern margin of the Sand Voe Group is marked by the Virdibreck Shear Zone, along which the rocks of the Queyfirth Group have been thrust westwards. The Queyfirth Group is composed of volcanic 'green beds' with quartzite, psammite and semipelite and meta-limestone units. The lithologies have been correlated with the higher parts of the Dalradian Supergroup found in south-east Shetland and on the Scottish mainland.

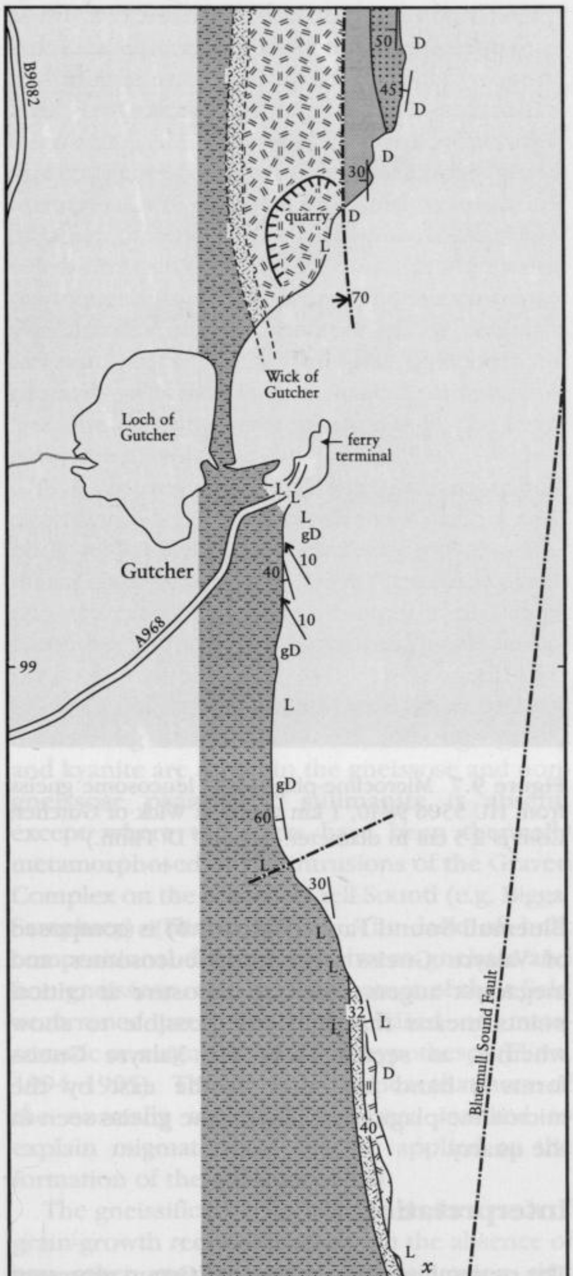
Some 2 km to the south of the coastal section, the Devonian Ronas Hill Granite truncates and hornfelses the successions described above, and this structural sequence is not seen elsewhere. Thus, the Uyea to North Roe GCR site is unique in that it provides the only well-exposed and coherent section across the Caledonian Front in Shetland.

GUTCHER (HU 549 990–HU 551 999)

D. Flinn

Introduction

The section at Gutcher, on the east coast of the island of Yell, provides easily accessible exposures of a variety of rocks typical of the psammitic succession of the Yell Sound Group (formerly the Yell Sound 'division') (Figure 9.6). These include psammites, partly gneissose psammites, microcline-bearing gneisses, microcline-megacryst augen gneisses (the Valayre Gneiss) and hornblende schists. The Yell Sound Group has been correlated with the Glenfinnan Group and Loch Eil Group rocks of the Moine Supergroup in the North-west Highlands of Scotland (Flinn, 1994, 1995).



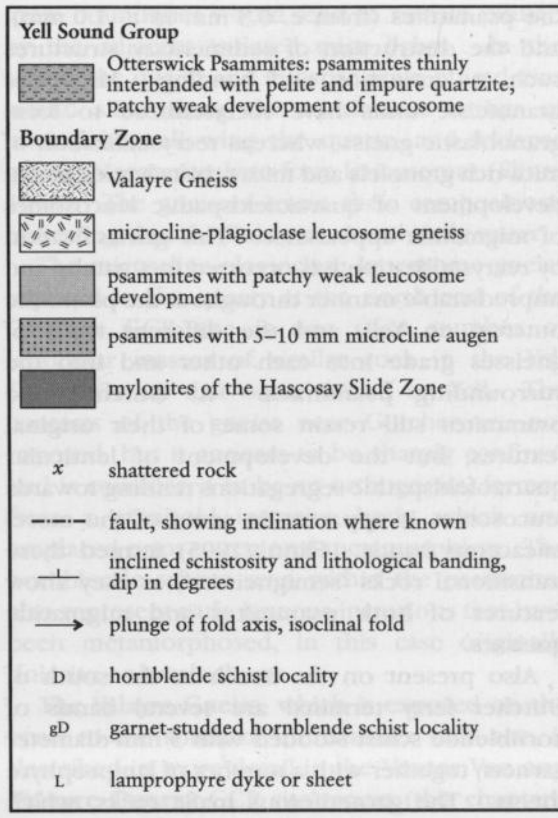


Figure 9.6 Map of the north-east coast of Yell, around the Gutcher GCR site.

Description

The rocks exposed to the south of the ferry terminal at Gutcher belong to the Otterswick Psammites, the highest unit in the Yell Sound Group (Flinn, 1994). Interbanded psammitic and pelitic rocks are exposed on the beach for about 500 m to the south of the pier. The banding is on a scale of 10–20 cm, and is principally defined by variation in mica content of the rocks. Flinn (1994) showed that the fabric of the Yell Sound Group psammites varies gradationally from granofelsic to schistose as a result of increasing preferred orientation of mica flakes and/or increasing grain-size or content of mica. Variation in mica content is typically manifested in the form of lamination and banding, such as that seen at Gutcher.

Over about a third of Yell, the granofelsic and schistose psammites have been transformed partially or completely to gneisses by recrystallization (Flinn, 1995). This process results in a more than three-fold increase of the grain size of the psammites (from c. 0.3 mm to c. 1.0 mm), and the destruction of sedimentary structures such as lamination and banding. Mica-poor granofelsic units have recrystallized to form granoblastic gneiss, whereas recrystallization of mica-rich granofels and mica schists has led to the development of quartzofeldspathic leucosomes of migmatitic appearance. This gneissification by recrystallization has occurred in a patchy and unpredictable manner throughout the psammite outcrop on Yell, and the different types of gneisses grade into each other and into the surrounding psammites. At Gutcher, the psammites still retain some of their original features, but the development of lenticular quartzofeldspathic segregations tending towards leucosomes is apparent in some of the more-micaceous bands. Flinn (1995) termed these transitional rocks 'semigneisses', as they show features of both psammites and migmatitic gneisses.

Also present on the beach to the south of Gutcher ferry terminal are several bands of hornblende schist studded with 5 mm-diameter garnets, together with a number of lamprophyre sheets. The garnetiferous mafic rocks, which represent original doleritic or basaltic sheets and dykes, are commonly found within the Yell Sound Group.

In the quarry to the north of the Gutcher ferry terminal are good exposures of shattered microcline-plagioclase leucosome gneiss that show a complex flow-like structure (Figure 9.7). This lithology is bounded by faults and by non-exposure, but is probably a granitic orthogneiss, analogous to similar rocks occurring elsewhere in the Yell Sound Group (Flinn, 1994). East of the gneiss, exposed in the cliffs but separated by a fault, are partially gneissified psammites, which pass east into interleaved hornblende schist and psammite containing small microcline-megacryst augen. Microcline megacrysts of this kind are typical of the Valayre Gneiss, in which the megacryst augen lie within a matrix composed of the local adjacent lithologies. However, the matrix seen here does not match that of the Valayre Gneiss against which the Yell Sound Group rocks are faulted to the north of the GCR site, and the microcline megacrysts are atypically small. The correlation of these rocks with the Valayre Gneiss is therefore uncertain.

The southern 800 m of the Gutcher coastal section, immediately north of the outcrop of the Bluemull Sound Fault (Figure 9.6) is composed of Valayre Gneiss with both leucosomes and megacryst augen. Lack of exposure at critical points means that it is not possible to show whether, as seems likely, the Valayre Gneiss forms a band bounded to the east by the microcline-plagioclase leucosome gneiss seen in the quarry.

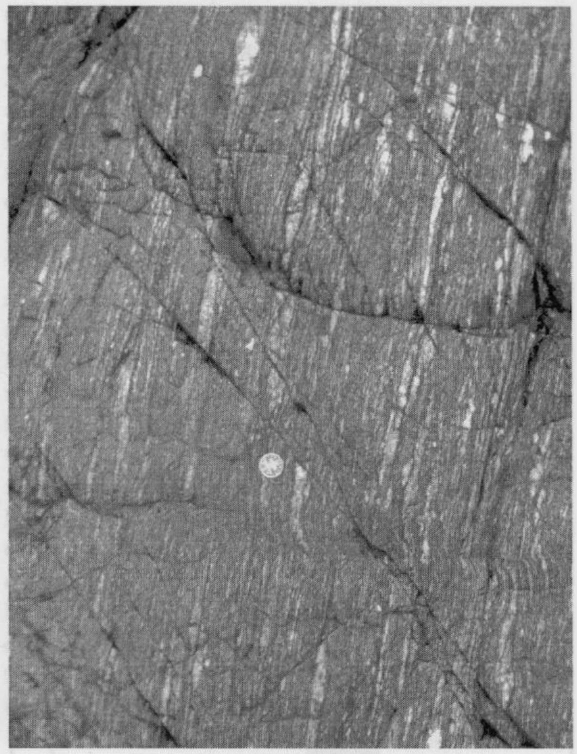


Figure 9.7 Microcline-plagioclase leucosome gneiss from HU 5506 9840, 1 km south of Wick of Gutcher. Coin is 2.5 cm in diameter. (Photo: D. Flinn.)

Interpretation

The psammites of the Yell Sound Group represent a metamorphosed sedimentary succession, which has been correlated with the upper parts of the Moine succession of mainland Scotland, and so is considered to be Neoproterozoic in age. The compositional banding and lamination shown by the unrecrystallized psammites are believed to be relict sedimentary features. However, cross-bedding, grading and conglomeratic units are absent, and the thick succession is characterized by a relatively uniform sedimentary facies, suggesting that it was deposited in deep water. The psammites appear to have originated as sandstones of greywacke composition with a grain size little different to their present state.

The leucosome 'semigneisses', which can be seen at Gutcher are, by textural definition, migmatites, i.e. gneisses that are 'pervasively inhomogeneous on a macroscopic scale' (Ashworth, 1985). Migmatites may be formed by a variety of processes, which include magmatic injection, melting, metasomatism or metamorphic differentiation. The granoblastic gneisses that occur elsewhere in Yell resemble diatexites, not migmatites, and diatexites are normally interpreted as a product of extensive melting of the host rock (Brown, 1973; Ashworth, 1985).

The intimate association of leucosome gneisses and granoblastic gneisses that is seen on Yell appears to require a single process for their production (Flinn, 1995). If so, this would eliminate metamorphic differentiation, as it could not explain the formation of the homogeneous granoblastic gneisses. The metamorphic grade of the psammites and gneisses is too low for melting to have occurred; although garnet and kyanite are found in the gneissose and non-gneissose psammites, sillimanite is absent, except where the rocks have been thermally metamorphosed by the intrusions of the Graven Complex on the islands in Yell Sound (e.g. Bigga, Samphrey) (Flinn, 1994). The lack of bulk compositional differences between gneisses and non-gneissose rocks and the nature of their field occurrence preclude origins based on metasomatic or magmatic injection hypotheses (Flinn, 1994, 1995). Thus, it would appear that none of the normally accepted processes invoked to explain migmatization may be applied to the formation of the gneisses of Yell.

The gneissification appears to be the result of grain-growth recrystallization. In the absence of any other mechanism of gneissification that explains these features satisfactorily, Flinn (1995) suggested that the recrystallization resulted from the pervasive passage of a fluid through the rock along grain boundaries. Fluid flow along the grain boundaries would facilitate the inter-grain diffusion needed for growth, while the differences between the grain-boundary fabrics of the granofels and the schists would lead to differences in the textures of the resultant recrystallized gneisses. The granofels would coarsen to a rock with a similar grain-boundary fabric because the quartz and feldspar grain boundaries would tend to remain pinned by the adjacent isolated mica flakes. In the schists the quartz and feldspar grain boundaries would slide along the continuous strings of mica flakes, allowing the quartz, and feldspar grains to grow freely to form leucosomes (Flinn, 1995). The gneisses retain their compositions indicating that the fluid was dominantly water.

The microcline-plagioclase leucosome gneiss exposed in the quarry at the north end of the Gutcher GCR site is one of a number of lenticular masses of similar rock in the Yell Sound Group that occur inland on Yell. The contacts of the gneiss near Gutcher are not exposed, but it appears to be sharply confined and is considered to be an orthogneiss, formed from a granitoid intrusive body, which was emplaced prior to regional metamorphism. The hornblende schists seen within the psammites also represent early igneous intrusions that have been metamorphosed, in this case originally dolerite or basalt sheets.

The Valayre Gneiss, which is exposed on the coast to the south of the Gutcher GCR site, is described in more detail in the **Voxter Voe and Valayre Quarry** GCR site report (this chapter). This microcline-megacryst augen gneiss is inferred to represent a lithological and tectonic break in the East Mainland Succession, but has not been interpreted further. The microcline augen are believed to be porphyroblasts, which grew during coeval deformation, localized movements and regional metamorphism in the area (Flinn, 1994).

Conclusions

The Gutcher GCR site contains exposures of typical rocks of the Yell Sound Group, which has been correlated with parts of the Moine Supergroup of mainland Scotland. To the south of the Gutcher ferry terminal are metamorphosed sandstones (psammites), which have been in places partially recrystallized during metamorphism to form 'semigneisses'. Also present within the site are microcline-rich leucosome gneisses, possibly formed by metamorphism of a granitic intrusion, and a microcline-augen gneiss of as yet uncertain origin. The site is one of national importance as it provides easily accessible exposures of many of the different types of gneiss that make up the largely drift-covered island of Yell.

NORTH SANDWICK (HU 550 957–HU 550 969)

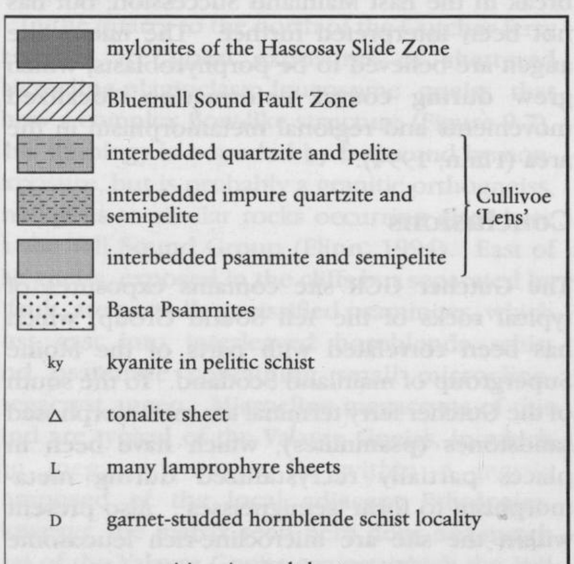
D. Flinn

Introduction

The section at North Sandwick, on the east coast of the island of Yell, provides over 1 km of continuous coastal exposure of banded psammites and pelites of the Yell Sound Group, which underlies most of Yell, and is an easily accessible locality for the study of these rocks (Figure 9.8). In particular, this site provides excellent exposures of a unit of quartzite, pelite and semipelite known as the Cullivoe 'Lens' (Flinn, 1994). Rocks of the Hascosay Slide Zone are also exposed.

Description

Psammites and semipelites of the Cullivoe 'Lens' are especially well exposed on the beach at Sand Wick (HU 548 966) where they have been polished by the sea and sand. The bedding dips steeply to the west and the rocks are banded on a scale of about 10 cm, reflecting small variations in mica content (Figure 9.9). They have a strong schistosity parallel to the compositional banding, and a weak mica-fabric lineation that plunges northwards at about 10°, parallel to the axes of small-scale, intrafolial, tight to isoclinal folds. The layer-parallel schistosity is a characteristic of the rocks of Yell, whereas the lineation



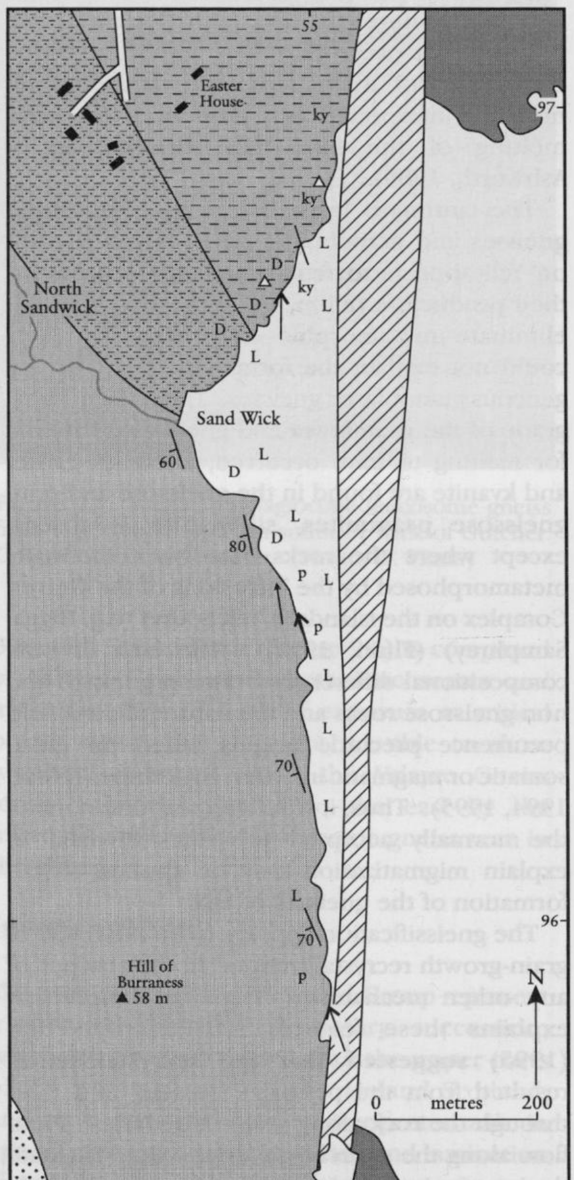


Figure 9.8 Map of the north-east coast of Yell, around the North Sandwick GCR site.

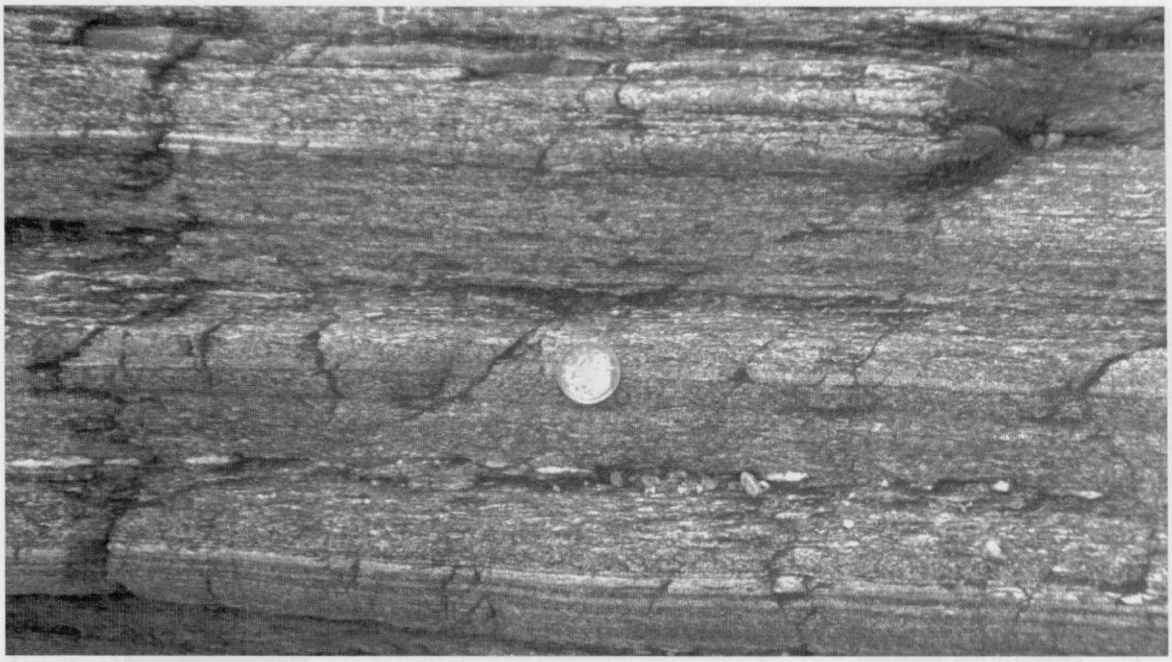


Figure 9.9 Interbanded mica-rich and mica-poor psammites in the Cullivoe 'Lens' on the south side of Sand Wick (HU 5487 9655). Coin is 2.5 cm in diameter. (Photo: D. Flinn.)

development is much more variable across the island (Flinn, 1994).

Exposure is continuous in the cliffs to the north and south, but there the rocks are less favourably weathered. The lithology remains constant to the south, but to the north the psammites become increasingly siliceous and eventually quartzitic, whereas the micaceous bands become more pelitic.

At the beach at Sand Wick the more mica-rich bands are somewhat coarser in grain size than the mica-poor bands, probably due to the onset of recrystallization, as described by Flinn (1995) and as seen in the **Gutcher** GCR site. This is supported by the presence in places of near-microscopic quartz-feldspar augen (proto-leucosomes). The coarser micaceous bands have a fissile schistosity causing them to break into flakes when hammered. This fissility increases gradually but continuously to the south, so that hammering the rocks close to the Bluemull Sound Fault produces only a handful of postage-stamp-like flakes. The rocks look sheared, but are shattered, with the fractures coincident with the schistosity.

At the northern end of Sand Wick (HU 551 970), quartzite beds varying from several centimetres to several metres in thickness are interbedded with coarse-grained, schistose pelite units that contain laths of blue kyanite up to 2 cm long, together with garnet and staurolite. Along the mica schist band to the north, there are coarsely crystalline quartz-kyanite segregation veins up to 10 cm across. Close to the Bluemull Sound Fault the rocks have been shattered, giving rise to crushing of the quartzites and highly fissile pelitic rocks. The shattering becomes extreme for a few metres adjacent to the broad band of powdered rock, probably deeply weathered cataclasite, which forms the fault zone, and which has been preferentially eroded to form a prominent bay at HU 552 970.

A variety of early and late igneous rocks can be seen within the North Sandwick GCR site (Flinn, 1994). Sparsely dispersed among the metasedimentary rocks are conformable hornblende schist bands of sub-millimetre grain-size studded with *c*. 2 mm garnets. These early intrusive mafic sheets are characteristic of the Yell Sound Group. Later intrusions include late-metamorphic tonalite sheets, irregular thin cross-cutting red-feldspar pegmatite veins and conformable late Caledonian lamprophyre sheets, many of which are xenolithic.

At the south end of the section, some 100 m along the beach beyond the last exposure of fissile shattered psammite, and on the east side of the Bluemull Sound Fault, is an isolated exposure of the Hascosay Slide Zone. This structurally complex mixture of hornblende-rich rocks and pegmatitic veins is described in more detail in the **Cullivoe** and **Hascosay** GCR site reports (this chapter). The outcrop here is composed of laminated amphibolitic mylonite, partially mylonitized hornblende-feldspar gneiss and pegmatitic veins cut by veins of fine-grained hornblendite. The contorted mass is cut by veins of red-microcline pegmatite, which in turn are cut by a thin lamprophyre dyke. This single small exposure provides an insight into the structure and lithology of the Hascosay Slide Zone. The Hascosay Slide Zone is also exposed in the cliffs at the north end of the site, again to the east of the Bluemull Sound Fault. These exposures are particularly instructive with respect to the residual coarse-grained hornblendic gneiss masses contained in the laminated and banded mylonites.

Interpretation

The psammites, pelites and quartzites of the Yell Sound Group represent a metamorphosed sedimentary succession, which has been correlated with the Moine Supergroup of mainland Scotland, and thus is considered to be Neoproterozoic in age. Flinn (1994) suggested that the sedimentary succession was deposited originally in a deep-water basin, possibly by turbidity currents, and that the pelites and quartzites probably represent original facies variations.

These sedimentary rocks subsequently underwent a regional metamorphism during the Caledonian Orogeny, leading to the formation of psammites and pelites. Before or during the early deformation and metamorphism, dolerite or basalt sheets were intruded into the sedimentary rocks and were subsequently metamorphosed to form the garnetiferous hornblende schists. These mafic meta-igneous rocks, which are abundant in the Yell Sound Group, are also seen in the Glenfinnan and Loch Eil groups in mainland Scotland.

The main fabric formed in the rocks at North Sandwick during the regional metamorphism was the penetrative schistosity that developed parallel to the compositional layering and was subsequently reactivated a number of times (Flinn, 1994). The intrafolial folds seen at Sand Wick probably formed early in the metamorphism, but then continued to develop by becoming increasingly compressed. Associated with this deformation was the formation of the Hascosay Slide Zone, which appears to have formed through intense shearing of mafic and subsidiary felsic Lewisianoid gneisses, and minor psammites.

The Bluemull Sound Fault, which is seen in the North Sandwick GCR site, offsets the geological features of Yell by approximately 5 km dextrally (Flinn, 1994). Just to the south of Yell, this fault joins a major fault known as the Nesting Fault, which has an offset of some 16 km. These faults have probably been reactivated at several times, but their main movement is believed to be Jurassic in age.

Conclusions

The North Sandwick GCR site is of national importance in that it contains excellent exposures of the more-uncommon lithologies of the metasedimentary Yell Sound Group, namely quartzite and kyanite-bearing pelite and semi-pelite of the Cullivoe 'Lens'. It also shows examples of the garnet-studded hornblende schists that represent early intrusive mafic sheets. These features assist its correlation with the Moine succession of the North-west Highlands of Scotland, and notably with the rocks of the Glenfinnan and Loch Eil groups. Also within the site are small, but instructive exposures of the Hascosay Slide and the Bluemull Sound Fault.

HASCOSAY (HU 554 915–HU 561 917)

D. Flinn

Introduction

The cliffs on the south-east side of the small island of Hascosay, off the east coast of Yell, are unique in that they expose a complete section through the Hascosay Slide Zone, here only some 400 m wide. The slide-zone rocks are in contact with the rocks of the Boundary Zone on either side (Figures 9.10 and 9.11). Much of the trace of the Hascosay Slide Zone lies offshore and although it can be traced sporadically for 15 km along the north-east coast of Yell, only partial sections are seen. The slide zone lies within the Boundary Zone, which separates the Moine and Dalradian rocks in Shetland, but its role and mechanisms of formation are unclear.

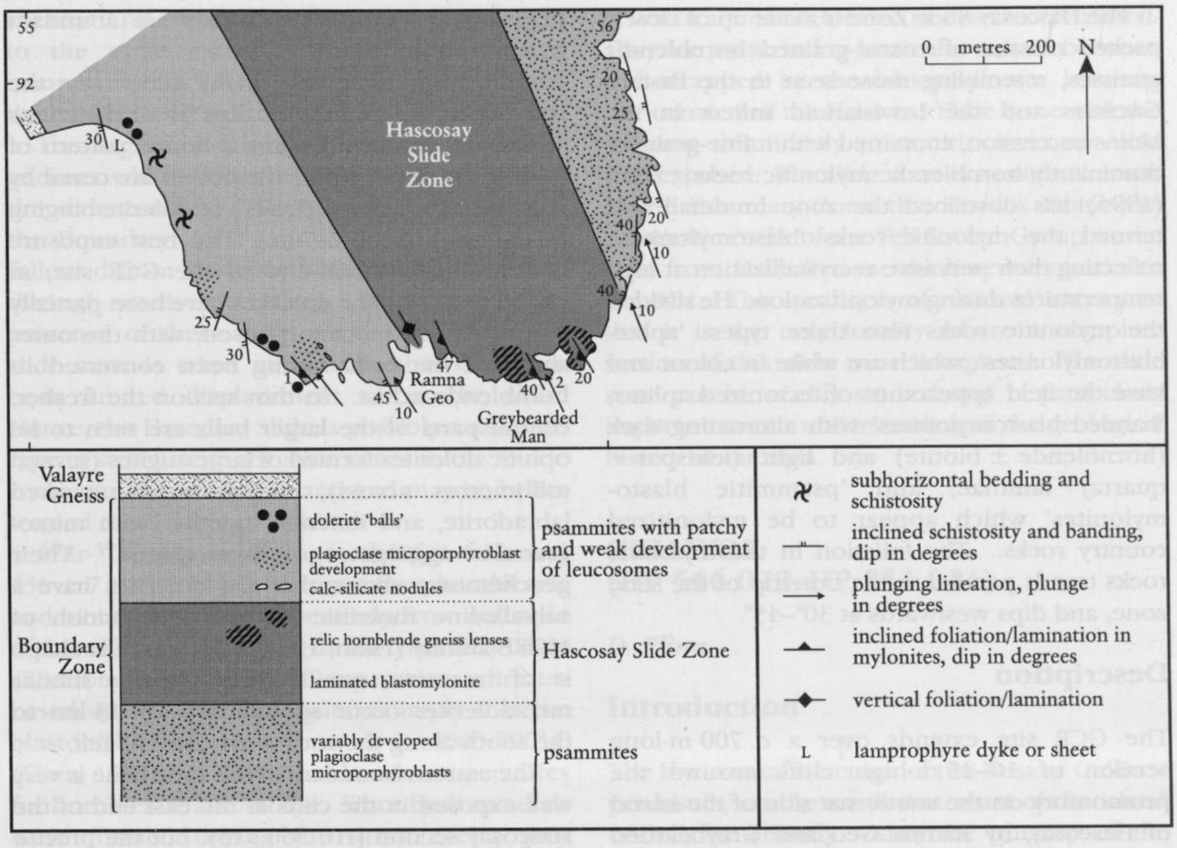


Figure 9.10 Map of the south-east part of the island of Hascosay.

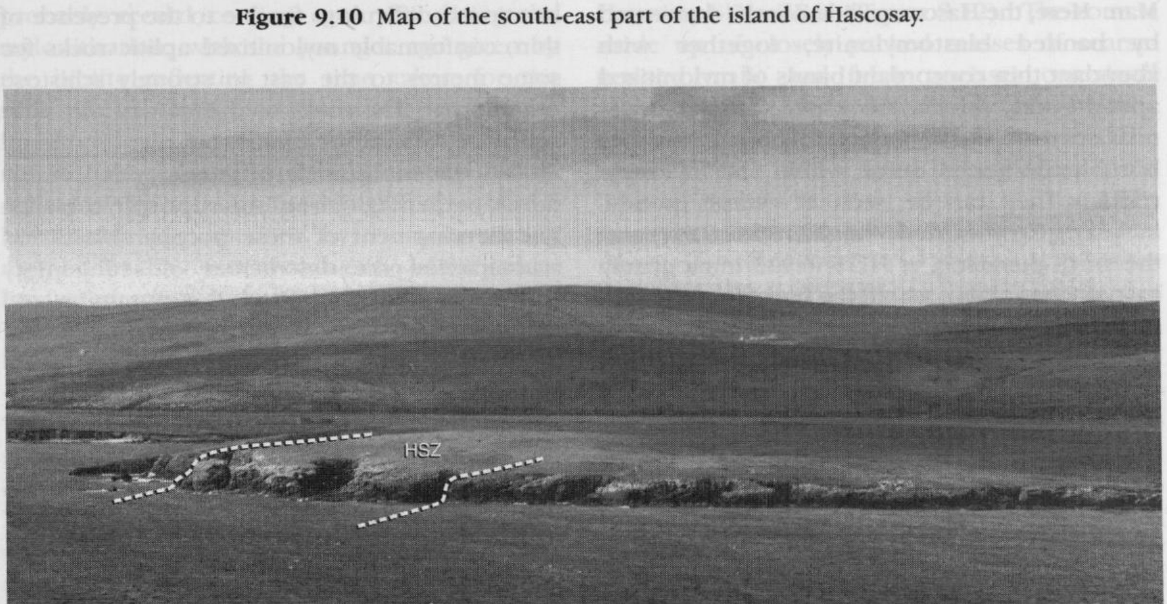


Figure 9.11 View of the south-east part of Hascosay with the east coast of Yell behind. The cliff section through the Hascosay Slide Zone is indicated (see Figure 9.10). (Photo: D. Flinn.)

The Hascosay Slide Zone is made up of closely packed masses of coarse-grained hornblendic gneisses, resembling those seen in the Eastern Gneisses and the Lewisianoid inliers in the Moine succession, contained within fine-grained, dominantly hornblendic mylonitic rocks. Flinn (1994) has described the zone in detail and termed the mylonitic rocks 'blastomylonites', reflecting their pervasive recrystallization at high temperatures during mylonitization. He divided the mylonitic rocks into three types: 'aplite-blastomylonites', which are white in colour and have the field appearance of tectonized aplites; 'banded blastomylonites' with alternating dark (hornblende ± biotite) and light (feldspar + quartz) laminae; and 'psammitic blasto-mylonites' which appear to be mylonitized country rocks. The foliation in the mylonitic rocks trends parallel to the outcrop of the slide zone, and dips westwards at 30°–45°.

Description

The GCR site extends over a *c.* 700 m-long section of 10–25 m-high cliffs around the promontory on the south-east side of the island of Hascosay, by Ramna Geo and Greybearded Man. Here, the Hascosay Slide Zone is dominated by banded blastomylonite, together with abundant thin concordant bands of mylonitized aplitic rocks, which are especially numerous near its eastern boundary. Relict masses of hornblende gneiss occur within the mylonitic rocks. They can be seen at various points, including Greybearded Man (HU 5582 9147) and the small peninsula at HU 556 915 immediately east of Ramna Geo, where the hornblende gneiss is heavily sheared and partially mylonitized. Farther east, at HU 5594 9151, are little-deformed relict mafic gneiss masses formed dominantly of clinopyroxene, garnet and brown hornblende. At HU 5597 9155 a relict lens of quartzofeldspathic gneiss is seen. The resistant masses form lenticular bodies which are wrapped by the laminae in the surrounding mylonites, and which grade into the mylonites over a few centimetres, both on their external margins and in internal ductile shear-zones.

The western margin of the slide zone is exposed at Ramna Geo, where the mylonites are in sharp contact with psammites of the Boundary Zone. The psammites are well bedded in parts and even flaggy. In places they exhibit weakly developed leucosomes, and plagioclase microporphyroblasts are abundant in some areas.

Along the coast west of the slide zone the layering in the psammites dips in all directions at shallow angles reflecting a domal pattern of folding. In some places the domes are cored by near-spherical masses ('balls') of dolerite ranging in diameter from 2–7 m. The best exposure is near the western end of the GCR site, at HU 5547 9147. The dolerites have been partially or completely metamorphosed, with the outer shells of the balls having been converted to hornblende schist. In thin section the fresher, central parts of the larger balls are seen to be ophitic dolerites formed of large augites (several millimetres across), well-twinned unzoned labradorite, and ilmenite together with micro-granular aggregates of hypersthene. Their geochemistry shows that the dolerites have a sub-alkaline tholeiitic basaltic composition of MORB affinity (Flinn, 1994). The globular shape is of intrusive, not tectonic, origin; similar metadolerites occur sporadically for 13 km to the south along the south-east coast of Yell.

The eastern boundary of the slide zone is very well exposed in the cliffs at the east end of the Hascosay section (HU 560 915), but the precise location is difficult to fix due to the presence of thin, conformable mylonitized aplitic rocks for some metres to the east in strongly schistose psammites. The rocks to the east of the slide zone are typical psammites of the Boundary Zone, containing areas of gneiss with variably developed plagioclase microporphyroblasts. The development of these porphyroblasts has accompanied the destruction of sedimentary bedding and banding. Both the psammites and the microporphyroblast gneiss contain bands of hornblende schist, with minor agmatite veins and aplitic sheets that show both conformable and cross-cutting relationships.

Interpretation

The Hascosay Slide Zone has formed through intense deformation and recrystallization under amphibolite-facies metamorphic conditions. Prior to the deformation, the rocks of the slide zone appear to have comprised masses of hornblendic gneiss, together with felsic gneisses, mafic and ultrabasic igneous rocks, psammites, aplitic microgranites and pegmatitic granites. The less-resistant rocks have been mylonitized, whereas the more-resistant elements have been sheared and recrystallized but not mylonitized to the same extent. These more-massive competent rocks form the relict gneiss masses that can be seen in the Hascosay section.

The plagioclase-microporphyroblast psammitic gneisses which form the rocks on either side of the slide zone on Hascosay are found only in the Boundary Zone (Flinn, 1994) and can be followed from Hascosay NNE to Unst and SSW through south-east Yell to Lunna Ness. The presence of these rocks on both sides of the slide zone is taken to indicate that there has been limited displacement across the slide. Hence, the Hascosay Slide is possibly a different type of structure to the slide zones in the Moine rocks of north-west Scotland and may be better termed the 'Hascosay Welt'.

^{40}Ar-^{39}Ar step-heating ages of 496 ± 6 Ma and 436 ± 7 Ma have been obtained from hornblende and biotite separates respectively, from a sample of hornblendic mylonite in the Hascosay Slide (Roddom *et al.*, 1994). Temperature estimates based on mineral compositions imply that the blastomylonites were formed at 600°–700° C (Flinn, 1994), i.e. above the closure temperatures for hornblende and biotite. Since both minerals were formed during the same event, they probably record cooling ages post-dating the mylonitization, with the younger age given by the biotite reflecting the time taken for the slide to cool from the closure temperature for hornblende to that for biotite. It should be noted that the hornblende age from the blasto-mylonites is not significantly different to the hornblende age obtained by the same dating method for the onset of obduction of the ophiolite in Fetlar to the east (Flinn *et al.*, 1991).

Conclusions

The low cliffs of the south-east coast of the island of Hascosay provide a complete and continuous section through the Hascosay Slide Zone. Here, mafic and felsic gneisses, mafic and ultramafic intrusive bodies, psammites, and aplitic and pegmatitic granites have been intensely deformed under amphibolite-facies metamorphic conditions, leading to the formation of blastomylonites. The rocks within the zone were mainly hornblendic mafic gneisses, and deformation has occurred at sufficiently high temperature for recrystallization to take place continuously during deformation. Relict masses of the parent gneisses still remain, some of which are not deformed or even recrystallized. They are preserved as lenticular masses between and wrapped by the blastomylonite laminae. The contacts of the Hascosay Slide Zone with the adjacent dominantly psammitic rocks are also well exposed. The slide zone is a major element of the Boundary Zone that divides Moine-like psammitic rocks of the Yell Sound Group to the west from Dalradian metasedimentary rocks to the east. This locality is of national interest in that it is the only locality where a complete section of this slide zone is exposed. The slide zone can be readily studied and is particularly important to our understanding of the geological history of the area.

CULLIVOE (HP 546 029–HP 551 021)

D. Flinn

Introduction

The low coastal outcrops of the Ness of Cullivoe peninsula, on the north-east coast of the island of Yell, lie entirely within the outcrop of the Hascosay Slide Zone (Figure 9.12). The zone is made up of closely packed masses of coarse-grained mafic and felsic gneisses contained within fine-grained, dominantly hornblendic mylonitic rocks. Flinn (1994) has described the zone in detail, and termed the mylonitic rocks 'blastomylonites' as they appear to have been strongly recrystallized at high temperatures during mylonitization. The peninsula provides excellent clean and readily accessible exposures of these mylonitized mafic rocks, and complements the **Hascosay** GCR site, which provides a section through the whole slide zone.

Description

The GCR site encompasses the foreshore and low cliffs on the north-east and south-east sides of the Ness of Cullivoe peninsula. The majority of the rocks within the Cullivoe GCR site are fine-grained, mylonitic rocks with parallel laminae and bands, ranging in thickness from 0.1 mm to 2 cm (Figure 9.13). Pale-coloured quartz-plagioclase-dominated bands alternate with dark bands, composed mainly of hornblende and biotite with, locally, clinopyroxene and garnet. Flinn (1994) termed these rocks 'banded

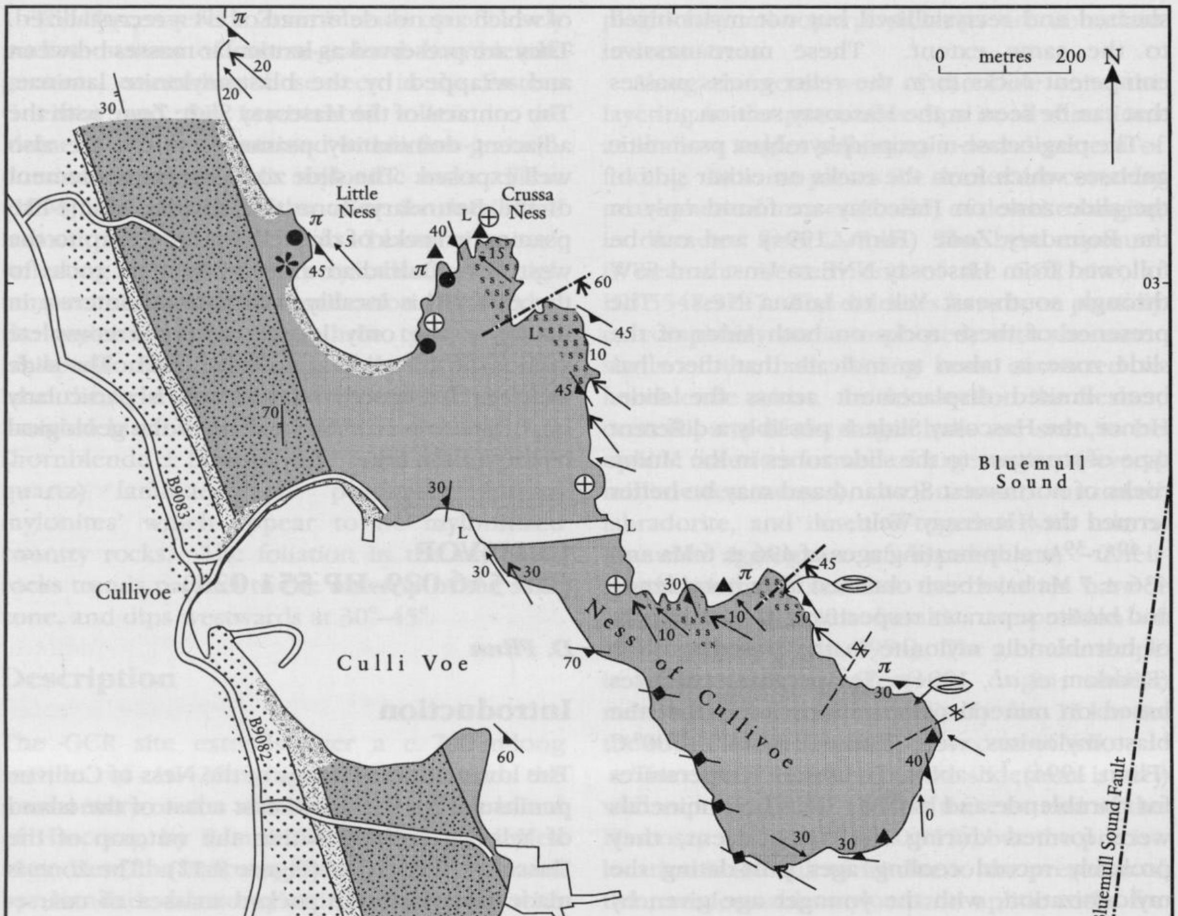
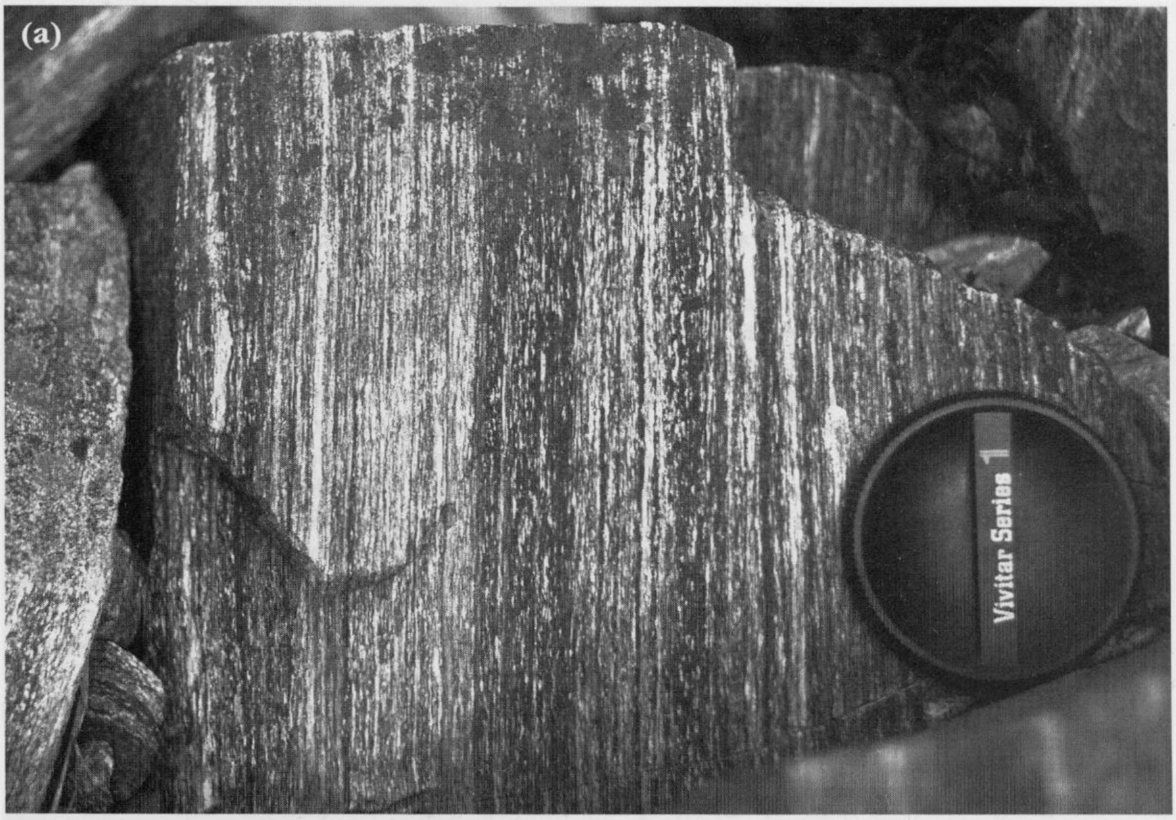


Figure 9.12 Map of the Ness of Cullivoe and the area around Culli Voe, on the north-east coast of Yell.



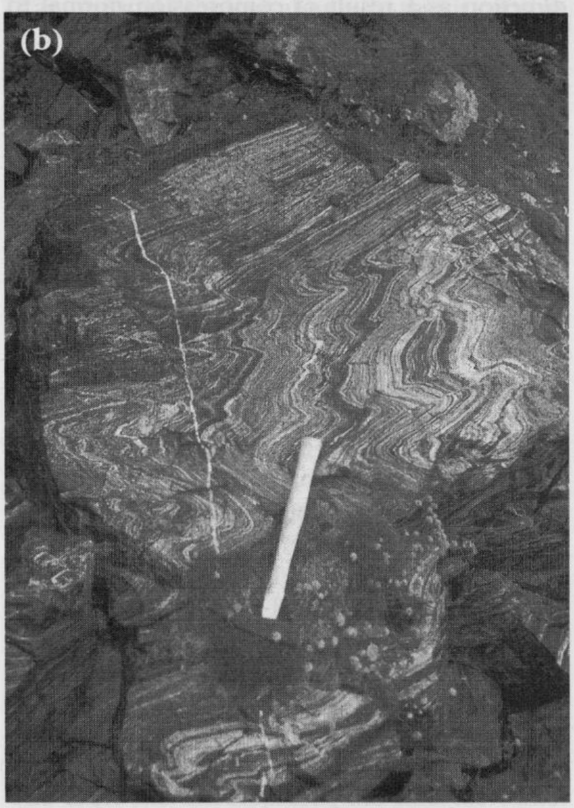


Figure 9.13 Typical blastomylonites of the Hascosay Slide Zone on the Ness of Cullivoe. ▲(a) 'Banded blastomylonite' with hornblende and biotite (HP 551 022). The lens cap is 7 cm in diameter. (Photo: D. Flinn, BGS No. P541972, reproduced with the permission of the Director, British Geological Survey, © NERC.) ◄(b) Folded blastomylonites (HP 548 028). The hammer is 40 cm long. (Photo: D. Flinn, BGS No. P541974, reproduced with the permission of the Director, British Geological Survey, © NERC.)

blastomylonites'. On the scale of the whole slide zone, the overall foliation of the mylonites lies parallel to the zone margins in both strike and dip, and the mineral lineation plunges on average about 20° to the NNW. However, in detail, the foliation shows considerable local variation in strike and dip due to small- and medium-scale folding.

The Cullivoe peninsula is particularly suited for studying folding of the banded blastomylonites. Throughout the peninsula the mylonites show irregular non-cylindrical folds, typically on scales of several metres. Smaller-scale isoclinal and intrafolial folds are unevenly distributed, generally in closely spaced groups, and spectacular examples can be seen in various localities (e.g. at HP 548 028). The folds generally plunge gently northwards, roughly parallel to the mineral lineation, but their axial planes have no preferred orientation and they exhibit a variety of shapes and profiles. Many of these intrafolial folds take the form of isolated detached lenses contained between the laminae of the mylonites.

A unique structure exposed in the cliff at Little Ness (HP 544 031) testifies to the orthorhombic (coaxial) nature of the deformation within the slide. This structure takes the form of a thin pegmatitic vein folded into a pile of ptygmatic folds, but which truncates the laminations of an unfolded mylonite. The pile of ptygmatic folds crosses the laminations at 90° with the fold axial planes parallel to the laminations.

Unlike other exposed tracts of the Hascosay Slide, few undeformed residual masses of gneiss are recognizable on Cullivoe Ness. Those that are still recognizable include several small hornblendite lenses and some distinctive ultramafic relics. The latter include fist-sized lenses of lustrous green actinolite, and larger zoned masses up to 3 m in diameter. The zoned masses have steatite in the core, surrounded by concentric zones of anthophyllite, actinolite and biotite. At the south end of Cullivoe Ness (HP 553 022) are several nearly spherical masses of pyroxenite, up to 7 m in diameter, with thin skins of talc and/or serpentinite.

In the Hascosay Slide Zone the blastomylonites include mylonitized aplitic and pegmatitic rocks that are cut by thin undeformed very fine-grained hornblendite veins, which in turn are cut by undeformed aplitic and pegmatitic veins, and these by Late Caledonian lamprophyre sheets.

Interpretation

The Hascosay Slide Zone has formed through intense deformation and recrystallization at relatively high temperatures (600°–700° C; Flinn, 1994). Prior to the deformation, the rocks of the slide zone appear to have comprised mafic and felsic gneisses with masses of hornblendic gneiss, together with basic and ultrabasic igneous rocks, psammites, aplitic microgranites and pegmatitic granites. The less-resistant rocks have been mylonitized, whereas the more resistant have been variably sheared and recrystallized, but mylonitized to a lesser extent. The folds that can be seen at Cullivoe Ness appear to result from flow perturbations of the laminated mylonite, due to the lithological variations, high strain, and presence of resistant gneiss masses.

The intrafolial isoclinal folds are preserved within lenses contained within the foliation of the mylonites. These folds probably developed progressively during the mylonitization, being initiated as perturbations in the overall flow. Once formed, they resisted further deformation, causing the laminae to diverge around them while the lens continued to flatten. The shapes of the lenses together with the enclosing laminae have orthorhombic symmetry.

The overall symmetry of the blastomylonites in the slide zone, as shown by the preferred lattice and/or grain-shape fabrics, is orthorhombic. The plane of flattening dips to the west, and the extension direction, mineral lineation and fold axes plunge about 20° to the NNW. There is no consistent sense of overturning of the minor folds. Flinn (1994) stated that the lineation did not indicate the direction of monoclinic shearing, as is normally assumed in such zones, but instead represented the coaxial extension direction as a result of compression normal to the slide zone. Hence, Flinn (1994) interpreted the formation of the Hascosay Slide Zone as the result of orthorhombic deformation.

Late in the development of the Hascosay Slide, it was invaded by thin veins of tholeiitic basalt of Mid-Ocean Ridge Basalt (MORB) affinity, similar in composition to the globular meta-dolerite bodies seen in the country rocks adjacent to the slide zone in the **Hascosay** GCR site. These veins were metamorphosed to form the hornblendite veins that can be seen at Ness of Cullivoe. Later intrusions include pegmatitic and aplitic veins, and lamprophyre dykes. These minor intrusions are commonly found cutting the Yell Sound Group and early meta-igneous rocks on Yell, and examples are also seen cutting the Hascosay Slide Zone within the Cullivoe GCR site.

Conclusions

The Cullivoe GCR site lies within the Hascosay Slide Zone, a NNW-trending zone of intense deformation and mylonitization, which lies within the Boundary Zone of north-eastern Yell. The foreshore and low cliff-section on the Ness of Cullivoe peninsula expose laminated and thinly banded mylonitic mafic and felsic gneisses with abundant amphibolitic mafic bodies and subsidiary psammites. This is the best location for the study of spectacular folds of the mylonites. In a number of places highly deformed and partially mylonitized relict masses of the parent gneisses are preserved, together with some metasomatically zoned masses of ultramafic rock. The Cullivoe GCR site is of national importance as it provides spectacular yet readily accessible examples of the structurally complex Hascosay Slide Zone and is ideal for detailed further studies and for teaching purposes.

VOXTER VOE AND VALAYRE QUARRY (HU 360 692–HU 362 706)

D. Flinn

Introduction

The Voxter Voe and Valayre Quarry GCR site contains several exposures of the Valayre Gneiss, including the Valayre Burn, where this unit was first described (Flinn, 1954). The Valayre Gneiss is an unusual lithological unit, in that it consists of microcline-megacryst augen in a variety of matrices. At the Valayre Quarry the matrix is a semipelite or micaceous psammite, but in other areas the matrix is pelitic and in places the gneiss resembles a deformed granite.

The Valayre Gneiss outcrop extends over a strike length of about 75 km. It occurs down the east coast of Yell (Figure 9.2) and across the Delting peninsula in the north of Mainland Shetland, where it marks the eastern limit of the Yell Sound Group, which is considered to represent the Moine Supergroup in Shetland. Accessible exposures of psammites of the Yell Sound Group occur in the GCR site in the cliffs to the north and south of Voxter Voe (Figure 9.14). The Valayre Gneiss generally marks the western limit of the Boundary Zone, which divides the dominantly Moine-like psammitic sequence to the west, from a more-mixed meta-sedimentary and metavolcanic succession to the east that is assigned to the Dalradian Supergroup.

Description

The GCR site encompasses the inlet of Voxter Voe and the adjacent shore and low cliffs of Sullom Voe to the north and south. It includes the lowermost part of the Burn of Valayre and the adjacent Valayre Quarry, which was formerly worked for roadstone and rock fill.

The key feature of this site is the Valayre Gneiss, which is exposed in the Valayre Burn, as well as at a number of other locations (Figure 9.14). The gneiss forms a zone containing abundant white microcline-megacryst augen, which varies in width up to 3 m in this area, but elsewhere can attain several hundred metres in thickness. The matrix lithologies are those of the local rocks, commonly with a mylonite-like schistosity. Thus, the unit varies from a schist, to a psammitic granofels, a leucosome-rich gneiss, a granoblastic gneiss, and even an anatectic gneiss in different parts of Shetland. The boundaries of the Valayre Gneiss are defined by the presence or absence of microcline megacrysts, and only rarely do they coincide with a change in matrix lithology. In this area the matrix rock-type is a schistose micaceous psammite or semipelite.

The microcline megacrysts vary from smoothly rounded to near-rectangular (up to 2:1), and are up to 5 cm long in their greatest dimension. Where the rock is lineated, the augen are best displayed on rock faces containing the lineation, and they commonly have tails composed of matrix-sized grains. The resulting augen having fat lenticular shapes that, together with the schistosity, impart a mylonitic appearance to the rock. The megacrysts are generally several centimetres apart; a typical example is seen where the gneiss crosses the Burn of Valayre (Figure 9.15) (HU 3676 6945) and on North Ward (HU 369 715). However, in the Valayre Quarry (HU 3684 6959) the augen are atypical in that they are small and commonly several tens of centimetres apart.

In thin section some of the smaller augen are seen to be composed of two or more grains, or even aggregates of smaller microcline grains. Plagioclase augen up to several millimetres in diameter also occur, and these can also be composed of single or multiple grains. Some of the large microcline augen have rims about one matrix-sized-grain thick, made up of plagioclase and microcline, giving the rock a rapakivi-like texture. Such rims are absent from the plagioclase megacrysts. Some of the microcline-megacrysts contain inclusions of biotite apparently similar to the matrix biotites, but somewhat larger and with a different orientation.

The augen are all closely wrapped by the schistosity, defined mainly by micas in the matrix,

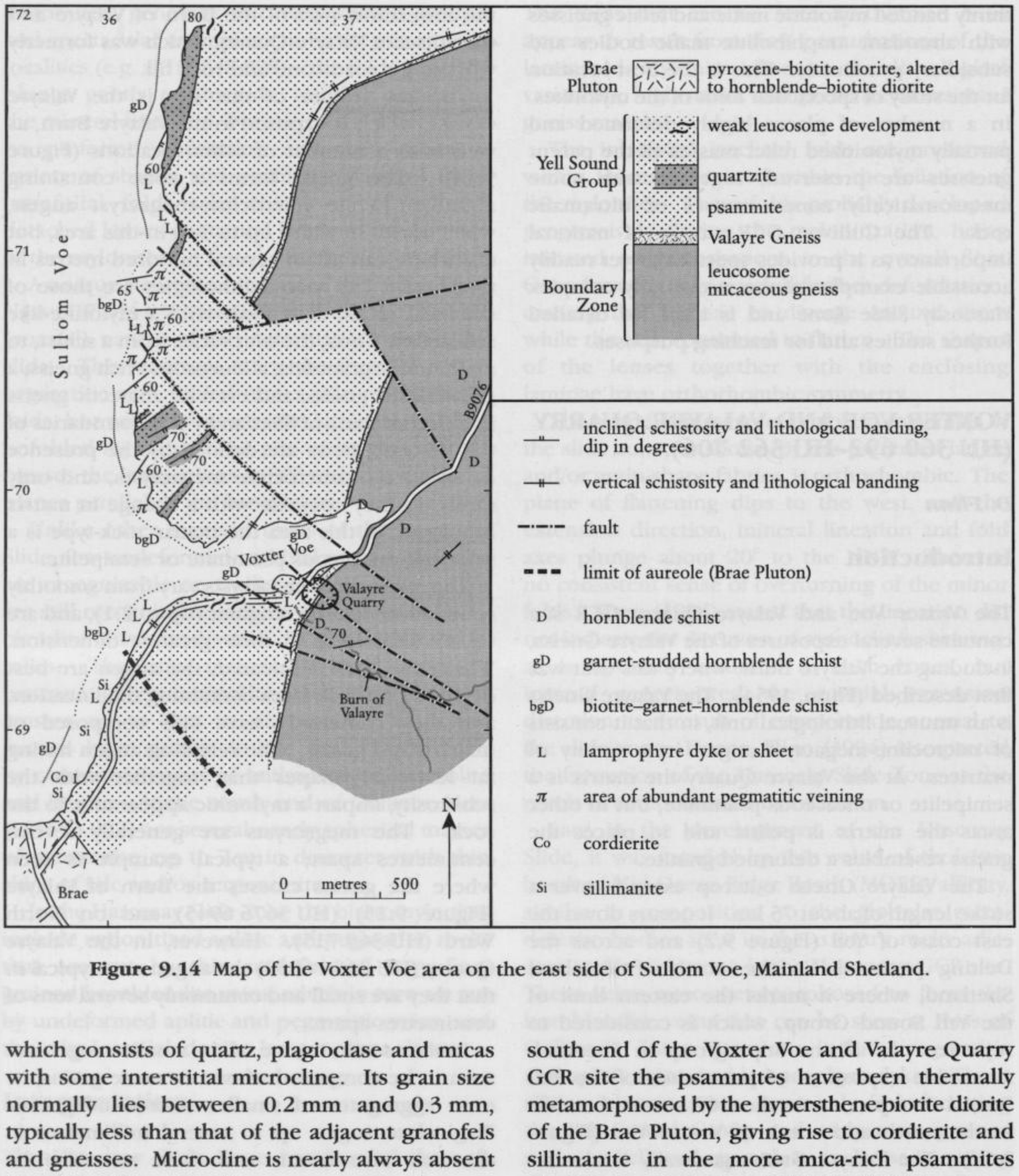


Figure 9.14 Map of the Voxter Voe area on the east side of Sullom Voe, Mainland Shetland.

which consists of quartz, plagioclase and micas with some interstitial microcline. Its grain size normally lies between 0.2 mm and 0.3 mm, typically less than that of the adjacent granofels and gneisses. Microcline is nearly always absent from the adjacent rocks.

The contact of the Valayre Gneiss with the Yell Sound Group can be seen in the Burn of Valayre, and these underlying rocks are exposed in the coastal cliffs of this GCR site. The dominant lithology exposed along the coastal sections is psammitic granofels. Where there is weak development of leucosomes, the psammites are termed 'semigneisses'. Similar rocks, again in the Yell Sound Group, are described in more detail in the **Gutcher** GCR site report (this chapter). At the south end of the Voxter Voe and Valayre Quarry GCR site the psammites have been thermally metamorphosed by the hypersthene-biotite diorite of the Brae Pluton, giving rise to cordierite and sillimanite in the more mica-rich psammites close to the contact and fibrolite farther away.

Interbanded with the psammites to the north of Voxter Voe are a number of distinctive beds of quartzite that are colour laminated on a centimetre-scale, with rectilinear parallel pale-brown stripes. Similar striped quartzites occur to the north on the small island of Bigga and at Copister on the southern tip of Yell, but are not seen elsewhere in Shetland.

Garnet-studded hornblende schist bands occur widely in the psammites of the Yell Sound

Figure 9.15 Microcline-megacryst augen gneiss of the Valayre Gneiss in the Burn of Valayre, Voxter (HU 3676 6945). 20 p coin for scale. (Photo: D. Flinn.)

Group along the coastal section at the Voxter Voe and Valayre Quarry GCR site, with garnets locally up to 1 cm across. In a number of places, particularly at Brei Wick (HU 363 708), narrow bands of coarse-grained biotite schist occur which are similarly garnet-studded, while adjacent hornblende schist bands tend to have coarse-grained biotite schist selvages and/or scattered flakes of biotite. The exposures show all gradations, from hornblende schist bands with no biotite, to biotite schist bands with no hornblende, both with and without garnet. In thin section the biotite schist bands are seen to contain some recrystallized hornblende, and the field occurrence is consistent with potash metasomatism having transformed the hornblende to biotite.

The coastal section to the north and south of Voxter Voe has suffered much intense cataclasis as it forms part of the shatter zone along the Walls Boundary Fault (Flinn, 1977). The quartzites are particularly heavily shattered, while the psammites to the south of Voxter Voe have been contorted around vertical axes for 500 m to the east of the contact with the diorite of the Brae Pluton.

The rocks to the east of the Valayre Gneiss are mostly mica-rich leucosome psammitic and semipelitic gneisses belonging to the Boundary Zone. These gneisses contain rare hornblende schist bands, but no garnetiferous examples are seen, either here or elsewhere in the Boundary Zone gneisses.

Interpretation

The Valayre Gneiss marks the eastern boundary of the Yell Sound Group, and can be traced along strike for some 75 km up across northern Mainland Shetland and along the east coast of

Yell. The gneiss appears to form a near-continuous element of the geology, apart from interruptions by late faults, and is undoubtedly a significant feature in the geological history of Shetland. It coincides with a major, but not instantly obvious, lithological and tectonic break. Close study of these rocks has shown that the rocks of the Boundary Zone to the east of the Valayre Gneiss are notably different to those of the Yell Sound Group to the west (Flinn, 1994). However, the Valayre Gneiss does not mark the contact between the Moine and Dalradian in Shetland. About 1 km to the east of the Valayre Gneiss in the Voxter area is the Skella Dale Burn Gneiss, which is characterized by parallel-orientated ovoid microcline augen, about 1 cm long, in a quartzofeldspathic matrix. Like the Valayre Gneiss, it can be followed for more than 50 km along strike, and marks the eastern margin of the Boundary Zone and its contact with the Scatsta 'division', the lowest part of the Dalradian Supergroup in Shetland (Institute of Geological Sciences, 1981).

In some places the Valayre Gneiss has a mylonitic appearance in the field, but in thin section it is obvious that a mylonitic fabric has been modified by later pervasive recrystallization. The augen have the appearance of porphyroblasts, not porphyroclasts, and Flinn (1994) suggested that they grew in a zone of movement, coeval with the regional metamorphism of the area. This movement brought the Moine and Dalradian blocks together to form the East Mainland Succession. Similar megacryst augen elsewhere in the world have been interpreted as relict phenocrysts (Vernon, 1990), but this explanation does not seem appropriate for the Valayre Gneiss, whose genesis has yet to be fully explained.

The hornblende schist and biotite schist bands at this site that represent early mafic intrusive sheets and bodies in the Yell Sound Group have been analysed for major- and trace-elements. Their geochemistry shows that potassium contents increase with increasing biotite content, whilst calcium content decreases. Biotite schists of this type occur only in the proximity of the Brae Pluton, a two-pyroxene-mica-diorite (Gill, 1965), and of the Graven Complex, a cluster of predominantly appinitic granodiorite intrusions that lies north of the GCR site (Flinn, 1985). Biotite from one biotite schist band has been dated by the K-Ar method at 391 ± 12 Ma (J.A. Miller, pers. comm.). A similar age of 392 ± 6 Ma was obtained from late-stage biotite from an altered two-pyroxene-mica-diorite of the Brae Pluton (Miller and Flinn, 1966). However, biotite from an unaltered two-pyroxene-mica diorite gave an age of 437 Ma (Gill, 1965). Biotites from the Graven Complex all give ages of about 407 Ma (Miller and Flinn, 1966). These dates have been recalculated using currently accepted decay constants. It is concluded that the hornblende schists were metasomatized soon after the emplacement of the Graven Complex, by late-stage fluids associated with the intrusions.

Conclusions

The Voxter Voe and Valayre Quarry GCR site contains the type locality of the Valayre Gneiss, first described by Flinn (1954). This microcline-megacryst augen gneiss lithology, which can be traced across Mainland Shetland and Yell, marks the eastern boundary of the Yell Sound Group, the Shetland equivalent of the Glenfinnan and Loch Eil groups of the Moine Supergroup on the Scottish mainland. Rocks of the Yell Sound Group are exposed in the coastal sections of this site. The Valayre Gneiss also marks the western margin of the Boundary Zone, a 1–2 km-wide tectonically assembled band of mostly gneissose rocks that lies between the Moine and Dalradian group equivalents in Shetland. It remains unclear as to the origin and full geological significance of the Valayre Gneiss, but the site is undoubtedly of national importance and suitable for further study.